

UNIVERSITY OF BIRMINGHAM

A Decision Support System for Optimum Selection and Placement of Sustainable Urban Drainage System (SUDS) in Arid and Semi-Arid Region

By

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Abstract

The sustainable management of stormwater runoff in urban areas has been a key subject of interest in recent years, leading to the introduction of Sustainable Urban Drainage Systems (SUDS), such as green roofs and permeable pavements as an alternative to traditional grey infrastructure approaches. SUDS offer many benefits such as stormwater runoff and quality control, improved air quality, reduced temperatures and other social benefits. However, the most significant challenges of SUDS implementation is the inherent complexity in the determination of the most effective SUDS type and their optimum location due to various local and regional variations in catchment and climate parameters. Due to limited application of SUDS in arid and semi-arid regions (ASARs), there is lack information regarding their effictiveness and financial cost.

This research describes the development of a decision support system (DSS) for optimum selection and placement of SUDS for urban stormwater management in ASARs. A Survey was conducted to identify the suitable type of SUDS for ASARs and also the costs of building and maining them. The Environmental Protection Agency's Storm Water Management Model (SWMM) model was developed and calibrated for an urban study watershed in Jeddah, Kingdom of Saudi Arabia (KSA). The SWMM model was then connected to the Borg Multi-objective Evolutionary Algorithm to build the DSS also refered to as the SUDS-optimisation-framework. The DSS is capble of identifying optimum SUDS type and location based on the trade-off curves of two objectives: cost and runoff volume reduction. DSS was used to deterime optimum SUDS type and location in the study site for different scenarios of climate, land conditions and related SUDS constraints.

Based on the outcomes of a survey, four types of SUDS practices, namely, green roofs (GRs), permeable pavements (PPs), rain gardens (RGs), and bio-retentions (BRs), were selected. The Permeable pavement was identified as the most frequently selected SUDS option across all scenarios. The results also indicated an average stormwater runoff volume reduction of 17% across all scenarios. SUDS where found to have the most impact on the reduction of peak flow and runoff volume of 15.5% and 20%, respectively, in scenario 10: where a 100-year rainfall and SUDS option 1. SUDS option 1 involved application of SUDS options, PP, BR and RG without restriction, and along with application of GRs to all commercial and government buildings but no GRs on residential buildings. The outcome of this study highlighted that future climate change is likely to have a significant impact on urban stormwater management in

Jeddah City and, thus, is a significant factor which needs to be incorporated into the development of stormwater management systems to ensure that they are sustainable.

Dedication

This thesis is dedicated to my great father, my faithful mother, my dear brother, my beloved wife, my lovely daughter, and my sisters

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Contents

Abstract II
Acknowledgements V
Contents X
List of Figure XV
List of Tables XXI
List of Symbols and Abbreviations XII
Chapter One: Introduction 1
1.1 Background 1
1.2 Problem Statement 7
1.3. The Importance and Role of a Decision-Support-System for SUDS Selection and Placement 9
1.4 Aim and Objectives 11
1.5 Study Watershed 12
1.6 Original Contributions 12
1.7 Thesis Structure 13
Chapter Two: Literature Review 14
2.1 Overview 14
2.2 Evaluation of Sustainable Urban Drainage Systems (SUDS) 14
2.2.1 Introduction 14
2.2.2 SUDS and Hydrology 15
2.2.3 SUDS and Water Quality 17
2.2.4 Types of SUDS 20
2.2.5 SUDS in Arid and Semi-Arid Regions (ASARs) 31
2.2.6 The Most Effective SUDS for Arid and Semi-Arid Regions 35
2.3 Lifecycle Costs of SUDS 36
2.4 Regulations and Design Principles for SUDS 40
2.5 Computer Modelling of SUDS 43
2.5.1 Introduction 43
2.5.2 Reviewing Stormwater Management Tools 43
2.6 Stormwater Management Model (SWMM) 50

2.6.1 SWMM Overview 50
2.6.2 Infiltration and Runoff 50
2.6.3 Flow Routing 53
2.6.4 Input Parameters for SWMM 54
2.6.5 Hydrological Components 55
2.6.6 SUDS Representation in SWMM 56
2.7 Calibration of Rainfall-runoff Models 57
2.7.1 Introduction 57
2.7.2 Calibration of Ungauged Catchment 58
2.8 Current Studies on Selection and Placement Optimisation of SUDS 60
2.8.1 Modelling and Optimisation of SUDS 60
2.9 Optimisation in Stormwater Management 72
2.9.1 Overview 72
2.9.2 Multi-Objectives of Optimisation and the Application in Stormwater Management 73
2.9.3 Genetic Algorithms 74
2.9.4 The Non-dominated Sorting Genetic Algorithm-II (NSGAII) 77
2.9.5 Borg MOEA 79
2.10 Summary and Key Gaps in Knowledge 81
Chapter Three: Study of Watershed within Jeddah City 84
3.1 Introduction 84
3.2 Background for Jeddah City 84
3.2.1 Climate 87
3.3 The Study Area 88
3.3.1 Overview of Planning Area D 88
3.3.2 Soil and Slope 91
3.3.3 Existing Drainage System 92
3.4 Available Data 94
3.4.1 Topography, Geology and Existing Infrastructure Data 94
3.4.2 Rainfall Data 95
3.4.3 Flow Data 98
Chapter Four: Development of Jeddah-SWMM Model 103

4.1 Introduction 103
4.2 Building the Jeddah-SWMM Model (Model Development for Jeddah City) 103
4.1.1 Delineation of Drainage Area and Stormwater System Representation 104
4.1.2 The Default Parameter Values of the Jeddah-SWMM model 109
4.3 Calibration and Verification of Jeddah-SWMM Model 113
4.3.1 Sensitivity Analysis 113
4.3.2 Jeddah-SWMM Model Calibration and Selection of Rainfall Events for Calibration 115
4.4 Results and Discussion 116
4.4.1. Sensitivity Analysis: Results 116
4.3.2 Calibration for the 25/11/2009 Event 118
4.3.3 Calibration for the 29/12/2010 Event 120
4.3.4 The Calibrated JEDDAH-SWMM Model 123
4.4.5 Verification of the Jeddah-SWMM Model 124
4.5 Conclusion 125
Chapter Five: Research Survey by Questionnaire 126
5.1 Introduction 126
5.2 Methodology 126
5.2.1 Questionnaire Design 126
5.3 Data Analysis Methods 130
5.4 Results and Discussion 132
5.4.1 Theme One: The Suitability of SUDS for Jeddah City 134
5.4.2 Theme Two: SUDS Types Appropriate for Jeddah City 135
5.4.3 Theme Three: Challenges of SUDS Implementation in Jeddah City 138
5.4.4 Theme Four: Opinions and Comments 141
5.4.5 Theme Five: Government Regulations and SUDS in Jeddah City 142
5.4.6 Theme Six: Cost Estimates 143
5.5 Conclusions 146
Chapter Six: Design of SUDS Parameters in SWMM and Development of Cost Functions 148
6.1 Overview 148
6.2. SUDS Design Strategy 148
6.2.1 The Design of Green Roofs 148

6.2.2 The Design of Rain Gardens 151
6.2.3 The Design of Bio-retention Units 153
6.2.4 The Design of Permeable Pavements 155
6.3 Calculating SUDS Lifecycle Costs 159
6.3.1 Introduction 159
6.3.2 Methodology for Calculating SUDS Lifecycle Costs 159
6.3.3 The SUDS Layout and Total Lifecycle Cost Calculation 163
Chapter Seven: Selection and Placement Optimization of SUDS in the Jeddah Study Watershed 167
7.1 Overview 167
7.2 Optimisation Methodology 167
7.2.1 Layout of Optimisation Simulation Framework 167
7.2.2 Objective Functions 170
7.2.3 Decision Variables 171
7.2.4 Parameter Settings for the Optimisation Process 172
7.2.5 Verification of Optimisation Framework 175
7.3 Development SUDS optimisation scenarios for the Jeddah study watershed 176
7.3.1 Design Storm and Climate Change 176
7.3.2 SUDS Implementation Options 180
7.4 Results and Discussion 185
7.4.1 Overview 185
7.4.2 Scenario 1: 6-hour 2-year rainfall and SUDS option 1 185
7.4.3 Scenario 4: 6-hour, 10-year rainfall and SUDS option 1 191
7.4.4 Scenario 7: 6-hour, 25-year rainfall event and SUDS option 1 194
7.4.5 Scenario 10: 6-hour 100-year rainfall and SUDS option 1 197
7.4.6 Scenario 13: 6-hour 100-year rainfall under 30% CC and GR option 1 200
7.4.7 Comparison of Scenarios 203
7.4.8 SUDS Optimisation with a Fixed Annual Budget 213
7.5 Summary 219
Chapter Eight: Conclusion and Recommendations 221
8.1 Conclusion 221
8.1.1 Factors that Affect the Use of SUDS in Arid and Semi-Arid Regions (ASARs) . 221

8.1.2 Suitable Stormwater Simulation Model for SUDS Selection and Placement 222
8.1.3 SUDS in Arid and Semi-Arid regions: Survey by Questionnaire 222
8.1.4 Parameterising and Calibrating SWMM for the Study Watershed 223
8.1.5 Selection of Appropriate Optimisation Algorithm and Setting-up of the SUDS Optimisation Framework 223
8.1.6 SUDS Optimisations in the Study Watershed 224
8.2. Recommendations for Future Research 225
References 228
Appendices 251
Appendix A: The Jeddah Watershed Data 251
A-1 Geological Map 251
A-2 Historical Rainfall Data 252
A-3 Techniques and Procedures for Calculations of Flow Estimations 253
A-3-1 SCS Curve Number Method (SCS-CN) 253
A-3-2 Development of Run-off Curve Numbers for Selected Study Watershed 255
A-3-3 Time to Peak and Peak Flow Calculation 256
A-4 List of Tables Used for Estimation of Flow Calculations 260
A-5 Data of Existiong Storm Drainage Network 263
A-6 Intensity – Duration – Frequency (IDF) Curves 265
Appendix B: The Jeddah Watershed Hydrologic Models (Jeddah-SWMM Model) 266
B-1 Results of Calibration and Verification 266
B-2 SWMM Input fille 283
Appendix C: Information's related to Survey by Questionnaire 290
C-1 A Copy of an email that sent to participants 290
C-2 Consent Form 291
C-3 A full copy of the distributed questionnaire 294
C-4 Ethical Review Aproval (ID: ERN_19-1054) 297
C-5 The full tabulation of the questionnaire survey for each question under each theme. 298
Appendix D: Code of SUDS Optimisation Framwork and Simulation results 308
D-1 Linking SWMM Model with MATLAB Script 308
D-2 Fitness Function: 309
D-3. Main Code of the Borg MOEA that Optimise a multiobjective problem 311

D-4 Results of Simulation 311

List of Figure

Figure 1-1 The distribution of global climatic zones (Ma, 2016). 2

Figure 1-2 Present day rainfall levels of the Arabian Peninsula for each climate zone (Jennings et al., 2015) 2

Figure 1-3 Traditional stormwater management in urban areas (Hillsbor, 2019) 3

Figure 1-4 Sustainable urban drainage practices (hidrologiasostenible.com) 5

Figure 1-5 A comparison of annual runoff values and different pollution values for scenarios assumed and tested by Jia et al. (2014). 6

Figure 2-1 SUDS to target specific areas of urban drainage in the United Kingdom – clockwise from left: highway draining biofilters, storage basin, swale and linear wetland (Ashley et al., 2015, p.3). 17

Figure 2-2 The order of preference (rank one is the best) for SUDS interventions developed by Ellis, et al., (2012 p.175) based on the ability of each option to remove suspended solids and organic pollutants concentration in urban stormwater runoff. 19

Figure 2-3 Example of Green Roofs (Navy, 2013) 21

Figure 2-4 An example of a rain garden (EPA, 2020). 23

Figure 2-5 Bio-retention incorporated into sidewalk and parking lot from right to left, respectively (EPA, 2013) 25

Figure 2-6 The structure of a permeable pavement (Lucke and Dierkes, 2015 p.16). 26

Figure 2-7 The pareto fronts developed by Vincent et al., (2017) to indicate the cost and benefits of two SUDS scenarios with and without the consideration of the benefits derived from ES (Vincent et al., 2017 p.855). 39

Figure 2-8 Showing the comparison between rainfall runoff models and transport models (Haris et al., 2016) 44

Figure 2-9 The conceptualisation of surface runoff within a subcatchment where d equals the depth of water over the subcatchment and ds is the maximum depression storage. Adapted from Rossman (2015). 51

Figure 2-10 The conventional curve number model where *P* = rainfall and *Q* = surface runoff (Chin, 2018 p.188) 53

Figure 2-11 A conceptual diagram of the layers representing a BR within the SWMM model. Adapted from Rossman (2015 p.78). 56

Figure 2-12 Example of Pareto-optimal front. Adapted from (Ref) 74

Figure 2-13 An example of two parent solutions undergoing single genetic crossover to create two child solutions, where WW1, WAREA, WW3, WSLOPE and WW5 represent the sensitive runoff parameters that are being altered (Wan and James, 2002, p.94). 76

Figure 2-14 An example of a mutation operation whereby a child solution undergoes mutation to create a new solution., where WW1, WAREA, WW3, WSLOPE and WW5 represent the sensitive runoff parameters that are being altered (Wan and James, 2002, p.96). 77

Figure 2-15 A flow chart of the NSGAII process (Garg et al., 2012, p.1998) 78

Figure 2-16 gives an overview of this study, including all processes. 83

Figure 3-1 The geographical location of Jeddah City and b. Jeddah City with primary road networks (Alijoufie et al., 2013a, p.495).....85

Figure 3-2 The watersheds and sub-watersheds draining into the urban area of Jeddah City (Al Saud, 2010). 85

Figure 3-3 Illustrates the Jeddah flood 2009-2011 respectively (Arab News, 2012; Fatlemaeus, 2011) 87

Figure 3-4 The planning areas of Jeddah City and the surrounding rural area as described by AECOM (2014). The study site, area D, is delineated in black. 88

Figure 3-5 The future composition of planning area D (outlined in purple) according to current development plans. The Haramain highway is indicated by the red line (AECOM, 2014). 89

Figure 3-6 Flooding hot spots in planning area D. Planning area D is outlined in purple and the flooding hot spots are indicated by red rings, the larger the ring the more prolific the flooding in the past. The blue line indicates the Northern Channel. The numbers refer to IDs of suggested stormwater system (Pipes). The selected study site within planning area D is approximately indicated by the black line. (AECOM, 2014).....90

Figure 3-7 The topography of planning area D. The red arrow indicates the general direction of the slope within the area. The black trapezoid outlines the approximate area of the study site and the black line indicates Al Haramain Road (AECOM, 2014). 91

Figure 3-8 The surface runoff management infrastructure for planning area D (boundaries indicated by purple line). The locations of dams are indicated by the green crosses, the surface drainage channels are indicated in light blue and the subsurface drainage network is indicated by dark blue lines (AECOM, 2014). 94

Figure 3-9 Rain gauges within the Jeddah urban area (AECOM, 2014).....96

Figure 3-10 Hyetograph for daily rainfall for Stations J134 and 41024 97

Figure 3- 11 The land use and land cover for the selected study site including the existing stormwater drainage system. 99

Figure 3-12 Estimation flows, which are considered as “observed flow” of the 25/11/2009 event at each subcatchment outlet 102

Figure 4-1 A flow chart overview of the methodology and process used in this chapter. 104

Figure 4-2 The ground elevation within a digital terrain model of the selected study site within Jeddah City at a resolution of 5m. 105

Figure 4-3 The stream network diagram utilised to develop the stream network for the Jeddah-SWMM model. In the legend, 1 represents the highest elevation stream and 5 the lowest, hence water flow is from streams 1 to 5. 106

Figure 4- 4 The land use and land cover for the selected study site including the existing stormwater drainage system. 108

Figure 4-5 The SWMM model map of the selected study site within Jeddah City. 113

Figure 4-6 the sensitivity analysis of the Jeddah-SWMM model performed on subcatchments 1 & 12 for the parameter of CN, the sensitivity analysis output is given as the variation in the modelled hydrographs. 117

Figure 4-7 Calibration outputs of the 25/11/2009 event across six subcatchments using default parameter. 119

Figure 4-8 Calibration outputs of the 29/12/2010 event across six subcatchments using default parameter. 121

Figure 5-1 The analysis process for part one of the questionnaire survey responses. 131

Figure 5-2 The respondents' ranking of SUDS options for Jeddah City where PP = permeable pavement, RH = rainwater harvesting, BR = bio-retention, RG = rain garden, IT = infiltration trench, SW = swales and GR = green roofs. The ranking of each SUDS option is given on the bar and the percentage of respondents is also shown. 136

Figure 5-3 The percentage of respondents that indicated as to whether each of the four most popular SUDS options was either appropriate or inappropriate in the context of Jeddah City. Where PP = permeable pavement, BR = bio-retention, RG = rain garden and GR = green roofs. 138

Figure 5-4 The average cost estimates for both new (installation on new buildings) and retrofitted (installation on existing buildings) SUDS in Jeddah City. Where GR = green roofs, PP = permeable pavement, RG = rain garden and BR = bio-retention. The cost estimates are given on the cost per m2. 144

Figure 5-5 The cost estimates in $/m2 provided by each respondent for both new and retrofitted green roofs. 146

Figure 6-1 The structure of a green roof as modelled within SWMM. 150

Figure 6-2 A diagram of a permeable pavement system and water flows through the system (Zhang and Guo, 2014 p.2). 156

Figure 7-1 Borg-SWMM model framework showing the pathways of data flow between the two combined components. 169

Figure 7-2 The SUDS-optimisation-framework 169

Figure 7-3 Comparing between different numbers of function evaluations and using an epsilon value of 0.01. 174

Figure 7-4 The comparison between the outputs for epsilon values of 0.2, 0.1, 0.01 and 0.001 with 10,000 function evaluations. 174

Figure 7-5 The rainfall distribution hyetographs for the 6-hour design rainfall event for the 2-year, 10-year, 25-year, 100-year, 100-year + 30% CC and 100-year + 45% CC scenarios, developed by applying the alternative block method 178

Figure 7-6 Pareto-optimal front of SUDS solutions for scenario 1: 6-year, 2-hour rainfall and SUDS option 1. 186

Figure 7-7 SUDS percentage coverage in each subcatchment for scenario 1's selected optimal solutions. 189

Figure 7-8 Pareto-optimal front of SUDS solutions for scenario 1 using peak flow and cost objective functions. 190

Figure 7-9 Pareto-optimal front of SUDS solutions for scenario 4: 6-hour, 10-year rainfall & SUDS option 1. 191

Figure 7-10 SUDS percentage coverage in each subcatchment for scenario 4's selected optimal solutions. 193

Figure 7-11 Pareto-optimal front of SUDS solutions for scenario 7: 6-hour, 25-year rainfall event & SUDS option 1. 194

Figure 7-12 SUDS percentage coverage in each subcatchment for scenario 7's selected optimal solutions. 196

Figure 7-13 Pareto-optimal front of SUDS solutions for scenario 10: 6-hour 100-year rainfall & SUDS option 1. 197

Figure 7- 14 SUDS percentage coverage in each subcatchment for scenario 10's selected optimal solutions. 199

Figure 7-15 Pareto-optimal front of SUDS solutions for scenario 13: 6-hour 100-year rainfall +30%CC & SUDS option 1. 200

Figure 7-16 SUDS percentage coverage in each subcatchment for scenario 13's selected optimal solutions 202

Figure 7-17 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 and using a 2-year return period design storm. 204

Figure 7-18 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 2-year return period design storm. 204

Figure 7-19 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 10-year return period design storm. 205

Figure 7-20 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 10-year return period design storm. 205

Figure 7-21 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 25-year return period design storm. 207

Figure 7-22 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 25-year return period design storm. 208

Figure 7-23 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm. 208

Figure 7-24 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event. 209

Figure 7-25 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm with 30% CC. 210

Figure 7-26 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event with 30% CC. 211

Figure 7-27 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm with 45% CC. 211

Figure 7-28 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event with 45% CC 212

Figure 7-29 The pareto optimal front obtained for year 1 considering construction costs only. The most effective SUDS solutions that could be constructed with the $3M budget is found using the red circle. 214

Figure 7-30 The SUDS optimal solution (SUDS percentage coverage) on a per subcatchment basis for year 1 215

Figure 7-31 The pareto optimal front obtained for year 2 considering construction costs in year 1 ($3M) and year 2 ($1.5M) 216

Figure 7-32 The SUDS optimal solution (SUDS percentage coverage) on a per subcatchment basis for year 2 ($4.5M investment). 216

Figure 7-33 The pareto optimal front obtained for year 3 considering construction costs in year 1 ($3M), year 2 ($1.5M) and year 3 ($0.81M) 217

Figure 7-34 The optimal SUDS solutions for each subcatchment derived from the optimisation framework simulations conducted for years 1, 2 and 3. 218

Figure A-1 Planning Area D's geology informations (AECOM, 2014 & Saudi geological Suvey) ... 251

Figure A-2 The rainfall distribution hyetographs for historical rainfall events 252

Figure A-3 IDF curve for the Jeddah Coastal Plain (AECOM, 2014) 265

Figure B-1 Calibration outputs of the 25/11/2009 event across twelve subcatchments using default parameter 267

Figure B-2 Calibration outputs of the 29/12/2010 event across twelve subcatchments using default parameter 270

Figure B-3 Calibration outputs of the 14/01/2011 event across twelve subcatchments using default parameter 273

Figure B-4 Calibration outputs of the 30/12/2010 event across twelve subcatchments using default parameter 276

Figure B-5 Verfication outputs of the 15/01/2011 event across twelve subcatchments using calibrated parameters 280

Figure B-6 Verification outputs of the 14/01/2011 event across twelve subcatchments using calibrated parameters 282

Figure D-1 Pareto-optimal front of SUDS solutions for scenario 2: 6-hour, 2-year rainfall event & SUDS option 2.....312

Figure D-2 SUDS percentage coverage in each sub-catchment for scenario 2's selected optimal solution.....314

Figure D-3 Pareto-optimal front of SUDS solutions for scenario 5: 6-hour, 10-year rainfall event & SUDS option 2.....315

Figure D-4 SUDS percentage coverage in each subcatchment for scenario 2's selected optimal solutions. 317

Figure D-5 Pareto-optimal front of SUDS solutions for scenario 8: 6-hour, 25-year rainfall event & SUDS option 2.....318

Figure D-6 SUDS percentage coverage in each sub-catchment for scenario 8's selected optimal solutions. 319

Figure D-7 Pareto-optimal front of SUDS solutions for scenario 11: 6-hour, 100-year rainfall event & SUDS option 2.....320

Figure D-8 SUDS percentage coverage in each sub-catchment for scenario 11's selected optimal solutions. 321

Figure D-9 Pareto-optimal front of SUDS solutions for scenario 14: 6-hour, 100-year rainfall + 30%CC & SUDS option 2.....322

Figure D-10 SUDS percentage coverage in each sub-catchment for scenario 14's selected optimal solutions. 323

Figure D-11 Pareto-optimal front of SUDS solutions for scenario 17: 6-hour, 100-year rainfall + 45%CC & SUDS option 2.....324

Figure D-12 SUDS percentage coverage in each sub-catchment for scenario 17's selected optimal solutions. 325

Figure D- 13 Pareto-optimal front of SUDS solutions for scenario 3: 6-hour, 2-year rainfall event & SUDS option 3.....326

Figure D-14 SUDS percentage coverage in each sub-catchment for scenario 3's selected optimal solutions. 327

Figure D-15 Pareto-optimal front of SUDS solutions for scenario 6: 6-hour, 10-year rainfall event & SUDS option 3.....328

Figure D-16 SUDS percentage coverage in each sub-catchment for scenario 6's selected optimal solutions. 329

Figure D-17 Pareto-optimal front of SUDS solutions for scenario 9: 6-hour, 25-year rainfall event & SUDS option 3.....330

Figure D-18 SUDS percentage coverage in each sub-catchment for scenario 9's selected optimal solutions. 331

Figure D- 19 Pareto-optimal front of SUDS solutions for scenario 12: 6-hour, 100-year rainfall event & SUDS option 3. 332

Figure D-20 SUDS percentage coverage in each sub-catchment for scenario 12's selected optimal solutions. 333

Figure D-21 Pareto-optimal front of SUDS solutions for scenario 15: 6-hour, 100-year rainfall 30%CC & SUDS option 3. 334

Figure D-22 SUDS percentage coverage in each sub-catchment for scenario 15's selected optimal solutions. 335

Figure D-23 Pareto-optimal front of SUDS solutions for scenario 18: 6-hour, 100-year rainfall + 45%CC* & SUDS option 3. 336

Figure D-24 SUDS percentage coverage in each sub-catchment for scenario 18's selected optimal solutions. 337

List of Tables

Table 1-1 The site pollution index (SPI) identified for total suspended solids (TSS), polyaromatic hydrocarbons (PAH), organic pollution (org) and heavy metal (HM) pollution under no treatment and treatment with three types of SUDS (Ellis et al., 2012). 7

Table 2-1 The hydrological parameters measured at four sites (the neighbourhoods of Royal Bank, NATS, Emmock and W Grange) in the Dunfermline location with a comparison between areas of traditional stormwater management and SUDS. Where IRL = Initial Runoff Loss results are averages across a number of rainfall events (Macdonald and Jefferies, 2003, p.5). 16

Table 2-2 A summary table of the barriers/limitations of each potential SUDS option and the necessary conditions for each SUDS option to function correctly 34

Table 2-3 The whole life costs for different SUDS options in London, the United Kingdom (Ossa-Moreno et al. 2017, p.416). 37

Table 2-4 The calculated capital expenditure (CAPEX) and operational expenditure (OPEX) for different SUDS,adapted from Chow et al.(2014, p.347). 38

Table 2-5 Comparing models in terms of functionality and accessibility. Adapted from Haris et al. (2016). 45

Table 2-6 Comparing characteristics of representatives. Adapted from Haris et al. (2016). 45

Table 2-7 Comparison between popular SUDS modelling tools (Jayasooriya and Ng. 2014). 46

Table 2-8 A summary of the identified articles using modelling to aid in the optimisation of SUDS in urban areas.....67

Table 3-1 Shows available topography, geology and existing infrastructure data.....95

Table 3-2 Rain Gauges within the Jeddah Urban Area and its location to selected area 97

Table 3-3 Historical rainfall events selected and used for this study.....98
Table 3-4 Shows estimation flow data (considered as observed data).....100
Table 4-1 The land use and land cover details for the entirety of the selected study site. 107
Table 4-2 The input parameters used for each subcatchment in the Jeddah-SWMM model. 110
Table 4-3 Historical rainfall events that were used to calibrate and validate the Jeddah-SWMM model. 116
Table 4-4 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 25/11/2009 event.....118
Table 4-5 The values of the calibrated parameters for the Jeddah-SWMM model for the 25/11/2009 event.....120
Table 4-6 Results of the Jeddah- SWMM hydrologic model for each Subcatchment includes the deviation in peak flow rate and flood volume for the 29/12/2010 event.....122
Table 4-7 The values of the calibrated parameters for the Jeddah-SWMM model for the 29/12/2010 event.....123
Table 4-8 The average values of the parameters after calibration with five historical rainfall events. 124
Table 5-1 Survey themes including questions and aim for each theme. 127
Table 5-2 The groups of relevant experts identified and the number of individuals contacted in each group. 129
Table 5-3 The abbreviations that were used in the tabulation and analysis to identify the individual survey respondents.....133
Table 5-4 The tabulation table method used to record the findings of the thematic analysis.....133
Table 5-5 The emergent patterns from the three questions addressing the theme of SUDS suitability for Jeddah City in the distributed questionnaire. 135
Table 5-6 Emergent patterns from answers to questions (Q5) and (Q6) in theme two of the questionnaire: Appropriate SUDS for Jeddah City. 137
Table 5-7 Emergent patterns from the three questions in theme three of the questionnaire: challenges of SUDS implementation in Jeddah City. 139
Table 5-8 Emergent patterns from the responses to questions (Q10) and (Q11) in theme four of the questionnaire: opinions and comments on SUDS data requirements.....142
Table 6-1 Green roof surface layer parameters. 150
Table 6-2 Green roof soil layer parameters. 151
Table 6-3 Green roof drainage layer. 151
Table 6- 4 Rain garden surface layer parameters.....152
Table 6-5 Rain garden soil layer parameters. 152
Table 6-6 Rain garden storage layer parameters.....153
Table 6-7 Bio-retention, surface layer parameters.....154

Table 6-8 Bio-retention soil layer parameters. 154

Table 6-9 Bio-retention, storage layer parameters. 155

Table 6-10 The permeable pavement surface layer parameters. 157

Table 6-11 The permeable pavement layer parameters 158

Table 6-12 The permeable pavement, storage layer parameters. 159

Table 6-13 The total lifecycle cost calculations for each SUDS option, including inflation rate. All calculations were based on $1m^2$ of SUDS surface area (A=1) & 25-year lifespan). 162

Table 6-14 Maximum number of each type of SUDS in each subcatchment for option one (Green roofs only on commercial and governmental roofs) 165

Table 6-15 Maximum number of each type of SUDS in each subcatchment for option two (GR on commercial and governmental roofs + 20% of private homes) 166

Table 7-1 Range of Borg internal parameters tested for this study 173

Table 7-2 Parameter settings (defaults for this study) for the SUDS optimization framework 174

Table 7-3 The outcomes of the known 6-hour 2-year rainfall and SUDS option scenario in comparison to the simulated outcome from the same scenario run in SWMM. 175

Table 7-4 An overview of the scenarios that were studied. 182

Table 7-5 The outcomes of the simulations conducted using the benchmark scenario for all scenarios. 184

Table 7-6 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 1 (6-hour 2-year rainfall and SUDS option 1). 187

Table 7-7 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 4 (6-hour 10-year rainfall and SUDS option 1). 192

Table 7-8 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 7 (6-hour 25-year rainfall and SUDS option 1). 195

Table 7-9 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 10 (6-hour 100-year rainfall and SUDS option 1). 198

Table 7-10 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 13 (6-hour 100-year +30 CC rainfall and SUDS option 1). 201

Table A-1 Subcatchment Curve Number Estimates for Selected Areas 256

Table A-2 Shows results of SCS calculations 259

Table A-3 Peak factors of hydrograph and limb ratio (Wanielista et al., 1997) 260

Table A-4 Soil group definition (NRCS, 2009) 260

Table A-5 SCS curve numbers for urban areas 261

Table A-6 SCS soil group and infiltration rates (AECOM, 2014) 262

Table A-7 Manning' coefficient for overland flow (McCuen, et al. 1996) 262

Table A-8 Ratios for dimensionless unit hydrograph and mass curve (used for estimation flow) 263

Table A-9 The conduit properties for each identified conduit within selected study site within Jeddah City.....264

Table B-1 The values of the calibrated parameters for the Jeddah-SWMM model for the 25/11/2009 event.....268

Table B-2 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 25/11/2009 event.....269

Table B-3 The values of the calibrated parameters for the Jeddah-SWMM model for the 29/12/2010 event.....271

Table B-4 Results of the Jeddah- SWMM hydrologic model for each subcatchment includes the deviation in peak flow rate and flood volume for the 29/12/2010 event.....271

Table B-5 The values of the calibrated parameters for the Jeddah-SWMM model for the 14/01/2011 event.....274

Table B-6 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 14/01/2011 event.....275

Table B-7 The values of the calibrated parameters for the Jeddah-SWMM model for the 30/12/2010 event.....277

Table B-8 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 30/12/2010 event.....278

Table B-9 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 15/01/2011 event.....280

Table B-10 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 14/01/2011 event.....282

Table D-1 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 2 (6-hour 2year rainfall and SUDS option 2).....312

Table D-2 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 5 (6-hour 10-year rainfall and SUDS option 2).....315

Table D-3 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 8 (6-hour 25-year rainfall and SUDS option 2).....318

Table D-4 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 11 (6-hour 100-year rainfall and SUDS option 2).....320

Table D-5 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 14 (6-hour 100-year rainfall + 30%CC and SUDS option 2).....322

Table D-6 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 17 (6-hour 100-year rainfall + 45%CC and SUDS option 2).....324

Table D-7 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 3 (6-hour 2-year rainfall and SUDS option 3). 326

Table D-8 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 6 (6-hour 10-year rainfall and SUDS option 3).....328

Table D-9 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 9 (6-hour 25-year rainfall and SUDS option 3).....330

Table D-10 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 12 (6-hour 100-year rainfall and SUDS option 3).....332

Table D-11 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 15 (6-hour 100-year rainfall 30%CC and SUDS option 3).....334

Table D-12 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 18 (6-hour 100-year rainfall + 45%CC* and SUDS option 3).....336

List of Symbols and Abbreviations

Arid and Semi-Arid regions	ASARs
Bio-Retentions	BRs
Curve Number	CN
Climate Change	CC
Decision Support System	DSS
Evolutionary Algorithm	EA
Finencial Cost	FC
Genetic Algorithm	GA
Green Roofs	GRs
Global Information System	GIS
Impervious depression storage	Dstore-Imperv
initial abstraction (initial loss)	I_a
Infiltration Trench	ITs
Infilation Rate	IR
LifeCycle Cost	LC
Low impact development	LID
Sustainable urban drainage system	SUDS
Manning's roughness coefficient	N
Maximum retention	S
Multi-Objective Evolutionary Algorithm	MOEA
Permeable Pavements	PPs
Pervious depression storage	Dstore-perv
Percentage zero	% Zero
Rain Gardens	RGs
Soil Conservation Service Curve Number method	SCS-CN
Stormwater management model	SWMM

Swales	SWs
Synthetic Unit Hydrographs	SUHs
Peak flow	Q_p
Total volume of surface runoff	R_n
Private Home	PH
Relative error peak flow	PF
Relative error flow volume	RV

Chapter One: Introduction

1.1 Background

Urban stormwater runoff is the precipitation in the urban environment which flows over impermeable surfaces, such as roads, houses, parking, etc. (Gogate et al., 2017). The twin factors of increasing urbanisation and the impacts of climate change (CC) mean that addressing the issue of urban stormwater management is an urgent concern, one which is extensively debated in the published literature (e.g. Jefferson et al., 2017; Wang et al., 2017). Within the urban environment, the high density of infrastructure, such as roads and buildings, in combination with high coverage of impermeable surfaces, has led to a reduction in the potential for water to infiltrate into the ground. Subsequently, this has caused an increase in the magnitude of surface runoff, proportionally increasing the potential for flooding and the transport of surface deposited pollutants to water bodies resulting in quality degradation, lack of potable water sources, economic losses and human and environmental health impacts (Muthkrishnan, 2004; FLOW, 2005; Tobio et al., 2015). Urban environments are potentially susceptible to both fluvial and pluvial flooding (Apel et al., 2016). Fluvial flooding occurs when the flooding water source is from rivers which have exceeded their capacity and burst their banks (Merz et al., 2010). Pluvial flooding occurs when extensive rainfall exceeds the capacity of drainage systems, this is also referred to as surface water flooding (Acosta-Coll et al., 2018). It is also possible for fluvial and pluvial flooding to occur simultaneously, particularly in urban areas situated nearby to riverine systems (Patra et al., 2016). Therefore, it is evident that effective solutions for urban stormwater management need to be implemented to prevent both urban flooding and environmental degradation.

CC is highly likely to have a significant influence on precipitation patterns across the globe, which is variable with geographical location (Trenberth, 2011). In many locations, it is predicted that precipitation events will occur which are of a longer duration and intensity than those which have occurred historically. This means that urban stormwater management systems may not be able to adequately cope with the increase of stormwater under future CC conditions (Arisz and Burrell, 2006). Thus, it is necessary that such systems are designed and managed in a manner which will enhance CC resilience and ensure that there is effective stormwater management capacity for now and in the future (Brown et al., 2008). Resilience is an important aspect of mitigating CC impacts, increasing resilience is tantamount to increase the capacity to cope with the effect of CC impacts (Tyler ad Moench, 2012). Where CC impacts are

unavoidable through mitigation, resilience strategies need to be implemented to ensure that communities and populations plan for and can recover from the adverse events which may occur under climate change (Meerow and Stults, 2016).

Arid and semi-arid regions (ASARs) are extensive on a global basis. ASARs are characterised by low average rainfall and high temperatures, with arid regions receiving lower rainfall than semi-arid regions (see Figures 1-1 & 1-2) (Modarres and de Silva, 2007). ASARs are predicted to experience similar issues arising from CC impacts (Modarres and de Silva, 2007; The Arab Water Council, 2009; Sharifi Garmdareh et al., 2018). The similar climates and the similarity in predicted CC impacts suggests that it is highly important that research is undertaken to develop a greater understanding of how ASARs will be impact by future CC.

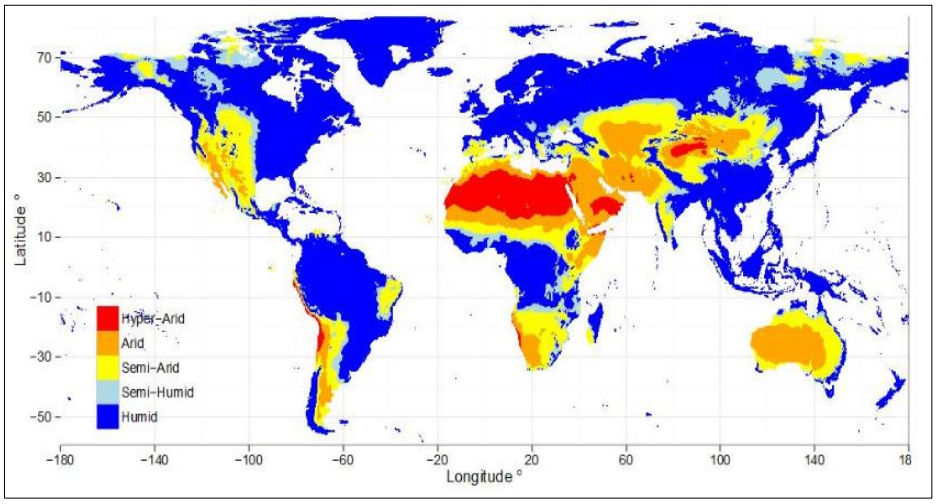


Figure 1-1 The distribution of global climatic zones (Ma, 2016).

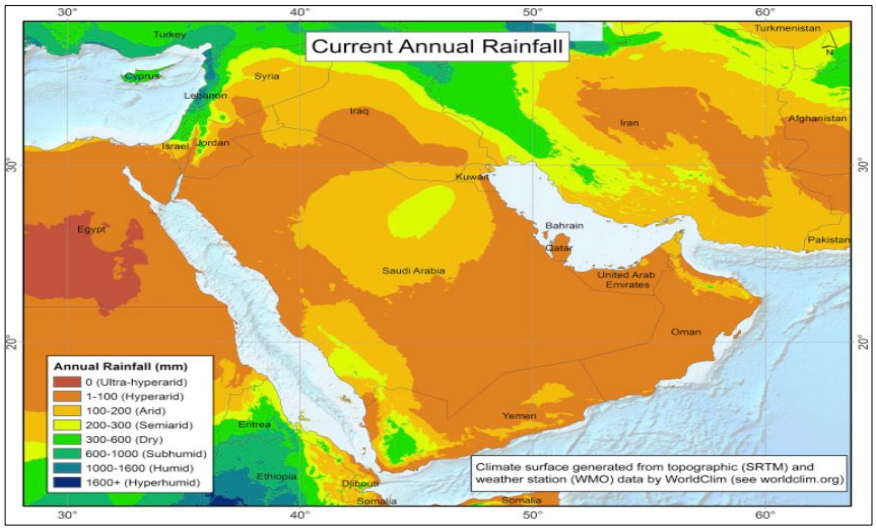


Figure 1-2 Present day rainfall levels of the Arabian Peninsula for each climate zone (Jennings et al., 2015)

Urban stormwater management has traditionally been achieved via the use of 'grey' infrastructure, for example piped drainage systems, as seen in Figure (1-3). The primary objective of grey infrastructure is simply to remove stormwater from the urban environment rapidly and effectively (Finewood, 2016). However, there are several potential disadvantages to grey infrastructure, including a lack of capacity adaptability to compensate for increases in rainfall duration and intensity under CC, high point discharges of pollutants to water systems and relatively high construction, repair and maintenance costs (Mehler and Ostrowski, 1999).

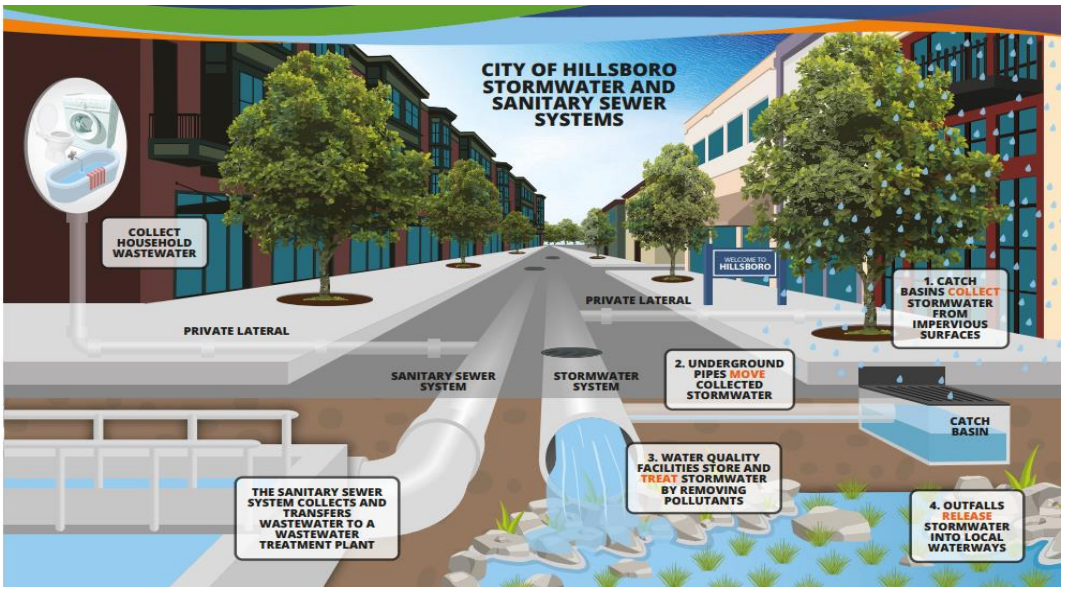


Figure 1-3 Traditional stormwater management in urban areas (Hillsbor, 2019)

Whilst the use of grey infrastructure still affords a viable option for managing stormwater in urban environments, alternative options have been suggested that offer the same services, but with additional benefits. Such benefits include the incorporation of structures designed to reduce the magnitude of surface runoff, rather than simply channelling it, or structures that include an element of filtration, thereby reducing the potential for pollutant loading from urban runoff and, in turn, reducing the potential environmental impacts and increasing the sustainability of stormwater management. These alternative options are referred to as Sustainable Urban Drainage Systems (SUDS) (Gogate et al., 2017). In addition, SUDS are approved to have many environmental benefits beyond improved water quality and reducing water runoff volume and peak flow, such as improvement of air quality, reducing the urban heat island effect, mitigating floods and positive social impacts (Fletcher et al., 2015; Pennino et al., 2016;).

The principle of sustainability is that the current generation should be able to utilise the natural environment and the resources it provides without impacting the potential for future generations to do the same and considers economic, environmental and social issues as interdependent aspects of a problem (Harris, 2000). In this context, sustainability means to implement more holistic and renewable strategies for improving and protecting the built and natural environment. SUDS are defined as a system that strives to emulate natural drainage by implementing strategies to deal with surface water runoff locally, by capturing, processing, and cleaning, before allowing it to slowly return into the environment (CIRIA, 2019). Some examples of the most common SUDS practices are green roofs (GRs), permeable pavements (PPs), rain gardens (RGs) swales (SWs), bio-retention units (BRs), etc. (Figures 1-4). SUDS is the common terminology which is used interchangeably with the terms green infrastructure in the UK, low impact development (LID), in the United States, and Water Sensitive Urban Design (WSUD) in Australia (Fletcher et al., 2015). Therefore, for consistency, the term SUDS will be used in this research to refer to all water management infrastructure which is addressed under the various terms used in different countries.

The major disadvantage of SUDS is that in their design stage can potentially have a greater cost and complexity than that of a traditional drainage system. This is due to the multiple types of SUDS that could be used and the need to ensure that the type selected is suitable for both the area in which it is applied to and the design objectives of the system. For example, if the SUDS is to be used for pollution control in addition to stormwater management, then the type of SUDS which is implemented can potentially have a significant influence on the pollution reduction potential, as highlighted by Scholz and Grabowiecki (2007). Thus, this need for extra time to be spent on the design of a SUDS system can potentially add additional financial costs to their overall cost.



Figure 1-4 Sustainable urban drainage practices (hidrologiasostenible.com)

SUDS practices, when implemented in urban environments, have shown to reduce peak runoff during stormwater and restore urban runoff timings to maintain watershed hydrology patterns as close to natural patterns as possible, given the development of the area (Yang et al., 2015). Evidence from Zellner et al. (2016) suggests that a SUDS surface coverage of only 10% can reduce around 30% of stormwater runoff volume depending on location and type of design. Another notable study is the work of Jia et al., (2014) who simulated and tested two stormwater runoff control scenarios in an urban setting in China with the aim of assessing the impact of using SUDS for stormwater management. Scenario one investigated SUDS implementation with lowest costs and utilised 11 BRs, 25 GRs, 6 SWs and 7 rain barrels. Scenario two focused on maximising SUDS performance and utilised 17 BRs, 35 GRs, 6 SWs, 10 PPs, 18 rain barrels and 2 wet detention ponds. Both scenarios were compared to the pre-development scenario that assumed no infrastructure (meaning that the site remained as before development), and the basic scenario, which was the existing development area without any SUDS. The findings (Figures 1-5) showed that there is a negative impact from urbanisation as the runoff volume and pollutant load were bigger in the basic scenario (no SUDS applied) compared to scenarios 1 and 2 that included SUDS practices.

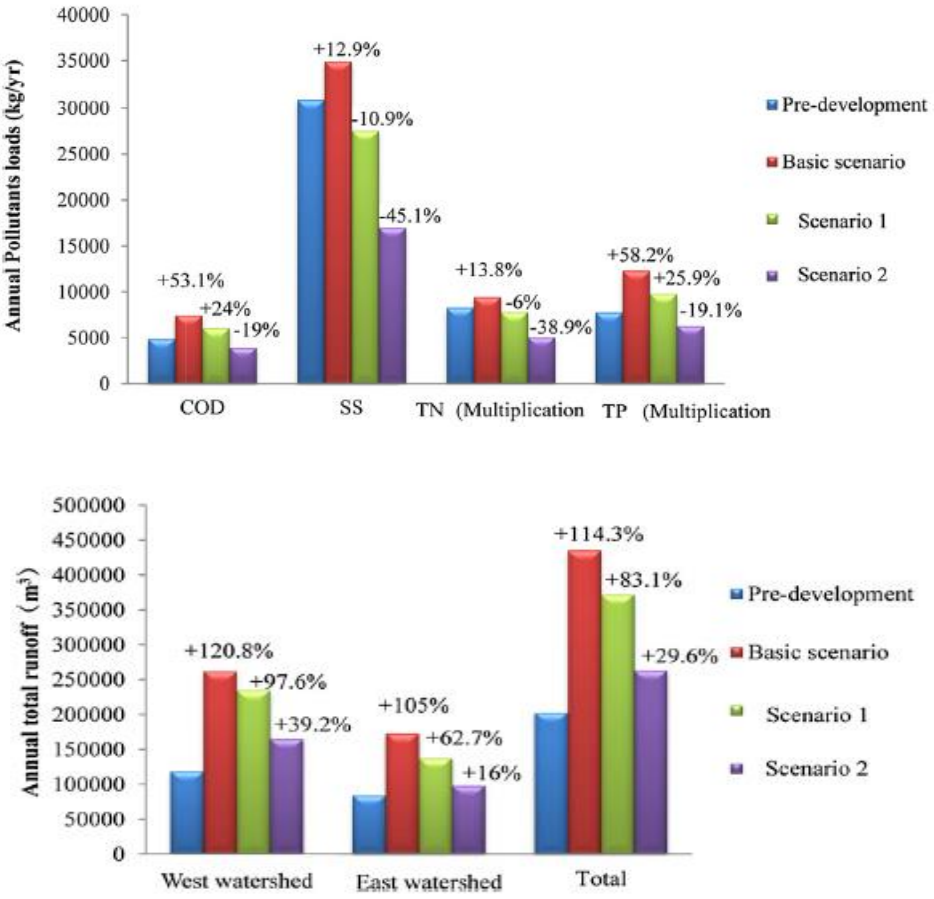


Figure 1-5 A comparison of annual runoff values and different pollution values for scenarios assumed and tested by Jia et al. (2014).

A positive impact of SUDS on water quality has also been identified in multiple studies (e.g. Ellis et al., 2012; Jia et al., 2014; Liu et al., 2016). For example, Ellis et al., (2012) demonstrated how different SUDS options could reduce the site pollution index (which is a measure of the magnitude of pollution) in the watershed adjacent to a motorway; their findings are given in Table 1-1. The findings of Ellis et al., (2012) indicate that the more intensive the treatment process, then the higher the resulting water quality. For instance, the application of an infiltration basin reduces all pollutant load to a SPI of 0.08 or less (see Table 1-1). In comparison, the use of a detention basin retains pollutant loads equivalent to an SPI of between 0.48-0.72 for the varied pollutants (see Table 1-1).

Table 1-1 The site pollution index (SPI) identified for total suspended solids (TSS), polyaromatic hydrocarbons (PAH), organic pollution (org) and heavy metal (HM) pollution under no treatment and treatment with three types of SUDS (Ellis et al., 2012).

Treatment option	Pollutant	SPI
No treatment	TSS	0.9
	PAH	0.9
	Org	0.7
	HM	0.8
Detention basin	TSS	0.63
	PAH	0.72
	Org	0.49
	HM	0.48
Surface flow constructed wetland	TSS	0.36
	PAH	0.18
	Org	0.14
	HM	0.16
Infiltration basin	TSS	0.05
	PAH	0.05
	Org	0.07
	HM	0.08

1.2 Problem Statement

The variety of SUDS in terms of mechanisms, sizes, specifications and construction and maintenance costs makes it difficult to choose appropriate types and their optimum locations in the watershed (Jia et al., 2014; Liu et al., 2016). Additionally, other factors, such as environmental, i.e. local climatic conditions and geographical characteristics (Poe et al., 2015), and existing urban infrastructure (Charlesworth et al., 2016) need to be considered alongside financial constraints in order to identify the most effective SUDS combinations for achieving maximum efficiency in stormwater retention and pollution removal. The optimum solutions are likely to differ between projects due to differences in watershed scale, complexity and variations in characteristics, such as soil properties and land cover/uses (Liu et al., 2016a). This complexity and uncertainty in the factors mentioned necessitates modelling possible scenarios and, thereby, identifying potential SUDS solutions which are optimal under different scenarios (Liu et al., 2016a). There is a growing body of evidence which suggests that the spatial level (watershed or subwatershed level) which is considered in the selection of SUDS solutions may

have a substantial influence on the identified optimal SUDS solutions. The development of a thorough understanding of how spatial scale can influence SUDS selection through the use of models provides a valuable tool for assisting decision-makers in understanding the problem and potential solutions (Liu et al., 2016a; Yi, 2016).

Considering the large number of influencing factors, the process of selecting an appropriate SUDS solution to urban drainage can be a complex and time-consuming process. This has resulted in the publication of numerous research articles seeking to enhance the process for SUDS selection by investigating methods for optimising such (e.g. Stovin et al., 2013; Li et al., 2017; Vincent et al., 2017; Macro et al., 2019; as detailed in Section 2.8). However, most of these researches have focused on climates that are described as temperate or tropical, and limited studies have investigated the optimisation of SUDS in an arid climate. This is likely due to limited application of SUDS in such climates; however, it also represents a substantial gap in the published literature and subsequent knowledge pool. The lack of knowledge regarding SUDS application in arid and semi-arid climates has been identified as a significant barrier to SUDS adoption (Piacentini and Rossetto, 2020). A study published by Alahmari (2018) highlighted that a lack of knowledge formed the primary barrier to SUDS adoption in Saudi Arabi, as it resulted in institutional challenges including a lack of operational standards (Hashmi et al., 2015). The discouragement of novel solution implementation due to the existing complexity and time-consuming nature of decision-making processes which would be further exacerbated if novel urban drainage solutions are to be implemented was also noted by Alahmari (2018). It is suggested that the lack of knowledge stemming from the relative lack of reporting on successful implementation of SUDS urban drainage solutions is a significant barrier to widespread SUDS adoption which will need to be overcome if SUDS use in arid and semi-arid environments is to become commonplace.

The lack of a reliable and accurate knowledge basis from previous applications of SUDS solutions in similar climates can potentially create difficulties for decision-makers seeking to implement SUDS solutions. This is because there is limited prior experience on which to base their decisions, and, where there is information available, it is unlikely to account for the specific conditions of their area of application due to local variations in factors, such as climate and geography and SUDS implementation cost (construction and maintenance costs) as detailed in Section 2.2.5 and 2.3.

1.3. The Importance and Role of a Decision-Support-System for SUDS Selection and Placement

The overall purpose of optimisation is to account for all the potential variables and ultimately present the SUDS selection and placement scenario that will result in the greatest reduction in stormwater peak flow and volume, thereby effectively managing stormwater drainage (Deb, 2011). However, whilst the primary objective of optimisation is the control of stormwater drainage, there are additional factors that can carry a similar level of importance when selecting the optimal solution. For example, the factor of available financial budget for SUDS implementation may be a significant factor influencing the final solution that is determined to be optimal. Hence, the need to determine the optimal SUDS that provides the maximum benefit (in terms of stormwater drainage management) at the lowest cost point (Vincent et al., 2017). This then alters the overall goal of optimisation slightly, to become the goal of identifying the optimal solutions for SUDS type and placement under different cost levels. It is, therefore, important that decision-makers have detailed and accurate information made available to them regarding the potential solutions that could fit within all their target needs. In locations where there is little or no access to data in regard to previous applications of SUDS solutions, it can potentially be difficult for decision-makers to obtain any pertinent information. Thus, there is a need to develop a decision-support-system (DSS) which will be able to provide decision-makers with an overview of the situation and a variety of solutions tailored to different financial constraints, allowing a comparison of outcomes under the consideration of financial outlay (Vincent et al., 2017).

DSS is defined as combining "analytical modelling with data access functions with an emphasis on flexibility and adaptability as a basis for enhancing user interaction and understanding" (Ellis et al., 2011 p.1). The DSS for SUDS placement is very important in the planning and design of SUDS systems (Cheng et al., 2006). The DSS for sustainable stormwater management must be supported by a geographical information system (GIS), hydrological simulation and a SUDS optimisation modelling tool as these help to facilitate the decision system build (Koutsoyiannis et al., 2003; Lee et al., 2012). A DSS will provide information on what SUDS combinations will meet the stormwater management goals in addition to providing information on the costs (construction and maintenance) of the identified solutions. This will then allow decision-makers to make an informed decision regarding which SUDS solutions will be the most appropriate to meet stormwater management goals within the bounds of their

available budget. A robust DSS will highlight areas where it is possible to achieve a trade-off through the provision of the optimal SUDS stormwater management system for a given cost. An additional benefit of a robust DSS is that it can also enable the identification of the point at which further implementation of SUDS solutions will not be optimal from a cost-benefit perspective.

There are multiple models which are commonly utilised to aid in the determination of effective urban drainage solutions to address issues of stormwater drainage (as detailed in Section 2.5). However, the majority of these models in isolation do not constitute as a DSS, as their principle purpose of is to define the optimal solution with regard to the factors of stormwater peak flow and volume (Eaton, 2018). Whilst this is likely to result in the optimal SUDS in terms of managing stormwater flow, it does not take into account other factors that will potentially influence the suitability of the finally selected solution, such as the economic costs of SUDS (Yazdandoost et al., 2013). It is the inclusion of additional factors into the modelled scenarios that elevate an urban stormwater drainage model to one that can be considered as a DSS (see also Ahmed et al., 2017; De Paola et al., 2017).

The knowledge gaps which may influence the ability of decision-makers to make informed decisions for SUDS implementation in arid and semi-arid regions (ASARs) include:

- Not knowing which SUDS types are appropriate for use in ASARs.
- Not having a basis for creating cost estimates, including both construction and maintenance costs.
- Not knowing how to reach a balance between the costs of SUDS implementation and maintenance and the different objectives which are inherent to a stormwater management system.
- A lack of availability of tools to support decision-making (DSS).

All of the knowledge gaps listed above could potentially severely hamper the ability of decision-makers to make robust decisions regarding the potential for SUDS systems to address stormwater management problems. Thus, it is clear that there is an urgent need for the development of a DSS, also referred to as the SUDS-optimisation-framework throughout this thesis, that can provide a tool for decision-makers in ASARs to enable them to make informed decisions.

1.4 Aim and Objectives

The aim of this study is to develop a decision-support-system (DSS) for the optimum selection and placement of SUDS in arid and semi-arid regions. The output of this system will be trade-off curves between cost of SUDS options and corresponding peak flow and/or runoff volume reduction, which can be used by researchers and decision-makers to make sustainable decisions and plans for stormwater management in arid and semi-arid urban areas. **The main aim is achieved through the following objectives:**

1. Identifying the factors that affect the use of SUDS in arid regions, such as land use, slopes, soil type, flow paths and existing drainage system, through a comprehensive literature review and analysing the selected case study watershed using global information system and watershed modeling (Chapter 2, 3 and 4).

2. Identifying a suitable stormwater simulation model and its required inputs through a comprehensive review of existing models, including the identification of an appropriate optimisation algorithm and objective function for SUDS selection and placement in arid regions (Chapter 2).

3. Developing and calibrating a stormwater simulation model for the study watershed (Chapter 4).

4. Conducting a survey by a questionnaire to gain information on the potential and feasibility of different SUDS options for use in arid areas (Chapter 5).

5. Designing and selecting suitable SUDS parameters for the case study watershed, and calculation of total financial cost over the lifespan for each designed SUDS (Chapter 6).

6. Linking the selected stormwater simulation model and optimisation algorithm to build an effective DSS framework for SUDS selection and placement in ASARs. The framework will be verified using a case study watershed, by running different simulations scenarios and identifying the trade-offs between stormwater retention/reduction and costs (Chapter 7).

1.5 Study Watershed

To test the developed DSS, an urban watershed within Jeddah city is selected. Jeddah is located in the west region of Saudi Arabia which is classified as a semi-arid region (Youssef, et al., 2016). Bounded by the Red Sea from the west and mountains from the east, the city experienced two disastrous flash floods in 2009 and 2011, killing 113 people and destroying infrastructure by damaging thousands of houses and vehicles, with the cost of the damage being estimated at around $ 2 billion (Ameur, 2016; Youssef et al., 2016). Geomorphological conditions and anthropogenic activities, such as rapid urbanisation, as well as potential increase of heavy rain events due to climate change, are the major causes of flooding in Jeddah. Solutions recommended and applied for protecting the city from floods are based on heavy structures such as dams, channels and culverts, which have cost and environmental impacts (Youssef et al., 2016). The study will investigate the application of SUDS in the study watershed using the developed DSS tool.

1.6 Original Contributions

The main novelty and contribution of this research lies in the conduction of a qualitative study specific to the KSA region. It has been identified that a significant barrier to the widespread adoption of SUDS solutions in KSA is derived from the lack of knowledge which quantitatively details the potential for SUDS solutions to provide a viable option of urban stormwater management in this region. Thus, the process of developing a decision support framework for the optimum selection and placement of SUDS for stormwater management in ASARs will provide quantitative dataset which will contribute towards supporting the viability of SUDS as a sustainable option. This framework can help decision-makers to evaluate, optimise and compare different SUDS scenarios in these environments. The SUDS-optimisation-framework is composed of a stormwater simulation model (SWMM), for assessing stormwater quantity conditions, connected to a Multiobjective Evolutionary Algorithm for optimisation (Borg MOEA). Three distinct scenarios will be examined by the SUDS-optimisation-framework for this study (as detailed in Chapter 7).

Moreover, lack of current implementation and application of SUDS in ASARs has made it difficult for managers to select the appropriate type of SUDS and evaluate their potential cost. A methodology based on conduction of a survey by questionnaire is followed to gather primary data pertaining to suitability, feasibility and costs of SUDS in ASARs, including Jeddah City,

which are implemented in the DSS. This will further contribute towards the development of a robust understanding of what institutional barriers exists and could provide direction for future studies seeking to overcome institutional barriers to widespread SUDS adoption.

1.7 Thesis Structure

The structure of this thesis comprises eight chapters, which are described in short as follows:

Chapter One provides the overview and introduction of the thesis, including background of the study, problem statement, aim and objectives of research.

Chapter Two presents a comprehensive review of the relevant literature

Chapter Three describes the study watershed in Jeddah city in terms of its importance, location, climate, topography, land use and land cover. Also, the raw data and information collected and used for developing the stormwater model for the study watershed are presented.

Chapter Four presents the parameterisation of the hydrologic components of the USEPA SWMM model for the study watershed. More specifically, this chapter includes the methodology, results and discussions for developing, calibrating and verifying the study watershed's SWMM model.

Chapter Five presents the description and aim of survey by questionnaire, which is to investigate a suitable type of SUDS among many SUDS options available and the effective cost of SUDS for ASARs using expert opinion. Also presented are results, findings and discussions of the questionnaire. This information is used to develop the objective functions in Chapter Six.

Chapter Six presents the design of SUDS parameters for GRs, RGs, PPs and BRs for the case study watershed, and the details of calculation of total financial cost over the lifespan for each of the designed SUDS.

Chapter Seven details how the SUDS-optimisation-framework is developed, and how this framework is subsequently applied to the study watershed.

Chapter Eight provides the summary and conclusions arising from this study; in addition, it offers some suggestions for future research.

Chapter Two: Literature Review

2.1 Overview

The aim of this chapter is to provide an overview of the important elements in the modelling, design and management of stormwater systems. These include evaluation of sustainable urban drainage system (SUDS), lifecycle costs of SUDS, modelling practices, calibration and validation of models, and current studies on selection and placement optimisation of SUDS, and optimisation tools. The review of the literature is conducted to identify the gaps in research knowledge related to SUDS optimisation and to clarify and justify the tools and methods selected for this research.

2.2 Evaluation of Sustainable Urban Drainage Systems (SUDS)

2.2.1 Introduction

Urbanisation negatively affects stormwater flow, such as an increase in the flow volume and flow runoff likely to cause flooding and water inundation (Lane et al., 2013). Stormwater in urban environment also reduces the quality of the water, which is polluted by movement over many impervious surfaces. Research has also identified how climate change (CC) and increased pressure for more water resources in cities has increased the requirement for a more resilient and secure water management plan, and evidence suggests that more rapid transition to utilising an integrated approach to water management is needed to ensure sustainable urban water management (Brown, et al., 2008).

Historically, stormwater has been managed by channelling it through a centralised system with the use of gutters, curbs and other grey infrastructure (which is comprised of all the man-made components of traditional stormwater management systems that are not classified as green, such as concrete pipes). This traditional approach focuses on a single benefit, which is saving the city from increasing flow volume by moving it out of the city. Whilst the use of this approach still presents a viable option for managing stormwater, it does not enhance sustainable urban development (Wong and Eadie, 2000; Mitchell, 2006; van Roon, 2007). Sustainable urban development refers to development which encompasses the principles of sustainability, namely that whilst the current generation should be able to utilise and benefit from natural resources, so to should subsequent generations, therefore the current generation should seek to responsibly use natural resources in a manner which is not degrading and where possible not consumptive (Luederitz et al., 2013). SUDS are considered a sustainable option due to the approach to water management. SUDS can conserve and treat water resources and

minimise the contamination of water bodies with anthropogenic pollutants (Charlesworth et al., 2003).

Research has highlighted that the management of stormwater in urban areas has changed significantly over recent years from originally a centralised system (Traditional approach) towards decentralised (on-site management) through controlling infiltration rates and hydrological flow rates (Heaney and Sansalone, 2009). Evidence from Heaney and Sansalone (2009) suggests that pollution associated of urban stormwater is reducing as a result of improved modern stormwater management practices; therefore, continuing to develop and maintain innovative on-site stormwater management strategies in urban areas is required.

SUDS are suggested as an alternative to traditional grey infrastructure for stormwater management in urban areas as they can perform the same function as grey infrastructure but can also reduce the potential environmental impacts and increase the sustainability of stormwater management (Morales-Torres et al., *2016*). In the following sections, the potential benefits and challenges of using SUDS will be reviewed, including the potential of SUDS in arid and semi-arid areas.

2.2.2 SUDS and Hydrology

The major difference between grey infrastructure and SUDS with regards to the hydrology of stormwater is that SUDS tackle the stormwater management issue with a wider scope, considering all aspects of stormwater interaction with the urban area rather than just the 'end-of-pipe' solution offered by grey infrastructure (Finewood, 2016). In comparison, SUDS seek to not only remove the stormwater from the urban environment, but also to reduce and slow down the movement of the stormwater within the urban space, thereby, reducing the volume of stormwater runoff and the volume of peak flows (Ashley et al., 2017; Butler, 2018). This can be achieved using a combination of methods that to reduce and manage stormwater flow, including harvesting, infiltration, storage and treatment options (Muthanna et al., 2018). Examples of SUDS are:

- Permeable pavements
- Rainwater harvesting systems
- Green roofs
- Bio-retention systems
- Trees and vegetation (green spaces; includes rain gardens and green gardens)

- Retention areas and wetlands, including swales
- Soakaways and infiltration basins/trenches (Davis and Naumann, 2017).

The selection of appropriate type of SUDS is dependent upon the characteristics of the area and the goal of sustainable water management. For example, in Berlin water quality and pollution was identified as a particular issue during periods of high stormwater runoff when assessing the impact of urban water drainage over the last decade (Zhang et al., 2015). Therefore, a SUDS solution that incorporated rainwater harvesting in combination with green rooftops was determined to be the most appropriate solution to retain pollutants and reduce flow volume (Zhang et al., 2015). In comparison, a study conducted by Grant et al. (2013) in Melbourne, Australia utilised rainwater harvesting and green rooftops as in the Zhang et al. (2015) study, but the end goals were to provide a non-potable water source to reduce the water demand of the city.

Dunfermline in Scotland is the longest running SUDS project in the United Kingdom (UK). A comparison of the areas with SUDS to the areas of the same site utilising traditional drainage approaches (therefore experiencing the same weather conditions) demonstrates that the use of a SUDS approach substantially reduces both the stormwater runoff and the peak flow during storm events as shown in Table 2-1 SUDS(Macdonald and Jefferies, 2003). Whilst this SUDS project was not conducted in an arid area, it has important implications for understanding the functioning of SUDS systems including how they can be successfully implemented and integrated.

Table 2-1 The hydrological parameters measured at four sites (the neighbourhoods of Royal Bank, NATS, Emmock and W Grange) in the Dunfermline location with a comparison between areas of traditional stormwater management and SUDS. Where IRL = Initial Runoff Loss results are averages across a number of rainfall events (Macdonald and Jefferies, 2003, p.5).

Parameter	**Royal Bank**	**NATS**		**Emmock**		**W Grange**	
		Tarmac	**Porous**	**Road**	**Swale**	**Road**	**Swale**
IRL (mm)	2.27	0.9	4.2	0.4	5	0.3	1.2
Lag time (min)	83	9.59	180	9.2	11.6	3.7	14.3
% Runoff	46.5	48.2	22.2	44.3	6.5	33.8	6.3
% Reduction of peak	N/A	N/A	77	N/A	52.2	N/A	65
Benefit Factor (%)	N/A	N/A	75	N/A	82.4	N/A	80.1
Events Retained (%)		N/A	60	N/A	52	N/A	40

SUDS can also be applied to an area as standalone small systems to reduce stormwater runoff and peak flows across a targeted urban area. In Figure 2-1, four examples of locally targeted SUDS are shown.



Figure 2-1 SUDS to target specific areas of urban drainage in the United Kingdom – clockwise from left: highway draining biofilters, storage basin, swale and linear wetland (Ashley et al., 2015, p.3).

The effect of the SUDS on stormwater runoff and the peak flows will be influenced by the type of SUDS that are implemented, for example, a green roof will have a different impact on stormwater runoff than an impermeable pavement. The water retention of GRs is variable depending upon the type of green roof that is installed (Zhang et al., 2019).

2.2.3 SUDS and Water Quality

In addition to impacting the hydrology of an area, SUDS can also be utilised to improve water quality. Grey infrastructure approaches to urban stormwater management typically discharge runoff directly into surrounding water bodies without prior treatment (McGrane, 2016). This can result in high point loads of pollutants, an issue that can be exacerbated if the stormwater management system is combined with the local wastewater and sewage systems (Pennino, et al. 2016). In particular, the first flush of a drainage system can introduce substantial pollutant loads, first flush is the term used to describe the initial runoff from a system that carries the highest concentration of pollutants deposited on urban surfaces (Di Modugno et al.,

2015). SUDS can potentially reduce stormwater pollutant loads by either acting as a filtration system or by reducing the pollutant loading of the runoff, thereby reducing the potential for substantial point pollution events to occur (Tedoldi et al., 2016).

Andres-Valeri et al. (2014) compared the pollutant loading of the stormwater outflow of two different linear (narrow structures along a straight line) SUDS and a traditional drainage system. It was found that there were significantly lower levels of pollutants in the outflow of the SUDS in comparison to the traditional drainage system (Andres-Valeri et al., 2014). However, it should also be noted that there was a difference in the outflow pollutant levels of the two SUDS, this is similar to the findings of other studies, such as Allen et al.,(2017) who found that linear (narrow, along a straight line) wetlands had a greater rate of fine sediment removal than wetland and swale combined systems. The deposition of fine material within SUDS is one of the reasons that periodic maintenance is required, in this case it is to ensure that the build-up of deposited material is removed to ensure the continued effectiveness of the SUDS system (Faram et al., 2005). If this maintenance is regularly performed (at intervals which will be dependent on the deposition rate), then there is theoretically no limit to the effect lifespan of many SUDS options (Faram et al., 2005). The importance of multiple SUDS approaches, with the runoff passing through several treatment approaches has been highlighted in multiple studies as the most effective method of reducing pollutants (Revitt et al. 2017). Ellis et al., (2012) used a semi-quantitative desk-based study approach to develop an order of preference for SUDS options to reduce total suspended solids and organic pollutants within stormwater runoff based on the performance of different SUDS options in reducing suspended solids and organic pollutants within stormwater runoff (Figure 2-2). Although this figure shows the order of preference (rank one is the best) for SUDS interventions developed by Ellis, et al., (2012), ranking system was not plotted using exact rankings such as 1st, 2nd. However that is the methodology that they chose and their findings are simply reported here as part of the review.

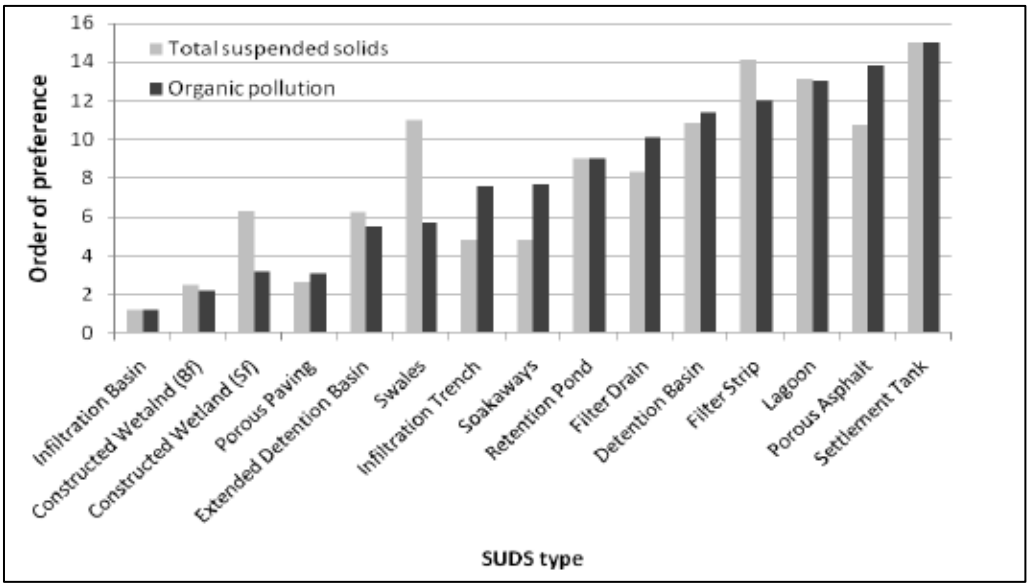


Figure 2-2 The order of preference (rank one is the best) for SUDS interventions developed by Ellis, et al., (2012 p.175) based on the ability of each option to remove suspended solids and organic pollutants concentration in urban stormwater runoff.

It is not just the type of SUDS which is implemented that can potentially impact water quality. Sañudo-Fontaneda et al. (2014) found that the type of material used in the construction of porous car parks such as porous asphalt and interlocking concrete block pavement, can have a substantial impact on the level of pollutant reduction, with the aggregate used for the sub-base found to have the greatest impact. This highlights that it is important to consider not only which SUDS is implemented, but also how the SUDS is implemented in terms of potential improvements for water quality.

There have been several studies published which have noted that SUDS can play a substantial role in the reduction of water pollutant introduction to waterbodies when a flash flood occurs (Ghani et al., 2008). This is primarily due to the reduction of water surface flow. During a flash flood, the relatively larger volume of water which is introduced to the urban environment has a greater potential to disturb and carry pollutants within the surface water runoff, this is due to the volume and velocity of the water (Whitehead et al., 2009). Whilst the primary purpose of a well designed SUDS system would be to halt the occurrence of a flash flood by providing appropriate stormwater management and drainage systems, there is always the possibility of rainfall occurring in excess of what the system is designed for. In this instance, whilst the SUDS system would not prevent the flash flood from occurring, the nature of the SUDS system is such that it is designed to store and/or treat water before it is

removed from the urban environment. Thus, in this instance, the SUDS system would reduce the pollutant loading of nearby water bodies through either reducing the rate at which flood waters are introduced into the nearby waterbodies, or by the inclusion of an aspect of water treatment, such as through infiltration, prior to reintroduction into the natural waterbodies (Imran et al., 2013).

When considering the potential for using SUDS to reduce detrimental impacts on water quality, attention is typically focused on ground level interventions, rather than rooftop level interventions as studies have demonstrated that the majority of pollutants are introduced to water bodies via ground level surface runoff (Liu et al., 2016). In comparison, runoff from rooftops carries a much lower pollutant load. However, it should be noted that rooftop interventions can potentially be a source of some pollutants that may impact water quality, such as nitrogen or phosphorous, which are attributable to the SUDS (Wang et al.2017). The following section provides a detailed review on each type of SUDS.

2.2.4 Types of SUDS

2.2.4.1 Green Roofs (GRs)

A green roof is "a roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane" an example is given in Figure 2-3. GRs are typically classed as either extensive or intensive; the classification is dependent upon the depth of the substrate, with extensive roofs being comprised of shallower substrates (Lim and Lu, 2016). Typically, GRs have been found to have retention rates of between 50 – 90% (Voyde *et al*., 2010; Speak et al., 2013; Razzaghmanesh, et al., 2014; Zhang et al., 2015). However, once GRs have reached saturation, they will no longer continue to retain water. This means that during prolonged or intensive rainfall events, the point at which GRs cease to reduce stormwater runoff may be quickly reached and studies suggest that there may be a substantial variation between the laboratory performance of GRs and that which is found in situ (Szota et al., 2017). For example, Lee et al. (2013) found that rainfall intensities greater than 20 mm per hour substantially decreased the water retention capacities of GRs. Some studies have suggested that the performance of GRs is not primarily a factor of retention by the substrate material, but rather is due to the potential evapotranspiration (Poe et al. 2015). However, it should be noted that there is still extensive debate in the literature regarding the relative importance of retention capacity or evapotranspiration for green roof performance (Zhang et al., 2019). Johannessen et al. (2018) found that increasing the depth of the substrate

material beyond 13 mm depth had little impact on increasing retention rates, suggesting that variations in the retention rates were instead due to the processes occurring between rainfall events and the actual evapotranspiration. This would suggest that the performance of GRs in reducing stormwater runoffs and peak flows would be impacted by the intervals between rainfall events, in addition to the composition of the rooftop, the longer the duration between rainfall events, then the greater the opportunity for evapotranspiration to occur, resetting the retention capacity back to optimum (Nawaz et al. , 2015; Wong and Jim, 2015). This highlights the importance of considering local climatic conditions when selecting SUDS. In an area that experiences monsoon weather conditions, a green roof would only be effective in reducing the stormwater runoff and the peak at the onset of the monsoon season (Chai et al. 2017). The frequent and intense rainstorms common to a monsoon climate would be unlikely to allow sufficient time for evapotranspiration to occur and recharge the retention capacity of a green roof in this environment (Akther et al., 2018).

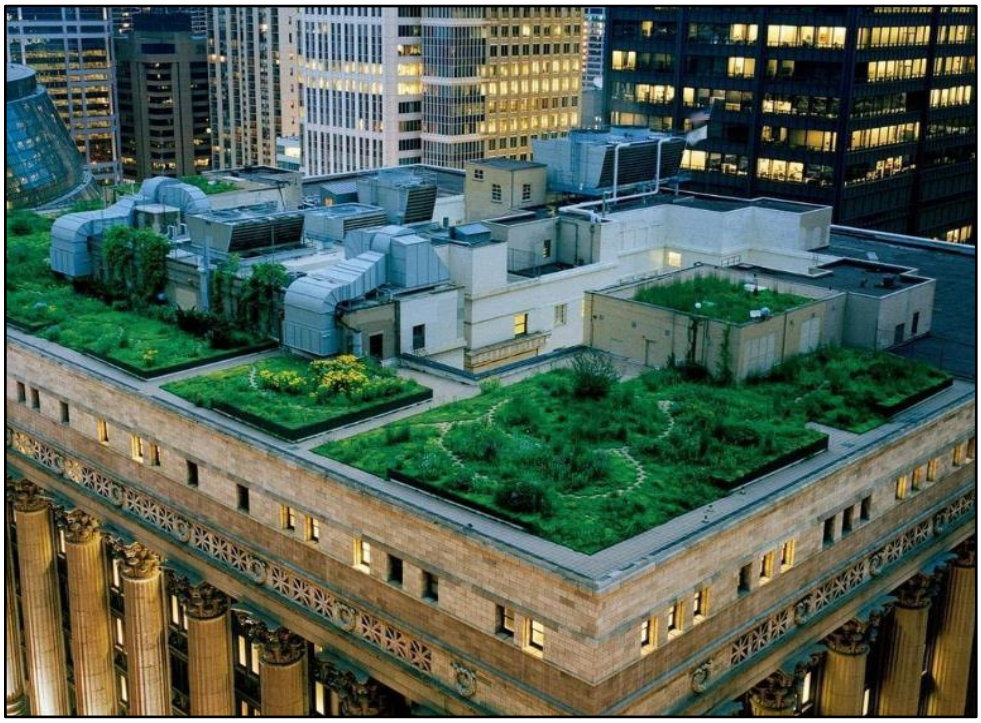


Figure 2-3 Example of Green Roofs (Navy, 2013)

The requirement of GRs to have regular irrigation, either from rainfall or from a manual application of water suggests that they may not be suitable for use in arid or semi-arid environments due to the potentially high water demand in areas which are already water scarce (Gioannini et al., 2018). There is a potential alternative which is the use of so termed 'brown roofs'. Brown roofs utilise the same principle of green roofs with the exception that they are solely comprised of the substrate material without any overlying vegetation (Schweitzer and Erell, 2014; Pradhan et al., 2019). Whilst this removes the need for regular irrigation, it does present some additional challenges which may impact upon their effectiveness. The first challenge is that the removal of vegetation also removes a water pathway, that of uptake by the vegetation through the rooting system (Cascone et al., 2019). This could potentially reduce the respiration/transpiration pathway; however, it could potentially increase the removal of water through the evaporation pathway due to the exposure of the substrate surface with shading by the vegetation (Cascone et al., 2019). A second potential challenge is related to the material which is selected for the substrate. In arid and semi-arid areas if the substrate becomes dry then there is the potential for substrate losses through wind removal of substrate particles (Schweitzer and Erell, 2014). This could potentially be costly, require regular replenishment of the substrate material as well as constituting a potential environmental pollutant through the dust which is created (Schweitzer and Erell, 2014).

2.2.4.2 Rain Gardens (RGs)

RGs are a type of SUDS that has many similarities with SUDS GRs, with the exception that GRs are placed exclusively on rooftops, whereas RGs are more flexible in their positioning. The principle of a green garden is that it acts as a retention area within which stormwater runoff can be collected and gradually infiltrated into the soil or surrounding drainage network; thus, the effectiveness of a rain garden is influenced by the volume of the collection area (Zhang and Guo, 2012). This means that RGs are frequently situated to collect the runoff from impervious surfaces, such as rooftops (Katsifarakis et al., 2015). Typically, RGs are shallow depressed areas (which allows for surface ponding of rainwater surface runoff) and are populated with plant species that are able to tolerate waterlogged conditions for a short period of time (typically designed for tolerating waterlogged conditions for approximately 48 hours; Katsifarakis et al., 2015).



Figure 2-4 An example of a rain garden (EPA, 2020).

Whilst RGs should function autonomously, they do require ongoing maintenance to ensure that they function as required. A study conducted by Asleson et al. (2009) found that a lack of maintenance can decrease the functioning of a rain garden in ways including continuous ponding of water on the surface (i.e. not infiltrating), the occurrence of hydric soils (a soil formed under saturated conditions such as flooding), the growth of emergent (wetland) plant species and the failure of planted vegetation to flourish. Thus, the type of maintenance which is required is comparable to that which is applied in a regular garden, including weeding, tending to plants and overturning the soil surface layer to prevent compaction. Due to the need for allowing ponded surface rainwater runoff to drain, RGs will not function correctly in areas where the water table is high as there is an increased risk of development into a wetland area rather than a rain garden. There is also the potential for RGs to reduce pollutant loading, although it should be noted that this reduction is more likely in scenarios where the rain garden drains by soil infiltration rather than when they are connected to the stormwater drainage network (Dietz and Clausen, 2005).

2.2.4.3 Bio-Retention Units (BRs)

BRs also function in a similar manner to RGs, in that they are designed to capture and store surface rainwater runoff to reduce the peak flow volume and gradually allow the

infiltration of collected surface water runoff through the soil either solely by percolation into the soil horizons or to gradually introduce the collected rainwater into the stormwater drainage network (Roy-Poirier et al., 2010). In comparison to RGs, BRs require dense vegetation, tighter design specifications and are preferable to implement around residential and commercial areas. Whilst this could potential impact upon their suitability for implementation in arid regions, the careful selection of vegetation could overcome this challenge, for example, the use of native plants species which are drought tolerant but have a relatively high water uptake and storage when water is available, such as cacti (Gioannini et al., 2018).

In a study conducted by Davis (2008) it was found that two BR units implemented at the University of Maryland campus in the United States were able to reduce the mean peak flow rates of stormwater runoff within their catchments by 49 and 58%. It should be noted that this reduction will be dependent on the rainfall patterns and the designed capabilities of the BR unit. As with RGs and GRs, a bio-retention unit is comprised of a soil filtration media with vegetation planted on the surface (Roy-Poirier et al., 2010). As with RGs and GRs there is also the potential for BR units to reduce the pollutant loading through pollutant removal as the rainwater surface runoff passes through the soil of the BR unit (Kim et al., 2003). One of the primary advantages of BRs in comparison to RGs and GRs is that they are typically designed to contain a greater volume of surface water runoff and therefore have the potential to perform better under higher rainfall intensities and durations. However, the performance of a bio-retention unit is likely to be substantially impacted by the choices that are made during construction, including the soil type and the vegetation cover. A study conducted by Gulbaz et al. (2016) found that both the soil type and the soil organic content had a significant impact on the performance of the bio-retention unit that varied with rainfall intensity and duration.



Figure 2-5 Bio-retention incorporated into sidewalk and parking lot from right to left, respectively (EPA, 2013)

2.2.4.4 Infiltration Trenches (ITs)

Infiltration trenches function in a manner that is similar in principle to that of BRs. The purpose of an infiltration trench is to collect surface rainwater runoff and allow it to slowly infiltrate into either the soil horizons or the stormwater drainage network, thereby reducing the peak stormwater flow rate (Chahar et al., 2012). The key difference in IT in comparison to other retention and infiltration-based SUDS is that ITs have a linear design (thin), similar to the drainage ditches that are often found alongside roadways. Additionally, infiltration trenches are not typically filled with soils, but rather are filled with gravel or stone (Chahar et al., 2012) In a study conducted by Martin et al. (2007), it was found that ITs were ranked as the most desirable option from a selection of retention SUDS, primarily due to the target of minimising cost output vs return. ITs can also be combined with other types of SUDS, for example an infiltration trench can be designed to underlay a permeable pavement, thereby increasing the rainwater capacity of the SUDS and reducing the likelihood for ponding to occur on the permeable pavement surface (Chaher et al., 2012). It is important that infiltration trenches are designed with the rainfall patterns of the region of implementation in consideration. This is due to the time period that will be required in between successive rainfall events to enable the infiltration trench to drain collected rainwater runoff between rainfall events. The effectiveness of ITs is adversely impacted when applied in areas that have a high water table as this negatively impacts the rate at which rainfall can infiltrate into the soil horizons (Locatelli et al., 2015).

2.2.4.5 Permeable Pavements (PPs)

PP is a type of SUDS that can potentially replace large urban impermeable surfaces including car parks, pathways and driveways (Scholz and Grabowiecki, 2007). The use of PP as roadways is not common due to concerns regarding the durability of permeable surfaces in this high use environment, linked to insufficient structural loading issues (Brattebo and Booth, 2003; Imran et al., 2013). The principle of PP is that it comprises two layers, a surface open-graded asphalt or concrete over an open-graded aggregate base, whereby open-graded means that the material is permeable (Scholz and Grabowiecki, 2007). The permeable surface is able to capture stormwater runoff on the surface layer, which then infiltrates into the base layers (Imran et al., 2013). In Figure 2-6 an example of a permeable pavement structure is given.

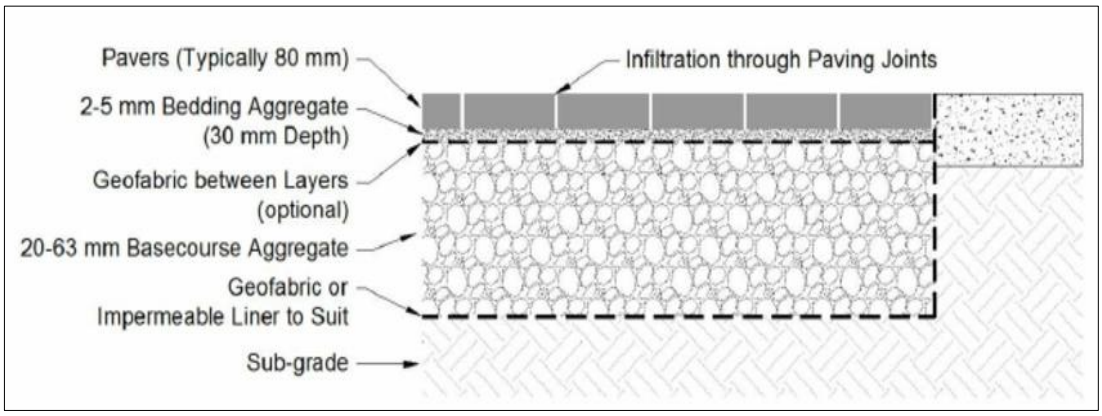


Figure 2-6 The structure of a permeable pavement (Lucke and Dierkes, 2015 p.16).

Types of PP materials include concrete blocks, permeable asphalt plastic grids and porous pavement (Imran et al., 2013; Li et al., 2013). The infiltration rate of permeable surfaces is one of the primary considerations when designing the SUDS as it will be a critical factor that influences the successful management of stormwater runoff (Li et al., 2013).

A study conducted by Li et al. (2013) found that there is a substantial difference between the infiltration rates of different types of permeable surfaces. It was found that an interlocking concrete paver permeable surface had the greatest infiltration rates (under saturation conditions) with an average hydraulic conductivity of 0.5cm s^{-1}. Permeable asphalt paving was found to have the lowest infiltration rates of 0.1cm s^{-1} under saturated conditions (Li et al., 2013). In comparison, Wanielista et al. (2007) found infiltration rates ranging from 0.00012 – 0.0126 cm

s^{-1} for permeable concrete surfaces, while Boogaard et al.(2014) reported infiltration rates of 0.00081 – 0.0095cm s^{-1} with porous concrete surfaces having greater infiltration rates than permeable surfaces formed of impermeable concrete blocks with infiltration channels in the joining areas. Thus, it is evident that there is a high-performance variability between different types of permeable surfaces. It is not just the infiltration rates that will impact the performance of PPs, the reservoir capacity of the aggregate base layer will determine the overall volume of stormwater that can infiltrate a PP, and, as reservoir drainage rates are typically lower than infiltration rates, there is the potential that a permeable surface will become saturated under high frequency of high intensity rainfall events (Li et al., 2013).

An additional factor that should be considered with permeable surfaces is the potential for them to become clogged over time and, thus, experience a decrease in infiltration rate that could adversely impact the ability of the system to cope with stormwater drainage and high peak flow rates (Deo et al. 2010). Pezzaniti et al. (2009) found that, over a 35-year period, this could potentially reduce the hydraulic conductivity of PPs by 59%-75%. The potential of PPs to clogging has been found to vary between surface types (Yong et al., 2008) and this is a factor that should be considered when selecting a permeable surface type as local conditions, such as high wind blown particles, may have an impact on the rate of clogging and, thus, the associated maintenance costs and periodic necessary for cleaning to improve drainage.

2.2.4.6 Swales

Swales share properties with permeable surfaces in that they are designed to improve the infiltration of stormwater away from the surface in urban areas. The primary difference between permeable surfaces and swales is that the latter perform by directing stormwater runoff from a catchment area into a swale, thereby concentrating the infiltration activity into one contained area, as opposed to the large surface infiltration area of PPs (Zakaria et al., 2010). In this manner, a swale is similar to a drainage ditch. Swales are most commonly long, thin, linear constructions that line the edge of a catchment area (Ghani et al., 2008) and typically include the use of vegetation lining their sides to reduce the peak stormwater flow into the swale (Zakaria et al., 2010). At the bottom of the swale, aggregate material, or specific soils, are layered for water infiltration (Zakaria et al., 2010).

The placement of swales is typically determined by the natural drainage patterns of a catchment area; therefore, swales are positioned in locales where stormwater runoff would typically pool on impermeable surface layers, essentially forming a stormwater runoff trap (Yang and Li, 2010). Swales, therefore, reduce the volume of urban stormwater runoff into nearby waterbodies by retaining the runoff. Yang and Li (2010) found that the use of a swale system in an urban development resulted in only a 26% increase in runoff volume in comparison to a traditional drainage system in the same area (therefore, the same rainfall patterns) which increased stormwater runoff by 110%. The use of a swale system increased the infiltration and evaporation of stormwater runoff before it can enter water bodies. The use of vegetated swales can also have the additional benefits of reducing the pollutant loads of stormwater runoff (Ayub et al., 2005). A study conducted by Xie et al.(2017) suggested that swales can be effectively implemented with other SUDS, such as a PP to aid in the management of stormwater runoff from high intensity rainfall events that are greater than the capacity of individual SUDS to cope with. For example, if a permeable surface becomes blocked, or the infiltration rate of the permeable surface is insufficient to cope with the rainfall intensity, the use of a swale can provide an additional capacity for the collection and infiltration of high stormwater runoff and peak flows (Xie et al., 2017). Swales can potentially be a lower cost option than PPs, particularly in existing urban areas as they do not require extensive infrastructure alterations and there are fewer materials needed, which will reduce the potential construction costs (Jackson and Boutle, 2008).

2.2.4.7 Rainwater Harvesting (RH)

The approach of RH is on the surface a relatively straightforward undertaking whereby rainwater is captured and stored (Torres et al., 2019). This stored rainwater can the be used for non-potable purposes, such as irrigation or flushing toilets (Torres et al., 2019). The water which is collected by RH is generally not designated as suitable for potable purpose unless additional treatment is applied (Al-Salaymeh et al., 2011). The concept of rainwater harvesting and storing for later use is not a novel practice, indeed it has been incorporated into the agricultural practices of many civilisation for millennia (Campisano et al., 2017). It has been suggested by some studies that the use of harvested rainwater, if it were to replace all non-potable water demand, would reduce the use of centralised clean drinking water systems by about 80-90% (GhaffarianHoseini et al., 2016). At the most basic end of the scale, RH can be accomplished by simply placing an open container in an area where rain can fall into it.

However, the type of rainwater harvesting which is utilised in a SuDs system is more complex, particularly in urban areas (Campisano et al., 2017).

Rainwater harvesting is most effective when the rain that falls on a large surface area can be collected and diverted into a storage location. In practice this typically means capturing the rain which falls on a rooftop and diverting it, such as through the use of guttering and a drainpipe, into the desired storage container (Baguma et al., 2010; Amin and Han, 2011). If the collected rainwater is to be used for purposes at ground level, such as car washing or for irrigating gardens, then it is often the case that the container will be placed at ground level (Walsh et al., 2014). However, if the collected rainwater is to be used for other purposes, such as flushing toilets, then the rainwater storage container will need to be place in a location where it can be connected to the point of use (Lawrence and Lopes, 2016). This will also require the consideration of what force will be used to move the water from the storage container to the point of use, if the storage container can be located above the ground, then the system can be gravity fed (Devkota et al., 2015).

When considering the implementation of a rainwater harvesting system, there are a number of factors which have to be accounted for. These factors include, the potential use of the collected water (as discussed in the previous paragraph), the positioning of the system, the storage capacity of the system and rainfall timing and intensity (Taffere et al., 2016). The time and intensity of rainfall is a factor which ties into the capacity of the storage system. In climates where rainfall occurs regularly, for example, in the Germany, then the storage system is likely to be regularly replenished (Geraldi and Ghisi, 2017). If the rainwater harvesting system is located in a climate where rainfall occurs infrequently with a higher intensity, such as in Indonesia which is subjected to a monsoon season, then the storage system would only be replenished infrequently (Susilo and Jafri, 2019). In the example of Indonesia, it would be suggested that a rainwater harvesting system would be likely to require a high storage capacity to achieve the maximum benefit from storing infrequent rainfall. If a high capacity system is implemented, then the stored water will last for longer without the need for replenishment (Susilo and Jafri, 2019). Thus, it is essential to ensure that the demands placed upon the harvested rainwater are aligned with the local rainfall patterns to enable maximum benefit to be achieved.

RH not only provides a non-potable water sources, it also contributes to stormwater management through the removal of potential substantial quantities of stormwater from the flow through system (Jiang et al., 2015). In an urban environment, rainwater which is harvested does not flow into the area's stormwater drainage network in the form of surface water runoff (Mahmoud et al., 2014). Thus, it could be suggested that the reduction potential is therefore dependent upon the storage capacity of the rainwater harvesting system, however, there have been several studies published which suggest that this is not the case. For example, in a study published by Walsh et al., (2014) it was suggested that the rainfall pattern and the disconnection of rooftop runoff had a greater impact upon the water volume reduction potential than storage capacity. The relative influence of the factors is however dependent upon location, for instance, in a study conducted by Tamaddun et al., (2018) in the arid region of Arizona in the United States found that a rain barrel with a capacity of 1.0-2.0 m^3 was sufficient to capture approximately 80% of the water from rainfall on the dwelling rooftop. In the study of Tamaddun et al., (2018), the capacity of the storage for rainwater was not the determining factor for runoff reduction, as indicated by the relatively small storage capacity, but rather the magnitude of the rainfall and the size of the collection surface. It is therefore suggested that in arid areas with limited rainfall the storage capacity does not need to be substantial in order to collect the majority of rainfall. The link between RH and the potential to reduce the occurrence of flooding was found by Freni and Liuzzo (2019) to be significantly related to the magnitude of rainfall. The Freni and Liuzzo (2019) study was conducted in an urban area of Sicily and simulated the addition of RH systems of 5 m^3 capacity on 408 dwellings, which comprised all the single family dwellings in the study area. The annual percentage reduction in flood volume was found to vary between 35% to 100% (Freni and Luizzo, 2019). There was found to be a flood volume reduction in each year of the simulation. Whilst the Freni and Lizzo (2019) was not conducted in an arid or semi-arid region, it has important implications when considering the application of RH in these climates due to the evidence of a link between the magnitude of rainfall and the potential for flood volume reduction. RH has been suggested in multiple studies as a nearly essential strategy which should be implemented in arid and semi-arid regions to address issues of water scarcity (Mahmoud et al., 2014). As was noted in the previous paragraph, the challenges of storage capacity and rainfall patterns will need to be carefully considered on an area by area basis in order to design RH systems which are suitable for the area in which they are to be implemented. A significant influencing factor for arid and semi-arid regions is the timing, intensity and duration of rainfall events (Amin et al., 2013; Mahmoud et al., 2014). If

the application of RH is for the purpose of preventing flooding in addition to providing non-potable water resources, then there will be a need for RH to be widespread in urban areas of these climates. The design of rainwater RH is that there is typically one storage collection point per rooftop. This would mean that in urban areas it would require participation from households and the consideration of the potential cost implications for households may present a barrier to the widespread adoption of this SUDS system (Mahmoud et al., 2014).

2.2.5 SUDS in Arid and Semi-Arid Regions (ASARs)

The weather patterns in ASARs result in particular climatic conditions that need to be accounted for when developing SUDS. Arid regions in particular can experience sustained periods of drought when it is necessary for water resources to be conserved (Kahil et al.2016). Whilst this is not a problem in terms of stormwater drainage and peak flow during times of drought, it is necessary for any SUDS implemented to take into account the need to harvest and store water during times of rainfall for use in times of drought (Mahmoud et al., 2016). Additionally, whilst ASARs are typically characterised by hot dry climates, there is a propensity in many regions for sustained torrential rainfall to occur periodically, for example, Sherif et al. (2014) reported that, in the United Arab Emirates, on the east coast, the maximum rainfall received in one day (out of a year) varied from 6.8 to 151.5mm within a 26-year period. This means that there is a high potential for urban flooding to occur if the urban drainage systems are not designed to cope with periodic high rainfall events. In many arid regions, the rainfall is confined to a small seasonal period, for example, in the City of Madinah, Saudi Arabia, rainfall occurs almost exclusively within a 2-month period each year with up to three months of the year experiencing little to no rainfall at all (Al-Saleem, 2018). This highlights the importance of designing an urban stormwater drainage system that can cope with the potentially high volumes of water in a short period of time (Salinas-Rodriguez et al., 2018). If a SUDs system is designed so that the maximum daily rainfall can be mitigated by the system, in the case of the United Arab Emirates 151.5mm, then the system will not be overwhelmed by this volume of rainwater (Voskamp and Van de Ven, 2015). If however the SUDs system is designed to lower specifications, for example based on the average daily rainfall, then the system will be unlikely to be able to mitigate the extremes of rainfall (Arnbjerg-Nielsen et al., 2013).

Urban development has also contributed to an increased potential for flash floods to occur in ASARs. For example, Al-Ghamdi et al. (2012) reported that the urban development in Makkah

City of Saudi Arabia had increased the urban area by 197% between 1990 – 2010 with a resultant impact of increasing the flood volumes by 248%. It was also noted that the increase in urban area was correlated with an increase in both the peak flow rate and the volume of floodwaters. This was primarily attributed to the increase in impermeable surface coverage in urban areas (Al-Ghamdi et al., 2012). Urban expansion is predicted to continue to increase in many areas of Saudi Arabia (Alqurahi et al. 2016). In Jeddah City, Saudi Arabia, urban flooding, due to poor stormwater drainage in combination with a decrease in urban permeable surface areas, has become a significant problem, for example, in 2009, a heavy rainfall of only a few hours duration resulted in widespread urban flooding causing more than 120 deaths and the displacement of more than 22,000 individuals (Momani and Fadil, 2010). It is, therefore, evident that SUDS need to become a critical component of urban design in ASARs areas to provide the dual purpose of increasing rainwater harvesting for drought periods and to reduce the potential impacts of urban flooding during rainstorms.

Whilst it is apparent that there is need for the introduction of SUDS in ASARs, there are a number of challenges associated with the implementation of SUDS in these environmental conditions. One of the major challenges is that there has been limited application of SUDS in such environments. The majority of instances where SUDS solutions have been implemented in real world scenarios have occurred in, primarily, temperate environments (Rathnayke and Srishantha, 2017). This means that there is a lack of background knowledge available to inform the development of ASARs SUDS to ensure that these systems perform appropriately reducing the risk of flooding from stormwater runoff and peak flow. There is a need to account for the different ASARs environments as they may not be the same as those which have been identified for other, more temperate environments. Gonzalez-Angullo et al. (2008) suggested that, in arid environments with high wind erosion of soils, permeable surface may become easily clogged. Eyre and Bhalchandra (2014) investigated the potential for the use of permeable concrete block paving to be utilised in the United Arab Emirates to increase the permeability of urban surfaces. The outcome of the Eyre and Bhalchandra (2014) supported the findings of Gonzalez-Angullo et al., (2008) regarding the potential for clogging, particularly by fine particles. In arid areas, a prolonged dry period is typically encountered each year, which increases the quantity of air-borne particles due to the drying of soils. Eyre and Bhalchandra (2014) suggested that this issue can be overcome by ensuring that the permeable surface is regularly cleaned to prevent

clogging, without which the infiltration rates could potentially be severely decreased, thereby reducing the potential of the permeable surface to contribute to stormwater drainage.

The climatic conditions of ASA areas may also potentially result in challenges to other methods of SUDS. For example, the use of GRs to reduce stormwater runoff and peak flow relies on the use of plants for effectiveness. In ASARs, there are prolonged periods of drought, which would require that the GRs are irrigated to ensure that the plants survive such periods (Feng, 2018). This could potentially be a barrier to the successful use of GRs under these climatic conditions as drought periods are typically accompanied by periods of limited water resources and it may not be possible for the increased water demand necessary for the irrigation of GRs to be met (Wang et al., 2017a). This barrier also applies to RGs. However, careful selection of the components of the systems (including plants and substrate material) could potentially aid in overcoming such obstacles (Herrera et al., 2018). There is potential for the irrigation of GRs to be conducted using grey water from households, as some studies have shown that this is an appropriate water source, particularly if the plant species are carefully selected to remove potential contaminants from the grey water (Chowdhury and Abaya, 2018). Additionally, the evapotranspiration potential of GRs must be carefully considered to allow for the rapid return to optimum retention capacities between the intense rainstorms that characterise the rainy season in these climates (Feng, 2018).

Whilst the implementation of SUDS in ASA climatic conditions has been limited, there are some examples where SUDS have been trialled in these environmental conditions. Perales-Momparer et al. (2014) reported on the use of roadside swales and GRs in the Valencia region of Spain, an area that is characterised by intense rainfall from September to December and little to no rainfall at other times of the year. It was found that the use of the SUDS effectively reduced the peak flow and stormwater runoff volume by increasing the threshold of rainfall at which surface runoff occurs from 1-2 mm without SUDS to thresholds of 4.6-9.4 mm for GRs and greater than 23.8 mm for locations with a swale and infiltration trench (Perales-Momparer et al., 2014). The difference in performance of the different SUDS system was attributed to differences in the design capacities and additionally it was suggested that the GRs need to have a period of time whereby the vegetation become established, essentially and equilibrium period, after which Perales-Momparer et al., (2014) suggest that this performance should improve.

Similar findings were reported by Andrés-Domenech et al. (2018) investigating the use of GRs under the same climatic conditions.

In Table 2-2 a summary of the SUDS options examined in the previous sections (Section 2.2.4 and 2.2.5) is presented including the potential barrier/limitation of each SUDS option and the conditions which are necessary to ensure that each SUDS option functions correctly.

Table 2-2 A summary table of the barriers/limitations of each potential SUDS option and the necessary conditions for each SUDS option to function correctly

SUDS Option	Barriers/Limitations	Necessary Conditions for Correct Function
Green Roofs (GRs)	• Requires Rooftops • Surface collection area limited by rooftop size • Requires irrigation during dry periods • Ceases to function when saturated • Limited by infiltration capacity and evapotranspiration rate	• Drying period between rainfall events • Thriving vegetation • Sufficient rainfall/irrigation to sustain vegetation
Rain Gardens (RGs)	• Ground level area required at a lower elevation than surrounding areas • Effectiveness limited by collection/retention capacity • Lack of maintenance could decrease functoing • High water table will prevent functioning	• Requires maintenance • Correct positioning relative to elevation of surrounding area • Relatively low water table
Bio-retention Units (BRs)	• Capacity limited by designed capabilities • Soil type and vegetation cover will influence functioning under different rainfall intensities and durations	• Dense vegetation • Native plant species with relatively high water uptake
Infiltration Trenches (ITs)	• Relatively lengthy linear area required • Rainfall patterns of region must be considered in design process to allow sufficient infiltration to occur between rainfall events to ensure that storage capacity is not exceeded • High water tables reduce effectiveness	• Linear area which is at an elevation which allows collection of surface water flow • Gravel or stone media for fill • Sufficient capacity or time periods between rainfall events to prevent exceeding storage capacity and allowing time for infiltration
Permeable Pavements (PPs)	• Requires paved area • Infiltration rate influences effectiveness, different materials have different infiltration rates • Degree of saturation affects infiltration rate • Reservoir capacity of base layer will influence rate of saturation and effectiveness • Potential for clogging to occur over time decreasing infiltration rate	• Paved area required • Regular maintenance to ensure that clogging does not occur • Sufficient time periods between high rainfall events to allow for infiltration or sufficient storage capacity to function effectively under multiple high frequency rainfall events

Swales (SW)	• Limited by the natural drainage patterns of a catchment area • Capacity is limited and influenced by infiltration rt. Rates	• Need to be located in an area which surface water flows to following natural drainage patterns
Rainwater Harvesting (RH)	• Requires a large surface are to collect rainfall runoff from • Storage capacity is limited to the capacity of installed storage containers • Collected water can only be used for non-potable purposes unless further treated • Rainfall patterns of the area will influence effectiveness • Requires individual installation and maintenance	• Surface area from which to collect runoff • Capacity to install storage containers of sufficient capacity

2.2.6 The Most Effective SUDS for Arid and Semi-Arid Regions

The limited applications of SUDS in ASARs means that it is difficult to determine which methodological approaches are likely to be the most effective solutions to urban drainage in these environments. However, from the current level of research, it is apparent that the SUDS solutions that are implemented in ASARs will need to account for the climatic conditions of these areas and that the performance of SUDS in these environments is likely to vary from that which has been observed in other climates.

It is recommended that permeable surface areas within the urban environment are used for SUDS in ASARs, as the increase of impermeable surface areas is one of the primary contributors to stormwater runoff in the ASARs urban environment. Additionally, the use of permeable surfaces is likely to be easier to implement than other SUDS options in high density urban environments lacking adequate grey infrastructure that could potentially be utilised.

It is likely that GRs and RGs could play a substantial role in SUDS in urban ASARs, although it should be noted that the plant species and substrate materials will need to be carefully selected to ensure that they are appropriate for the environmental conditions and will survive the periods of drought without substantially increasing the water demand of the household. It is suggested that this could be achieved by the use of drought-tolerant plant species, such as cacti, in combination with the use of household grey water for irrigation during the dry season, if the volume of greywater produced permits this and it is not prioritised for other purposes.

In conclusion, this study will consider the use of PPs, GRs, RGs and BRs to seek SUDS solutions in Saudi Arabia according to the findings of the literature review, which indicated that these SUDS are most likely to be appropriate for the scenario under consideration in as much as the findings of analysing selected areas showed the available locations for applying the different SUDS types mentioned. In addition, due to the lack information regarding implementing SUDS in arid regions and difficulty in deciding which is the most suitable type of SUDS in such region, survey through a questionnaire has been chosen and identified as the most appropriate method to gain information about the suitability of SUDS in ASARs (case study Jeddah City) and barriers that might be faced in applying SUDS in such region as well as gaining information regarding cost estimations (based on real market prices, see Chapter Five). This is then another novelty for this study.

2.3 Lifecycle Costs of SUDS

The absolute lifecycle costs of SUDS are likely to vary depending upon the geographical location of the type of SUDS that are to be implemented. It is likely that some forms of SUDS will incur higher lifetime costs than others due to the need for ongoing maintenance and the finite lifespan of some components, for example, some plant species used in GRs will need to be periodically replaced as they reach the end of their lifespan if they are not self-propagating or die from other causes (Fulthorpe et al., 2018). The whole lifecycle costs of SUDS include all aspects of the SUDS, from the production of components to the construction, maintenance and end of lifecycle financial expenses on a cradle-to-grave approach (Ossa-Moreno et al.2017).

Due to the relative novelty of SUDS, there are some assumptions that will need to be made when attempting to determine their cradle-to-grave approach whole lifecycle costs. Wolf et al., (2015) produced estimates of the whole lifecycle costs of a SUDS implemented in Dunfermline, Scotland. Two different methodologies were used to estimate the whole lifecycle costs and it was found that the difference in the cost estimates varied with SUDS methodology, by anything from 1% to 82% (Wolf, et al., 2015). This is a high degree of variation in cost estimates and is attributed to the differences in the maintenance costs calculated by each of the methodologies, as the construction costs for each SUDS method were the same in each cost estimate. When comparing costs between types of SUDS, it was identified that the primary driver of cost variation between different SUDS methods was attributable to the construction costs (Wolf *et al*., 2015).

Ossa-Moreno et al. (2017) investigated the whole life costs of various SUDS options located in London in the United Kingdom (Table 2-3). It was apparent that there is a high degree of variation and that these are influenced in part by the size of the SUDS. It is likely that these costs will vary with location due to local differences in the costs of materials and construction alongside ongoing maintenance costs.

Table 2-3 The whole life costs for different SUDS options in London, the United Kingdom (Ossa-Moreno et al. 2017, p.416).

SUDS	**Dimension (water capacity in m^3 and surface area in m^2)**	**Whole Life Cost (Capital Expenditure + Operational**
West Basin	1000m^3- 2000m^2	£54,131*
East Basin	7500m^3- 7500m^2	£405,980
Roof Disconnection	30,000m^3-350 Properties	£364,818
Infiltration Strips (Police St. Sub-catchment)	1532m^2	£139,083
Urban Wetland	1050m^3- 2100m^2	£62,150
Infiltration Strips (Whole Catchment)	4350m^2	£394,787
Bio Swale	609m^2	£15,416
Galvanised Steel Tank for Golders Green Station	1000m^3	£64,899

*The cost for each 1m^3- 1m^2 for each SUDS above can be found by deviding whole life cost to dimension.

The decision regarding the selection of SUDS options may in part be driven by their potential cost. Chow et al. (2014) calculated the cost of different SUDS options on a per unit (area) basis, including both the construction and operational estimated costs (Table 2-4). Although these costs estimates are for the United Kingdom, the authors suggest that they provide a fair representation of the relative costs of different SUDS options and can be adjusted with relative ease for application in different countries (Chow et al., 2014). It can be seen that there is a large range in per unit cost of the different SUDS options.

Another consideration that must be accounted for in assessing whole life cost estimates of SUDS options is whether the SUDS is to be implemented within new construction, or to be retrofitted to an urban area. It is likely that there will be different costs by unit for SUDS options when comparing new construction to retrofitting.

Table 2-4 The calculated capital expenditure (CAPEX) and operational expenditure (OPEX) for different SUDS,adapted from Chow et al.(2014, p.347).

SUDS	Range of Annual Unit Cost (£)		Unit of Measurement
	CAPEX	OPEX	
Filter Drain	130.8 – 183.1	0.3 - 1.4	/m^3 stored volume/Year
Infiltration Trench	73.2 – 83.7	0.3 - 1.4	/m^3 stored volume/Year
Soakaway	130.8 (avg.)	0.1 (avg.)	/m^3 stored volume/Year
Permeable Pavement	287.7 – 418.5	0.6 – 1.4	/m^3 stored volume/Year
Infiltration Basin	15.7 – 20.9	0.1 – 0.4	/m^3 stored volume/Year
Detention Basin	20.9 – 26.2	0.1 – 0.4	/m^3 stored volume/Year
Wetland	31.4 – 41.8	0.1 (avg.)	/m^3 stored volume/Year
Retention Pond	31.4 – 52.3	0.6 – 2.0	/m^3 stored volume/Year
Swale	15.7 (avg.)	0.1 (avg.)	/m^2 surface area/Year
Filter Strip	5.2 (avg.)	0.1 (avg.)	/m^2 surface area/Year
Green Roof	57.5 – 120.3	0.2 – 0.7	/m^2 surface area/Year

An additional aspect that should be considered when assessing the costs of SUDS from a whole life perspective is the potential offsetting of costs that the use of SUDS will provide. SUDS can arguably result in cost reductions in other aspects of the urban environment, for example, the successful implementation of a SUDS that averts urban flooding, thereby reducing the financial outlay necessary to clean up and repair after flooding events (Davis and Naumann, 2017). It is, however, difficult to quantify the potential financial benefits of SUDS with regard to averting the future costs of potential events. One way in which this can be achieved is to examine the cost of previous urban flooding events and compare this to the cost of implementing SUDS options. For example, Vincent et al. (2017) estimated the monetary value of ecosystems services (including flood reduction) by the implementation of SUDS in the Montevideo Municipality of Uruguay. It was found that the total benefits afforded by ecosystem services and flood management of SUDS were always greater than the financial cost of SUDS (Vincent et al., 2017). In Figure 2-7 the pareto-optimal fronts developed by Vincent et al., (2017) for SUDS solutions with and without the consideration of ecosystem services (ES) benefits are shown. It can be seen that when ES are considered as part of the financial benefits there is consistent increase in the financial benefit with increased financial cost. In comparison,

when ES are not considered as a benefit the implementation of SUDS solutions attains a point at which increased cost does not equate to substantial increases in total benefits (see Figure 2-7). This highlights the importance of considering all the benefits which are imparted by a SUDS system when attempting to quantify the cost to benefits of SUDS.

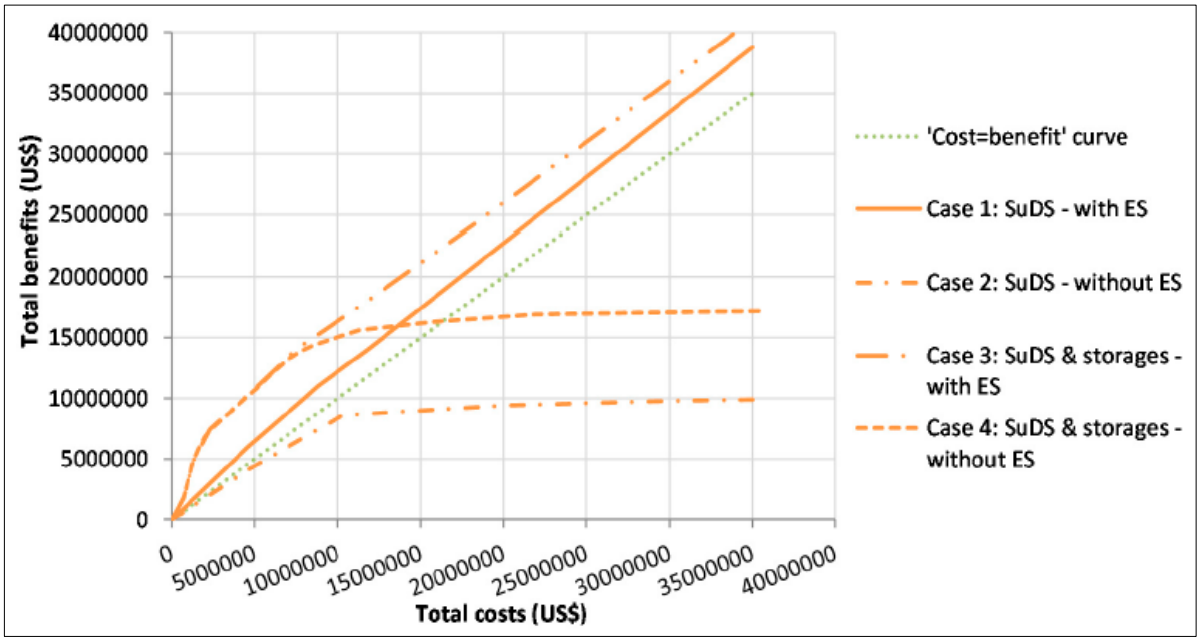


Figure 2-7 The pareto fronts developed by Vincent et al., (2017) to indicate the cost and benefits of two SUDS scenarios with and without the consideration of the benefits derived from ES (Vincent et al., 2017 p.855).

This can be used to justify the financial investments required for implementation of SUDS. However, it should be noted that some researchers advocate caution when using calculations of benefits to justify the use of SUDS due to the inherent uncertainties involved, such as future climate change impacts (Babovic and Mijic, 2019).

The potential cost of implementing SUDS in ASARs is difficult to quantify as, to date, very few SUDS have been implemented in these areas and those that have are typically experimental in nature, such as those implemented by Perales-Momparier et al. (2014) in a semi-arid region of Spain. It is likely that the costs incurred during the construction and maintenance of experimental SUDS are not reflective of the costs that would be incurred with widespread implementation. In addition, the maintenance costs associated with SUDS in semi-arid areas may differ substantially from the maintenance costs identified for SUDS in temperate and tropical areas, due to differences in the environmental operating conditions (Eyre and Bhalchandra, 2014).

The cost estimates that have been calculated for areas where SUDS implementation is more commonplace can be used as a starting point for estimating the potential cost of implementation in ASARs, providing a basis for decision-making on the comparative costs of the different SUDS options. The conduction of a survey through a questionnaire was identified as the most appropriate method for gathering data pertaining to financial costs of SUDS in arid areas for this study.

2.4 Regulations and Design Principles for SUDS

The relative novelty of SUDS systems means that there is not as yet a cohesive global approach to how SUDS systems should be regulated, what legislation should applied and the definitive design principles which should be utilised. Thus, at the current time there is a significant degree of variation to the extend and comprehensiveness of existing regulations which differ substantially depending upon the country in question (Bichai and Ashbolt, 2017). This variation in the extent of regulation and legislation is postulated to be correlated with the extent of SUDS implementation within the country in question. Therefore, countries which have relatively higher implementation rates for SUDS systems are more likely to have comprehensive regulations and legislations which have been established into national legally binding regulations. This is epitomised when the situation in Scotland is examined. In Scotland it is legally required that all newly implemented stormwater management systems must be under the design principles of SUDS (Aukerman et al., 2011). Therefore, it is no longer permitted to use grey infrastructure for stormwater management in new developments in Scotland and this has been the case since 2007 (Aukerman et al., 2011). As it is legally required to use SUDS systems, there is a corresponding thorough legislative and regulatory process when has been developed, thereby providing extensive guidance to developers as to what constitutes a SUDS system and what standards it needs to met regarding performance. This is highly advantageous in advancing the use of SUDS as it clearly sets out the requirements for developers and ensures that they meet regulated standards. In the absence of clearly defined regulation and standards there is a high potential for the performance of SUDS system to exaggerated and no legal recourse to ensure that the implemented systems are truly sustainable and advantageous for the environment (Pappalardo and La Rosa, 2020).

In contrast to the situation in Scotland, where it is very clear that regulations require the use of SUDS systems, in other countries the lack of regulation has been suggested as a

significant factor which contributes to the lack of SUDS implementation. For example, in England there are no centralised regulations and standards for SUDS. A study conducted by Lashford et al., (2019) highlighted how this lack of regulation in England meant that may developers were reluctant to incorporate SUDS systems into developments due to concerns regarding the future standards that may be implemented. These concerns were related to the potential for standards and regulations implemented in the future to exceed the design specifications of SUDS systems implemented before legal regulation (Lashford et al., 2019). This would potentially mean that costly works would have to be undertaken to develop the previously implemented SUDS system to bring them up to the legal standards. If this is a prolific concern among developers then there are two options which would avoid the issue, either chose to not use SUDS systems, or to implemented SUDS systems which represent standards which are likely to exceed those which may be introduced in the future (Ashley et al., 2015). Given the uncertainty of the second option, it would not be surprising if the majority of developers selected the first option of not implementing SUDS systems.

The lack of implementation of SUDS systems in arid and semi-arid areas could potentially be linked to the lack of regulation and standards. Unlike some countries where regulation is developing the wake of increased implementation, there is no such impetus in many arid and semi-arid areas due to the lack of implementation. It has been noted in some studies that the lack of regulation is one of the reasons for many developers to refuse to consider the use of SUDS systems and that strategies need to be implemented to overcome this barrier (Goulden et al., 2018). The lack of regulation and standards has been interpreted in this context as a lack of knowledge, expertise and guidance on the necessary steps to implement SUDS (Vasconcelos and Barbassa, 2020). The potential complexity of developing regulations is arguably one of the barriers to implementation of new legislation. Regulations for SUDS system will not only need to include standards for water quality and management but will also need to be integrated across different legislative departments, such as environmental and urban planning (Vasconcelos and Barbassa, 2020). Namekely et al., (2016) conducted a study in the semi-arid city of Erbil, located in Iraq and found that the decentralised nature of water supply and sanitation services across the city could potentially present a barrier to the implementation of SUDS if coordination could not be achieved. A comprehensive regulatory implementation would be likely to be able to overcome the institutional barriers as the use of SUDS systems would then be legally mandated.

The lack of regulation in the majority of countries regarding the use of SUDS systems does not mean that there is a corresponding lack of understanding as to what constitutes good designs principles for an effective SUDS system. There are several SUDS system manuals which are available that contain detailed protocols regarding how to adhere to SUDS principles and achieve sustainable urban stormwater management. One example of a comprehensive guide to SUDS principles is the free guidance manual which is offered by the Construction Industry Research and Information Association (CIRIA). The SuDS manual offered by CIRIA provides guidance on planning, design, construction and the maintenance of SUDS systems (CIRIA, 2015). Whilst the guidance manual is primarily based on the experience which has been garnered in the United Kingdom, the principles of the manual are applicable to worldwide scenarios. As the design principles which are supported are congruent with the principles of sustainable development and whilst they need to be adjusted for individual scenarios, the principles are the same worldwide. The SuDS manual which is published by CIRIA has been continuously updated and developed since the first edition was published in 2007, the current edition was published in 2015 and a comparison of the latest edition with the first edition clearly demonstrates how there has been significant progress in the understanding of SUDS systems, their principle, design strategies and implementation processes. This supposition is drawn from the fact that the current edition is more extensive and detailed than the 2007 edition with the 2015 being nearly double the length (in terms of pages) than the 2007 edition.

There are four principles which are held to be central to the design of SUDS systems according the CIRIA SuDS manual. These principles are water quantity, water quality, biodiversity and amenity (CIRIA, 2015). It is noted that the guidance offered by the CIRIA SuDS manual is based on the current body of knowledge. As discussed in the previous paragraph, there has been significant progress made through research and practical application of SUDS solutions over the past decade. However, as the guidance is based on experience thus far it is potentially questionable with regards to how much guidance can be provided for the implementation of SUDS systems in arid and semi-arid areas, given that there has been limited applications of SUDS systems in these regions, therefore there is limited experience to draw from. The majority of the guidance which is provided is therefore based upon the experience of SUDS implementation in climates which are of a more temperate nature. Whilst this does provide valuable insight into the functioning and cost of SUDS implementation, the guidance on how SUDS systems may perform in arid and semi-arid areas is still relatively speculative.

In the future it is likely that there will be more robust guidance on SUDS systems in arid and semi-arid areas, if SUDS systems become more widely implemented in these regions then there will be practical experience to draw from. However, at the current time it is still questionable how much guidance can be drawn from manuals which are based on the implementation of SUDS systems in regions with differing environmental conditions.

2.5 Computer Modelling of SUDS

2.5.1 Introduction

The implementation and maintenance of SUDS systems can potentially be highly complex and require substantial financial outlay. Thus, it is in the best interests of planners and developers to implement a SUDS solution correctly using the most appropriate system once, rather than having to revisit and revise an implemented system, as this would potentially incur significant additional costs. Thus, multiple software tools have been developed by researchers with the aim of understanding how an implemented SUDS solution will function when applied. The majority of the developed tools perform on the basis of integrating SUDS functionalities and watershed models. This subsequently enables multiple simulations to be conducted using numerous variations of SUDS potential solutions under different scenarios of potential water flow patterns. Ultimately, this allows planners and developers access to in-depth knowledge of the potential performance of SUDS solutions within the watershed of interest to enable the most effective and efficient solution to be identified. This aim of this sub-section is to review available stormwater models and the selection of a suitable model for this research.

2.5.2 Reviewing Stormwater Management Tools

Software tools have been utilised since the 1960s for the purposes of water resource management. More recently, technological advances have improved the functionality of these tools so that they are capable of modelling and simulating increasingly complex and detailed scenarios (Jayasooriya and Ng, 2014). The scope of software tools has been expanded from the primary purpose of water resource management to incorporate multiple specific objectives, such as the influence of stormwater runoff on water quality and the economic cost of management interventions (Harris et al., 2016).

Urban stormwater models can be broadly classified into two categories, those which model rainfall-runoff and those which model transport (Elliot and Trowsdale, 2007). In Figure 2-8 the differences between a rainfall-runoff model and a transport model are depicted. In general, a

rainfall-runoff modelling approach simulates the surface and sub-surface runoff attributed to rainfall and can also incorporate the accumulation of pollutants (Johnson, 2015). In comparison, a transport modelling approach typically simulates the stormwater flow in an urban environment through examination of the existing stormwater management infrastructure (Elliot and Trowsdale, 2007). The selection of either a rainfall-runoff model or a transport model approach to the problem of urban stormwater management will be dependent upon the urban area in question and the desired outcomes of the simulation. For example, in a situation where it is desired to implement a new approach to stormwater management, it would not be appropriate to utilise a transport model as this only considers existing stormwater management infrastructure.

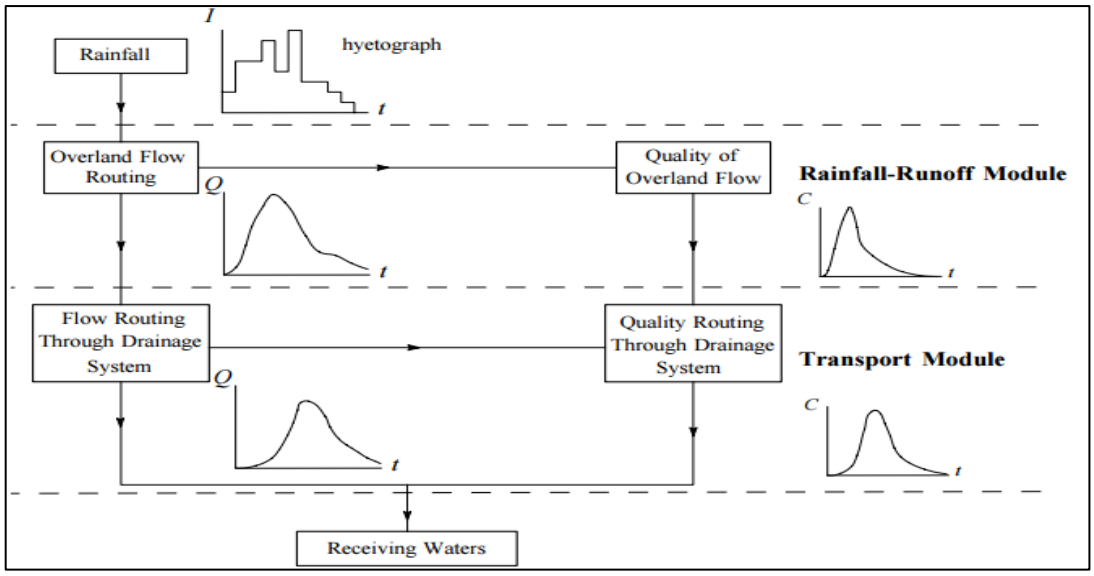


Figure 2-8 Showing the comparison between rainfall runoff models and transport models (Haris et al., 2016)

Harris et al. (2016) undertook a meta-analysis of ten existing software tools for assessing stormwater management whereby three aspects of functionality and two aspects of accessibility were assessed. A summary of this analysis is presented in Table 2-5 where it is indicated which of the software tools possessed the assessed attributes. The second aspect of the Harris et al. (2016) assessment compared the model characteristics of the routing level and modelling scale available, the outcome of which is illustrated in Table 2-6. From the findings, it is apparent that there is a high degree of variation in the attributes and flexibility of different models. This is similar to the findings presented in other studies, such as those by Jayasooriya and Ng (2014). In terms of selecting a software tool to conduct a modelling assessment, these findings indicate that it is very important to consider the attributes and functionality of the model which is to be utilised so as to ensure that the most appropriate model for the situation is selected. Thus, the

overall aim of the modelling study should be a highly influential factor which informs the selection of software tool to ensure that the aim of the study can be achieved.

Table 2-5 Comparing models in terms of functionality and accessibility. Adapted from Haris et al. (2016).

Urban Models	Functionality			Accessibility	
	Planning	Operational	Design	Public	Commercial
DRAINS	√	√	√		√
MOUSE		√	√	√	
Infowork RS		√	√		√
HSPF	√		√	√	
DR3M	√		√	√	
SWMM	√		√	√	
MIKE_SWMM	√	√	√		√
QQS	√		√		
STORM	√			√	
HEC-HMS		√			√
MSMA Design Aid and Database	√	√	√		√

Table 2-6 Comparing characteristics of representatives. Adapted from Haris et al. (2016).

Urban Models	Model Characteristics				
	Routing Level			Time-modelling Scale	
	Simple Storage	Hydrologic	Hydraulic	Continuous	Event
DRAINS	√	√	√	√	√
MOUSE	√	√	√	√	√
Infowork RS		√	√	√	√
HSPF	√	√		√	√
DR3M	√	√	√		√
SWMM	1	√	2		√
XP-SWMM	√	√	√		
MIKE_SWMM	√	√	√	√	√
QQS	√	√	√	√	√
STORM	√				√
HEC-HMS	√	√		√	√
MSMA Design Aid and Database	√	√		√	√

The research by Jayasooria and Ng (2014) also suggests that most stormwater models are limited by available data and the use of certain types of SUDS as opposed to a more generic/ integrated approach that can utilise data from a wide range of stakeholders to assess SUDS utility.

Table 2-7 Comparison between popular SUDS modelling tools (Jayasooriya and Ng. 2014).

Modelling tools	Owner and country	Types and number of SUDS supported	Scope of uses and comments
RECARGA	University of Wisconsin-Madison, USA	Supported **3** types of SUDS practices,: BR, RG and IT	To design and evaluate the performances of SUDS that software covered
P8 Urban Catchment Model)	Dr.WilliamWalker, Jr., Massachusetts, USA	Supported **6** types of SUDS practices: DT, Ponds, Wetlands, Infiltration Trenches, Swales, Buffer	It focuses on removing water pollution and improving its quality through SUDS practices.
Stormwater Management Model (SWMM)	Environmental Protection Agency (EPA), USA	Supported **8** types of SUDS practices: BR, IT, PP RB, Vegetative Swales, GR, Street Planters and Amended Soils	Planning, analysis and design of the performances of different SUDS. Improving quality and quantity of stormwater runoff. Has many features despite its complexity.
WERF and LID Modelling tools	Water Environment Research Foundation, Alexandria, Egypt	Supported **9** types of SUDS practices; GR, PP, Planters, RG, Retention, BR Ponds, Swales, Cistern and Extended Detention Basins	Can calculate whole lifecycle cost for SUDS practices It evaluates each SUDS practice by using different spreadsheet tools designed
SUDS Valuation Toolkit	Natural Economy North West UK	Supported **1**type of SUDS practices: Green Cover	To assess the social and environmental benefits of SUDS in monetary terms
CNT	Center For Neighborhood Technology, Chicago, USA	Supported **10** types of SUDS practices: GR, Planter Boxes, RG, Cisterns, Native Vegetation, Vegetation Filter Strips, Amended Soils, Swales, Trees and PP	Comparing the performance, cost and benefit of SUDS practices Allows the user to select the optimum SUDS or combination of SUDS with lowered cost that meets a runoff reduction goal
SUSTAIN	Environmental Protection Agency (EPA), USA	Supported **12** types of SUDS practices: BR, Cisterns, Constructed Wetlands, Dry Ponds, Grassed Swales, GR, Infiltration Basins, IT, PP, RB, Sand Filters (Surface and	Planning of SUDS implementations for discharge and pollutant management Allows user to assess the effective cost of SUDS

		Non- Surface); and Vegetated Filter Strips and Wet Ponds	
MUSIC	eWater, Australia	Supported **11** types of SUDS practices: BR, IT, Media Filtration Systems, Gross Pollutant Traps, Buffer Strips, Vegetated Swales, Ponds, Sedimentation Basins, Rainwater Tanks, Wetlands, and Detention Basins.	More helpful in making decision for which SUDS practices would be appropriate Can evaluate SUDS to achieve more effective cost, higher water quality and in reducing runoff
LIDRA	eDesign Dynamics, New York, USA	Supported **10** types of SUDS practices: GR, Planter Boxes, RG, Cisterns, Native Vegetation, Vegetation Filter	Cost reductions and SUDS Evaluates the efficiency of green space to reduce stormwater flow.
WinSLAMM	PV & Associates USA	Supported **6** types of SUDS practices: BR, IT, Street Cleaning, Wet Detention Ponds, Grass Swales, Filter Strips, PP	To improve the capability of SUDS in terms of reducing a pollutants and flow rate. For cost-effectiveness, sizing of SUDS needs to be modelled.

From the perspective of utilising a software tool for stormwater modelling in a situation where the aim is to assess the potential applications of SUDS solutions, one of the most important characteristics of the software tool which should be considered in the selection process is the types of SUDS options which are available within the software and how many options for SUDS utilisation the tool permits. For example, the RECARGA software tool only allows for three types of SUDS options, RGs, BRs and infiltration trenches, to be applied in the model (Jayasooriya and Ng. 2014). Similarly, the P8 software tool has a relatively limited SUDS type options with six SUDS options being available for inclusion in the model (see Table 2-7). In these software tool examples, there is a fairly limiting selection of SUDS options and, thus, these models will present limited solutions. In comparison, other software tools have been found to allow for 8–12 different SUDS options to be included. The benefits of including a greater number of SUDS options is that there is a greater scope for innovative solutions to be presented which utilise a combination of different SUDS options, thereby being more likely to present optimum solutions. However, it is not always necessary to select the software tool which has the greatest number of SUDS options available, as some of these SUDS options are slightly more unconventional and, thus, will not be applicable in many situations (Jayasooriya and Ng. 2014; Zhou, 2014). In the majority of situations, it will be sufficient to select a software tool which allows for the use of the most commonly applied SUDS solutions. In the case of this

research study, the selection of the SWMM software tool was determined to be suitable, even though, with only eight SUDS options, it had relatively fewer options than the majority of software tools, but these include those most commonly applied.

The majority of the software tools require that climatic data, the soil profile and land use data are necessary inputs. However, there is a high degree of variation in the additional data requirements between the available software tools. The greater the input data requirements, then the more complex the model which is conducted; however, a higher data input requirement is also likely to correlate with a higher degree of accuracy of outputs. This is due to the fact that, if a greater quantity of data is used in the model, then the more reflective the model will be of real-world conditions; limited data inputs will result in a simplification of real-world scenarios, which may reduce the accuracy of the model simulation. When developing SUDS solutions which are to be applied to the real-world, a higher data input is desirable as it will more accurately represent the functionality of the solution and, therefore,will be more likely to result in the selection of effective and efficient SUDS solutions.

The SWMM model is considered one of the most complex software tools as it requires relatively higher data inputs in comparison to other software tools, such as RECARGA, P8, LIDRA and WinSLAMM. Thus, it is suggested that the SWMM software tool is a more appropriate selection when considering detailed design of SUDS solutions, whereas the other software tools, such as P8, would be more suited to the initial planning stage of SUDS selection. One potential disadvantage of using a software tool that requires relatively greater data inputs is that the data has to be available for incorporation. Thus, in situations where there is limited dataset availability, it may not be possible to select a software tool which requires high data inputs. In this situation, the selection of a more simplified software tool with limited data requirements may be the only option (Jayasooriya and Ng. 2014).

The format and flexibility of the software outputs is another factor that will potentially influence model selection. In some software tools, the outputs are limited to the simulation of stormwater runoff in hourly time intervals, such as in the RECARGA, P8 and LIDRA software tools. In comparison, SWMM, SUTAIN, MUSIC and WinSLAMM have the ability to be more flexible in output time intervals, allowing both hourly and shorter time intervals to be used. This is important when a detailed analysis of the stormwater runoff patterns is required. The use of time intervals shorter than an hour would allow a more detailed assessment of runoff patterns to be investigated and, as rainfall intensity can potentially be highly variable over

relatively short timescales, the consideration of shorter timescale outputs could be essential for accurate representation of real-world scenarios within the model simulations (Jayasooriya and Ng. 2014).

The location of the real-world scenario to be modelled will be a highly influential factor when selecting which software tool to use in the study. This is because many of the available software tools have been developed for specific countries or locations. For example, the MUSIC software tool is most commonly applied in Australia, whereas the P8 software tool has been calibrated for and is used primarily in Rhode Island (Elliott and Trowsdale, 2007). Due to the high variability of environmental conditions and characteristics between different geographical locations there may be difficulties in using a model which has been refined and developed for a specific locale in a different location. However, some of the software tools have been developed with a high degree of flexibility with the aim of allowing the model to be adaptable for application to different geographical locations (Yang and Chui, 2019). The SWMM software tool is one such example and, due to the ability to include substantial quantities of data inputs, is applicable to one of the widest ranges of geographical locations and, theoretically, could be used in any global location for the purposes of stormwater runoff simulation (Jayasooriya and Ng. 2014). A secondary factor that is partially linked to the transferability of software tools is the scale at which they are able to perform. Some of the software tools are suitable for use in large-scale areas, whereas others perform better when considering solely a small scale area. Thus, the area of the simulations will also influence selection of the software tool.

Finally, the user interface and the handling of the tool is a factor which should be considered during selection. Some of the software tools, such as the SWMM model, are easily integratable with other tools, such as GIS and Matlab. This can mean that it is relatively easier to export and assess the outputs of the model in different formats, which can be important when needing to present the outputs in a format which is easily interpreted by decision-makers and planners.

Therefore, it is evident that there are several factors which need to be considered when selecting which software tool is appropriate to use when modelling different situations for the simulation and selection of SUDS options. When considering all these factors, it was determined that the SWMM presents the most viable option for conducting this study due to the tool's higher degree of flexibility and transferability to different geographical areas.

Additionally, the SWMM provides SUDS options which are appropriate for use in Jeddah City and it is likely that this model will produce the most accurate and appropriate outputs for the scenario to be simulated.

2.6 Stormwater Management Model (SWMM)

2.6.1 SWMM Overview

The Stormwater Management Model (SWMM) was developed by the United States Environment Protection Agency (US-EPA) in 1971 (Parajuli and Ouyang, 2013). Since its introduction, this model has undergone extensive development and expansion culminating in the currently utilised model, SWMM version 5.1 (Rossman, 2015). SWMM is a specialised model for simulating water flows in urban areas, particularly urban runoff quantity and quality. This dynamic rainfall-runoff model can be used to evaluate scenarios, including simulation of a single event, or long-term events using continuous simulations (Gironas et al., 2010). The latest improvements to SWMM incorporated within version 5.1 include a graphic user interface (GUI) enhancing the ability of the users to input data, run scenarios and offers multiple viewing platforms for the results (Rossman, 2010). SWMM is freely available to all on the US-EPA website (https://www.epa.gov/water-research/storm-water-management-model-swmm); however, whilst it is available for all, studies have suggested that the model is difficult to use for those individuals without sufficient experience and expertise in modelling due to the level of inherent complexity (Elliott and Trowsdale, 2007). Nonetheless, SWMM has proved popular among researchers modelling complete stormwater management systems in urban areas, including assessing the impact of climate change and the effect of SUDS (Elliott and Trowsdale, 2007; Abi Aad, et al., 2009; Damodaram et al., 2010; Burszta-Adamiak et al.2013). In addition, Zhang et al. (2013) and Giacomoni and Joseph, (2017) employed SWMM, together with algorithms, to optimise SUDS. In the following sub-sections, the components of SWMM are reviewed in greater detail, including assessments of the relative strengths and weaknesses of each aspect of the modelling software. Therefore, the next sub-sections are about infiltration and runoff; flow routing, hydrological components and SUDS representations in SWMM, respectively.

2.6.2 Infiltration and Runoff

In SWMM, the catchment area of the selected urban study site is divided into a number of subcatchments, where each subcatchment is assessed as a non-linear reservoir within only a

singular contributing water inflow, namely precipitation (Rossman, 2010). In some cases, addition inflow can be incorporated from designated upstream catchments (Rossman, 2010). The conceptualisation of surface runoff within a subcatchment is detailed in Figure 2-9. Surface runoff, calculated by the application of Manning's equation, will only occur when the depth of water within the modelled reservoir exceeds the given maximum depression storage (indicated by d_s in Figure 2-9).

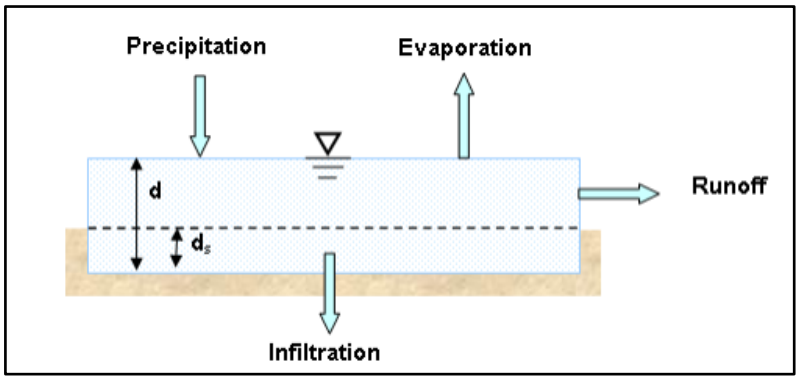


Figure 2-9 The conceptualisation of surface runoff within a subcatchment where d equals the depth of water over the subcatchment and ds is the maximum depression storage. Adapted from Rossman (2015).

Unlike runoff, which is calculated from one equation, the calculation that is applied to determine the infiltration rate of rainfall penetrating into the unsaturated soil horizon is determined by the user from one of three potential equations; Horton's Equation, Green-Ampt method or the Curve Number method (Cambez et al. 2008).

2.6.2.1 Horton's Equation

Horton's equation is based upon the observed occurrence of a change in infiltration rate as time from the commencement of precipitation increases (Rossman, 2015). Essentially, the Horton's equation accounts for the increasing saturation of the soil horizon. The relationship between infiltration rate is exponential in relation to time since rainfall commencement (Rossman, 2010). Thus, the initial infiltration rate at the onset of precipitation is the maximum infiltration rate and, depending on the duration and intensity of the rainfall, there is the potential for a theoretical minimum infiltration to be attained (Beven, 2004). The use of Horton's equation requires the following datasets to be inputted into the model parameters: maximum and minimum infiltration rates, a decay coefficient, which is describing the rate of infiltration

decrease over time, and the time period in which a fully saturated soil zone will be required to dry completely (Wang and Altunkaynak, 2011).

In the latest version of SWMM, there is the potential to use a modified version of Horton's equation that uses the cumulative infiltration above the minimum rate instead of using the time along the Horton's curve to determine the infiltration rate. This modified equation is most applicable in simulations where the rainfall intensity is low (Rossman, 2015).

2.6.2.2 Green-Ampt Method

The Green-Ampt method is based on the identified relationship between the depth of the soil and the soil moisture content (Bedient et al., 2008). Within this method, it is considered that there is a sharp wetting front that forms and separates the newly infiltrating precipitation at the top of the soil column from the soil at the base of the soil column which already contains moisture (Rossman, 2010). To use this method for infiltration calculation, it requires that the following parameters are defined; initial moisture deficit of the soil, the soil capillary suction head that forms along the wetting front within the soil and the hydraulic conductivity of the soil (Rossman, 2010).

2.6.2.3 Curve Number Method

The curve number method assigns a numerical value to each area of land (in this case, each subcatchment), this value is referred to as the curve number (CN) and is calculated based on the land cover, the hydrological soil type and the conditions of soil moisture before the onset of precipitation (Eli and Lamont, 2010). From the CN, the potential maximum soil retention of precipitation (i.e. the precipitation that infiltrates into the soil) can be calculated by the following equation:

$$S = \frac{1000}{CN} - 10 \qquad (2.1)$$

where S = potential maximum soil retention of precipitation after the onset of precipitation and CN = curve number (between 0 and 100).

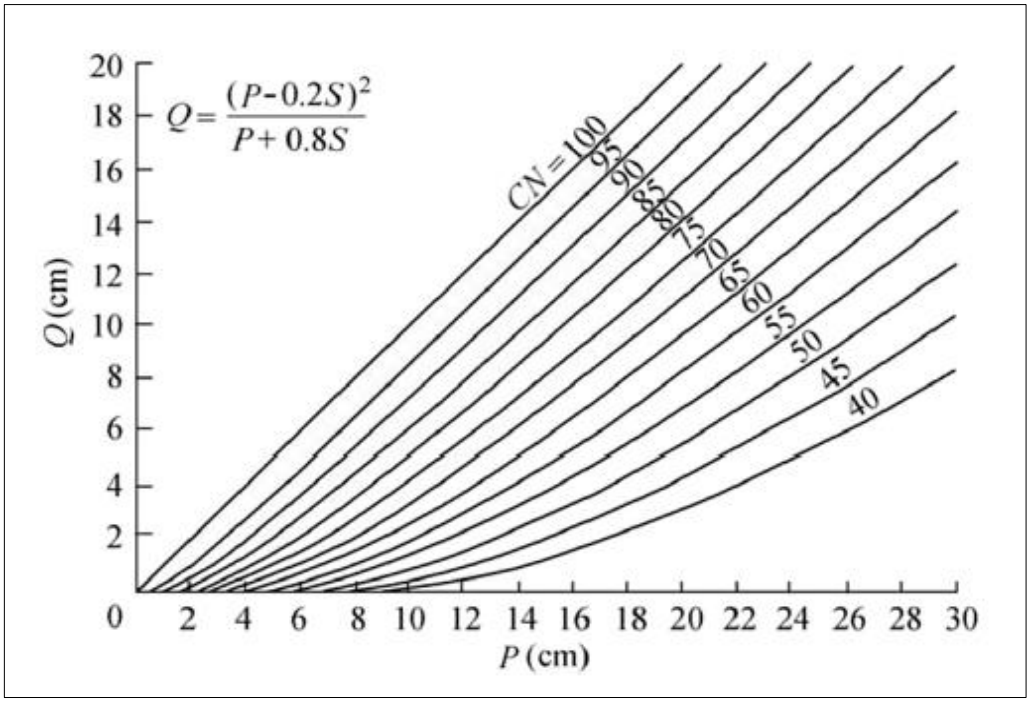


Figure 2-10 The conventional curve number model where P = rainfall and Q = surface runoff (Chin, 2018 p.188).

To calculate the infiltration rate using the curve number method, the parameters which are required to be inputted are: CN, the saturated hydraulic conductivity and the time required for a fully saturated soil to dry (Rossman, 2015). In comparison to the use of Horton's equation and the Green-Ampt method, the curve number method is relatively simple as it only requires one parameter to be specified, that of the CN, whereas the other two methods require a greater number of parameters to be defined (Ponce and Hawkins, 1996). For the purpose of this study, curve number method was chosen due to available data required for setting the mode parameters (Sections *2.7.2.1* and 3.4).

2.6.3 Flow Routing

The flow routing capabilities of the SWMM model has frequently been cited as one of the primary reasons why this model is selected to simulate urban stormwater management. This is due to the flexibility of the flow routing that is offered allows for multiple variations in the size and shape of conduits whilst also incorporating non-conduit structures, such as manholes, into the simulation as nodes in the routing network (Rossman, 2015). Thus, when the runoff within a subcatchment is directed to flow into a node, it subsequently flows through the conduits incorporated into the routing network (Burger et al., 2014).

SWMM allows the selection of one of three types of routing networks, steady flow, kinematic wave or dynamic wave routing (Rossman, 2010). The level of complexity varies depending upon the routing network selected. The dynamic wave routing network is suggested to be the most complex routing network choice; however, it has also been described as the most complete and theoretically accurate routing network for modelling urban stormwater runoff (Rossman, 2010). This accuracy is, in part, attributed to the solving of the one-dimensional Saint Venant flow equations which occur when using this routing method (Rossman and Supply, 2006). Additionally, the dynamic wave routing accounts for channel storage, entrance/exit losses, backwater, flow reversal and pressurised flow, thereby making this routing network the most suitable choice when simulating stormwater drainage systems which are likely to experience a substantial influence arising from backwater effects from downstream flow restrictions (Rossman and Supply, 2006). However, it should be noted that the time intervals which are used for this routing network are mandated at intervals of one minute or less (Rossman, 2010).

In comparison, the kinematic wave routing method does not account for any potential influence of downstream conduits on the flow, thus, the flow only occurs in the downstream direction (Nix, 1994). The flow in kinematic wave routing is calculated by two partial differential equations; the continuity and the momentum equations (Lockie, 2009). Thus, the kinematic wave routing is more simplistic than the dynamic wave routing method. The steady flow routing method is arguably the most straightforward of the routing choices as it is based upon the use of a hydrograph which does not account for any change in shape and only accounts for the lagging effects within the system (Rossman, 2015). Therefore, for more complexed stormwater drainage systems, it is likely that only dynamic wave routing can accurately account for the flow within the system.

2.6.4 Input Parameters for SWMM

The input parameters which are required for the SWMM model will be partially dependent on the methodology choices that are made, such as which equation is used for model infiltration and which routing method is chosen (see Sections 2.6.2 and 2.6.3). However, there are some parameters that will be necessary regardless of which methodology is selected. These include rainfall and climatology data, parameters for the hydrological components and the run time controls.

2.6.4.1 Rainfall and Climatology Data

Rainfall data can be entered in the simulation with a wide variety of options, including data intervals from one minute to 24-hour timescales and quantity in the form of intensity or as a cumulative accounting or incremental rainfall depth (Rossman, 2010). The time interval selection of the model, whether minutes, hours or days are selected depends on the desired output resolution of the model. If the model cumulative performance over a day is desired, then the interval selected would be 24-hours, if however it is desired to determine the model performance over a shorter time period, then smaller intervals will be selected.

If the simulation being undertaken is in the form of a continuous simulation, then it will be necessary to include climatology data to enable the calculation of evaporation effects (Rossman, 2010). In this instance, it will necessary to include data on the daily average air temperature, evaporation and wind speed (Rossman, 2015). Additionally, if the only data available are in a monthly format, SWMM applies an internal interpolation algorithm to generate estimates of the daily values of these variables (Rossman, 2010). This interpolation algorithm is based on a linear interpolation, whereby rainfall estimates are generated based on the discrete rainfall data points which have been entered. The accuracy of this method will be dependent upon the number of discrete rainfall data points which have been entered, the more data points then the more accurate the interpolation will be (Mair and Fares, 2011).

2.6.5 Hydrological Components

The hydrological components are comprised of two parts, firstly the parameters that define the subcatchment and secondly the parameters that define the stormwater drainage system. Whilst some of the parameters for defining the subcatchment are the same across all methodologies, including the subcatchment area, average land slope and percentage of impervious area, other included parameters will vary depending on the infiltration calculation equation that is selected. For example, the Green-Ampt method requires the soil capillary suction head to be included, whereas the Horton's equation method requires maximum/minimum infiltration rates (Rossman, 2015). The variance in available data is likely to be an influencing factor determining which infiltration equation is selected.

The stormwater drainage system also needs to be defined within the model. This will include the parameters for all the components of the system, including conduits and non-conduit

structures. This could be one of the most complex aspects of establishing the simulation parameters, for example, the conduit parameters include 23 pre-defined conduit shapes within the SWMM model that can potentially be selected (Rossman, 2010). Non-conduit aspects of the stormwater drainage system include junctions, storage units, flow dividers, weirs and orifices, and the characteristics of each individual occurrence of these aspects will need to be defined within the scenario to ensure that the simulation outputs accurately reflect the real-world conditions.

2.6.6 SUDS Representation in SWMM

SUDS within SWMM are referred to as low impact development (LID) units. The most recent iteration of SWMM includes a toolbox, which is specifically tailored towards including LID strategies within the simulation (Baek et al., 2015). However, it should be noted that, at the present time, the capabilities of the LID toolbox are limited to eight different types of SUDS, including BRs, RGs, GRs, ITs, PPs, SWs, rain barrels and rooftop descunicition (Rossman, 2010). The inclusion of a LID toolbox means that these SUDS can be included in the simulation simply by selecting the desired SUDS, choosing the area of coverage and defining the pecentage of the impervious surface area that routes to SUDS for replacing it to pervious area equivalent to the applied SUDS (Rossman, 2015).

In SWMM, SUDS are conceptualised as having different layers (Figure 2-11). Accordingly, SUDS will include a surface layer, representing the surface receiving the direct rainfall and runoff or a pavement layer representing the permeable surface layer of permeable pavements, a soil or sand layer and a storage layer representing water storage within the SUDS (Rossman, 2015).

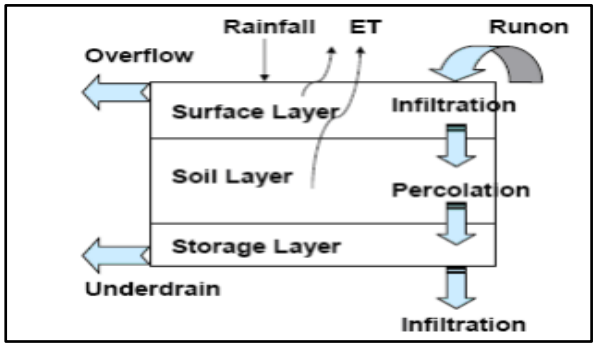


Figure 2-11 A conceptual diagram of the layers representing a BR within the SWMM model. Adapted from Rossman (2015 p.78).

2.7 Calibration of Rainfall-runoff Models

2.7.1 Introduction

Calibration is the process by which parameter values are assigned within a model and the modelled outputs compared with observed data; if the modelled outputs do not agree with the observed data, then the parameter values are altered until agreement is attained. Therefore, the first step in calibrating a model is to identify the sub-set of parameters. To select a sub-set of parameters for calibration, a sensitivity analysis is typically performed (the full details of the calibration method, including the sensitivity analysis and selection of parameters conducted for this study, are presented in Section 4.3).

The calibration of a catchment captured within a model is a highly important aspect of conducting a robust modelling study and directly influences the accuracy and reliability of the model outcomes (Barco et al., 2008). Each catchment that is modelled will need to be independently calibrated; this is because there is no one hydrological equation which can be applied to all scenarios to describe the water flow patterns (Blöschl, 2005). Other factors that contribute to the need for calibration include the function of calibration to account for biases within the inputs and the spatial variation of soil parameters (using a calibration allows for the incorporation of spatial variability), meaning that calibration can result in enhanced model outputs which, in turn, increases the performance of the model (Blöschl, 2005). Thus, it is evidenced that the calibration of a model will have a substantial influence over the modelled outputs. For example, Sun et al. (2012) compared the outputs of the SWMM model when calibrated at the macro and micro catchment level (one refers to large and one refers to small) and was found that the modelled scenario calibrated at the micro level produced outputs in which there was a higher confidence.

The calibration process that is undertaken will have an effect on the accuracy of the model outputs, for example, Shinma and Reis (2014) highlighted that the use of a multi-approach to calibration (using multiple datasets attained from within the modelled location) produced modelled outputs that were closer in nature to the observed outcomes than the modelled outputs attained when using single-approaches (only using one dataset from within the modelled location). This suggests that the effectiveness of calibration is linked to the dataset selected for the calibration process. However, when models are produced for catchments where there is either a limited or non-existent dataset regarding flow patterns, this can potentially

create a challenge for the calibration process (Krebs et al., 2016). These cases are referred to as ungauged catchments, i.e. where no flow data exist (Krebs et al., 2016). In these situations, a different approach needs to be developed, as the calibration process is still necessary for the reason given in the paragraphs above; therefore, a flow dataset for the ungauged catchment needs to be generated.

2.7.2 Calibration of Ungauged Catchment

The primary challenge in calibrating an ungauged catchment is how to derive the rainfall-runoff flow dataset that can used to determine the parameter values for calibration. There are two main methods that can be used to calculate these flow patterns for an ungauged catchment; either by using the rainfall-runoff process known for a similar gauged catchment, or, by calculating estimates based on hydrological response data other than rainfall-runoff (the use of empirical formulae; Blöschl, 2005). There are advantages and disadvantages to each method of calibration for an ungauged catchment and the method that is selected will be partially dependent upon the catchment that is being modelled and the available data.

The use of rainfall-runoff data from a gauged catchment is primarily reliant on there being data available for a catchment that has similar characteristics to the one being modelled (Bardossy, 2007). The principle of this method is that a gauged catchment of similar characteristics will have similar hydrological behaviour and, therefore, possess similar model parameters to the ungauged catchment (Bardossy, 2007). It has been suggested that catchments in close spatial proximity will behave in similar manner hydrologically, as will catchments that share similar catchment attributes (Blöschl, 2005). Whilst the frequency of gauged catchments in urban areas is low, there are some studies available where the gauged catchment availability in an urban area is sufficient to apply this method to calibrate ungauged catchments. For example, Chiang et al. (2010) used recurrent neural networks in an urban area of Taiwan, in combination with SWMM, to simulate the performance of both gauged and ungauged catchments of an urban sewerage system. They found that this method was appropriate and accurately predicted the hydrological behaviour of the study area. Similarly, Krebs et al. (2014) found that parameter values calibrated for small-scaled gauged urban catchments could be accurately applied to large-scale ungauged urban catchments. Their findings are particularly interesting for future studies using models such as SWMM in urban areas, as these findings suggest that it may only be necessary to have a dataset for a small-scale urban area, which

greatly enhances the potential for using similar catchment methods to calibrate large-scale urban areas as, typically, datasets are only available for small-scale areas in urban catchments.

However, in studies of urban stormwater catchment modelling, it is frequently observed that there are no data available from similar catchments that can be used as a calibration method (Mikkelsen et al., 2005). This is due to multiple reasons, including the uniqueness of different urban catchments and the frequency of study conduction in urban areas where the stormwater management system has not been studied in depth (Deletic et al., 2012). This was found to be the case for the study area considered for this research, Jeddah City. It was determined that there were no recorded flow data available for any of the catchments located within Jeddah City, or available data from regions with similar catchment characteristics. Therefore, it would not be possible to apply similar catchment methods, such as that utilised by Krebs et al. (2014) for calibration. This means that an alternative method must be utilised, that of applying empirical formulae to derive flow data from other hydrological response data.

2.7.2.1 Flow Estimation for Ungauged Catchment

There are multiple methods which can be applied to calculate flow data from hydrological response data using empirical formulae. The method which will be applied will be dependent both on the scenario under investigation and the hydrological response data available, i.e. different methodologies will require different data inputs and, thus, the datasets that are available will directly impact the methodology selection. It has been suggested that the most reliable method of calculating flow data within a catchment is to undertake a statistical analysis of datasets which have been collected over a long-term time period and from multiple locations within a catchment (Halefom et al., 2017). However, this is not always feasible if these datasets are not available. In these instances, alternative methods can be utilised, including the application of rainfall-runoff models or the use of regression equations (Lee et al., 2006). For the Jeddah City study site, the datasets which were available included rainfall, soil maps, land use maps and digital elevation models (DEM). Given this available information, it was determined that the use of the Soil Conservation Service Curve Number method (SCS-CN) and the production of Synthetic Unit Hydrographs could be applied to estimate the flow patterns in the Jeddah City catchment. This is due to the fact that the SCS-CN method requires limited data inputs, in the form of rainfall data and the calculated CN curve, all of which are available or can be calculated, for the Jeddah City catchment of this study (Cho and Engel, 2018). Subsequently,

the volume of the flows and the peak flows that would be generated via a model (SWMM model) would be checked and compared with estimates of flows derived from the SCS-CN technique; hence, this method of calibration is selected for this research for greater accuracy. (More details of the SCS-CN technique and Synthetic Unit Hydrographs can be found in Section A-3, Appendix A).

2.8 Current Studies on Selection and Placement Optimisation of SUDS

The following sub-section concerns relevant recent publications that have been reviewed to investigate common approaches to the modelling and optimisation of SUDS with the aim of identifying the relative strengths and weaknesses inherent to differing assessment approaches.

2.8.1 Modelling and Optimisation of SUDS

Optimisation of SUDS before implementation is vital to ensure that the implemented SUDS meet the stormwater management goals. In urban areas, the stormwater management goals are typically concerned with the reduction of surface runoff, the reduction of peak flows and, in the majority of instances, reducing the pollutant concentration in stormwater flows (Lamond et al., 2015). A number of articles were identified that investigated the optimisation of SUDS using modelling approaches and are summarised in Table 2-8.

Zare et al., (2012) used SWMM with the non-dominated sorting genetic algorithm II (NSGA-II) optimisation algorithm to provide a stormwater management solution for Tehran in Iran that would present the dual purpose of minimising stormwater surface runoff and peak flow whilst also reducing the pollutant concentration within runoff. The NSGAII was selected as it was determined that the non-dominated sorting and ranking selection provided enhanced capabilities applicable to the scenario that were not offered by similar algorithms. Only three types of SUDS were considered in this study, whilst they represent three of the most commonly utilised SUDS options, the selection of only three potential SUDS options limits the output of the study; it may be that the use of other SUDS options could potentially provide more efficient and effective solutions. However, the three SUDS options included in this study were carefully selected to reflect the urban conditions in Tehran, encompassing the limited nature of water resources in the area and the incorporation of the SUDS solutions within the existing urban infrastructure. To determine the pathway of flood waters, the kinematics wave method was

utilised with normal flow assumptions for determining the water flow pathway through the catchment areas.

Zhang et al. (2013) used SWMM to assess the relative financial costs and hydrological benefits of potential SUDS options for a relatively contained catchment area within a State College development, in central Pennsylvania. As in the study by Zare et al., (2012), only three potential SUDS options were considered, with the difference that GRs were selected instead of rain barrels, which reflects the different priorities for stormwater management in the case study areas. The case study area did not require the preservation of water resources and, instead, prioritised flow reduction. An adapted version of the NSGAII algorithm, referred to as ε-NSGAII, was used to perform optimisation. The addition of the ε-dominance archiving to the NSGAII algorithm allows the user to specific the precision of solution evaluation whilst also promoting a diverse representation of trade-offs (Zhang et al., 2013). The greater the ε-value, then the coarser the grid (used to represent the catchment area). This imparts a greater degree of flexibility to the assessment of potential SUDS solutions. The framework assesses the three selected SUDS options simultaneously rather than sequentially, which presents a greater opportunity for the development of integrated solutions, potentially providing a more robust evaluation of possible SUDS options. There was no consideration of water quality parameters (in terms of pollutant loading) in the simulations conducted by Zhang et al. (2013); however, they noted that the ε-NSGAII could be easily adapted to include water quality as an objective within the optimisation process.

Chow et al. (2014) presented an example of how optimisation within a decision-support-system can improve the selection of SUDS. As with the majority of other studies the algorithm utilised was NSGAII. The aim of their research was to provide an approach to SUDS selection that accounted for both drainage performance in addition to considering the financial costs associated with each option. To this end, their framework included 16 different SUDS (see Table 2-8), which is substantially greater than the number of SUDS options considered within the other identified studies (see Table 2-8). The model tested considered only one aspect of runoff, that of runoff retention, but did consider three indicators of water quality (suspended solids, nitrogen and phosphorus concentrations); this decision was made on the basis of integrating both hydrological and water quality concerns into the same framework. It was shown that, as the complexity of the scenario increases, by including additional objectives, the

number of potential solutions also increases (Chow et al., 2014). Whilst the NSGAII algorithm is used throughout the study, the authors note that the suitability of this algorithm for optimisation of scenarios with three or more objectives is questionable and that there are other algorithms that may potentially be more effective. Overall, the study demonstrated the complexity inherent to multi-objective SUDS optimisation scenarios and highlighted the necessity of using optimisation techniques to refine approaches to evaluate the potential outcomes of trade-offs in SUDS design.

Galindo-Calderon et al. (2015) also used SWMM with NSGAII to assess the most suitable SUDS and the optimal placements of SUDS to reduce peak flow within an urban catchment of Colombia. An additional aspect of their study is that they considered the potential of the identified solutions to provide solutions under future climate scenarios that are likely to arise due to CC impacts; seven potential SUDS options were included in the modelled scenario. Some assumptions were made during the modelling process, including that the implemented SUDS solutions could cope with surface runoff from all areas of the catchment. It was found that there was a high variability in the peak runoff reduction, with outputs ranging from 25% – 48% reductions; this was found to be correlated with the variable investment costs (of $25M - $110M), while the solutions that provided the greatest runoff reduction also had the greatest investment costs (Galindo-Calderon et al., 2015). Thus, it is suggested that the high variability in peak runoff reduction is linked to the magnitude of the drainage system which was implemented. This is inferred from the correlation between investment costs and runoff reduction whereby a higher investment cost indicates a more extensive or comprehensive SUDS system implemented. This highlights the need to compromise between the water management objective and the economic objectives within a SUDS design. Whilst there is a good range of SUDS options included in this study, there are multiple other potential SUDS options available (some comparable studies have included up to 16 SUDS options; see Table 2-8). It may be the case that the inclusion of additional SUDS options would present outcomes that could increase runoff reduction while also providing solutions that have lower investment costs.

Liu et al. (2016) was one of the few reviewed studies that did not use SWMM, instead it utilised a hydrological and water quality model. Long-Term Hydrologic Impact Assessment-Low Impact Development 2.1 (L-THIA-LID 2.1). As this model is used to assess outcomes, it was combined with an optimisation algorithm (AMALGAM) used within a multilevel spatial

optimisation framework to ensure that the objectives of the study were met (Liu et al., 2016). The use of AMALGAM allows multiple optimisation algorithms to be applied as it can run several algorithms simultaneously, including differential evolution (DE), adaptive metropolis search (AMS), particle swarm optimisation (PSO) and NSGAII. The model used by Liu et al. (2016) divided the overall watershed area into hydrologic response units, and, within these units, the land use and the soil groups were the same and each unit considered in isolation and assumed to not have an impact on adjacent units. In this manner, the SUDS solutions identified by the model are localised solutions. Optimisation was conducted in two stages, the first considered optimisation within each subcatchment. While the second conducted optimisation on an overall watershed basis. The outcomes identified by Liu et al. (2016) included consideration of the changing relative costs of different SUDS options, for example, whilst BRs were identified as more cost-effective than PPs, PPs were slightly more expensive. The optimisation process, therefore, prioritised BRs due to the financial implications and PPs were not considered until the bioretention had reached 100% capacity, at which point PPs became the more favourable option (Liu et al., 2016). This highlights the importance of ensuring that up-to-date and accurate data are entered into modelling software, particularly pertaining to SUDS costs, as it can have a substantial impact on the cost-efficiency relationships and, thus, the optimised SUDS options.

The study conducted by Giacomoni and Joseph (2017) only investigated the use of GRs and PPs as SUDS options. As with the majority of studies, SWMM software was utilised and the ε-NSGAII was used for optimisation. The authors justified the selection of the NSGAII algorithm stating that it outperforms the other commonly utilised algorithms in terms of the solutions presented. Unlike the majority of the other studies, the authors performed an additional analysis to determine if the optimisation findings were specific to the catchment that they used, or whether they could be generalised and applied to other catchments; this was achieved using a Monte Carlo simulation. It was found that there was a significant impact of local specificity in the effectiveness of the optimised SUDS selections, suggesting that the optimisation of SUDS is highly location-specific and, therefore, should be undertaken on a per catchment basis (Giacomoni and Joseph, 2017). In particular, Giacomoni and Joseph (2017) noted that the location of SUDS in downstream subcatchments had a greater impact on reducing peak flow, whereas SUDS placed in upstream subcatchments had a greater impact on improving the hydrologic footprint residence (which is a water flow measurement comprised of changes

to the flow regime and the area inundated after one rainfall event; Scott et al., 2011; Giacomoni and Joseph, 2017). In terms of overall optimisation of SUDS, it was found that there is a substantial influence of SUDS placement on effectiveness, with SUDS options implemented downstream found to be more effective at reducing the peak flow and overall runoff volume. It was also found that using the two investigated SUDS options (GR and PP) in combination was more effective than utilising either SUDS option in isolation.

Li et al. (2017) discussed an additional objective in their study that was not incorporated into the majority of the other identified studies, namely the potential for rainwater harvesting. The addition of this objective was primarily incorporated due to the study location (Beijing city, China) and the water resource issues that are encountered in this area. Only three potential SUDS options were considered, GRs, PPs and green lands due to the current levels of implementation of these SUDS options and the limited implementation of alternative SUDS options in the study area (Li et al., 2017). The NSGAII algorithm was used for SUDS optimisation, with the authors citing the robustness of this algorithm as identified in previous studies to justify their selection. It was noted that a substantial limitation of the study findings was related to the use of a constant precipitation volume, in comparison, rainfall records highlight that precipitation volume can potentially vary from year to year (Li et al., 2017). Thus, whilst the optimisation of SUDS may hold true for some years, where the precipitation is similar to the value used in the modelling study, the applicability of the optimisation for years where the rainfall varies significantly from the precipitation value is questionable. The optimal solutions identified by Li et al. (2017) were found to incur the highest investment costs and that there was a substantial influence of varying location climatic conditions and objectives for stormwater management on the optimum solutions identified.

Vincent et al. (2017) included the aspect of ecosystem services within the optimisation analysis as a factor that impacts the financial costs and benefits of SUDS. Ecosystem services are the benefits that humanity derives from a natural environment, thus ecosystem services can be highly variable ranging from carbon storage to water treatment to the psychological benefits of experiencing nature. The exact ecosystem services which are derived which be ecosystem and scenario dependent. This was the only identified study that included a non-monetary component as an influencing factor in the economic cost consideration of SUDS (see Table 2-8). As with the majority of studies, the authors used the SWMM software; however, the

algorithm that was used for optimisation was NSGAII. They also noted that the use of a 1D-1D model provides a simplified model of reality, whereas a 1D-2D model is more reflective of real-world scenarios. The 1D-1D model was used to allow the inclusion of roads into the model to more accurately portray flooding and, therefore, was a calculated trade-off within the simulation. As ecosystem services were included in the calculation of costs, the approach to the inclusion of cost values within the model was slightly different to that of other studies; therefore, social costs and benefits were assigned monetary values to allow for the inclusion of this variable in the overall optimisation assessment. Thus, the cost approach of this study included an assessment of the costs of flooding without the SUDS implementation and the financial savings made from the flood control offered by SUDS implementation (Vincent et al., 2017). The findings of the study indicated that, when including ecosystem services in the consideration of investment costs, there was no identified limit to investment costs that was not recouped by the monetary value assigned to the ecosystem services. However, it was also noted that, when optimising SUDS solutions to include ecosystem services as an objective, this had an influence on the suggested optimised SUDS solution. In comparison, when ecosystem services were not included as an objective, the optimised SUDS solutions that were calculated varied substantially (Vincent et al., 2017). This highlights the significant influence that the objectives being optimised for can have on the potential SUDS solutions identified as optimal.

Eckart et al., (2018) were the only researchers to use the Borg Multiobjective Evolutionary Algorithm (Borg MOEA) as opposed to the more commonly utilised NSGAII algorithm. They justified this selection by suggesting that the Borg MOEA meets or exceeds the performance of other commonly used algorithms and that it is due to the relative novelty of the Borg MOEA that it has not been more widely utilised in research. In the consideration of investment costs, they only considered the capital investment costs and ongoing costs, such as maintenance were not considered, nor were additional investment costs, such as land acquisition. This could potentially have a significant effect on the outcome of the SUDS optimisation for investment costs, as the construction costs only provide a partial indication of the cost of a SUDS. The other associated lifetime costs can potentially be highly variable with different SUDS solutions and, thus, could have a substantial impact on the outcome of the optimisation process if they were incorporated into the model. The primary aim of the study was to provide an optimisation for SUDS solutions based on a cost benefit analysis; therefore, the decision to exclude a substantial portion of the costs associated with SUDS creates extensive

doubt with regards to the accuracy and robustness of the SUDS solutions presented within this study.

The SWMM model was selected by Macro et al. (2019); however, it was coupled with an Optimisation Software Toolkit for Research Involving Computational Heuristics (OSTRICH) which utilises multiple parallelised algorithms rather than the singular algorithm utilised by the majority of studies (see Table 2-8). They suggested that the use of OSTRICH is advantageous as it allows the most applicable algorithm for the scenario to be applied, thereby improving the optimisation process. To illustrate the potential implications of algorithm selection, they conducted the same optimisation analysis using three different algorithms and it was found that there was a substantial difference in the optimal solutions presented by each algorithm, in terms of run time, number of model evaluations, the median cost of solution and the median stormwater flow reduction (Macro et al., 2019). This study, therefore, highlights the importance of algorithm selection when conducting optimisation analyses for SUDS solutions.

Table 2-8 A summary of the identified articles using modelling to aid in the optimisation of SUDS in urban areas.

Article Reference	Drainage Area	Location	Main Objectives	Type of SUDS	Software Used	Algorithm	Main Findings
Zare, Saghafian and Shamsai, 2012	Urban area	Tehran, Iran	Minimising flooding. Reducing runoff pollutant loading Reducing peak stormwater flows	Rain barrels, PPs BRs	US Environmental Protection Agency's Stormwater Management Model (SWMM)	Non-Dominated Sorting Genetic Algorithm (NSGAII).	The use of the decision-making tool reduced potential solution scenarios from 200 to 10, which is a more manageable number for decision-makers to deal with. The scenario selected as the optimal effectively reduced pollution and runoff with the lowest cost.
Zhang et al., 2013	Small urbanising watershed	Pennsylvania, USA	To identify methods of cost-effective low impact development. Peak-flow management.	GR PP BR	SWMM	Epsilon-Non-Dominated Sorting Genetic Algorithm II (ε-NSGAII)	37 scenarios were identified that attained a point where there were diminishing marginal benefits in peak flow reduction as the overall cost increased. The combination of SWMM and a multi-objective approach can inform decision-making.
Chow et al., 2014	Urban area	Australia	The maximisation of multiple benefits from one decision support system for SUDS	16 types of drainage systems including: Swales PP, Retention pond, Storage tanks	Multi-criteria evaluation framework	NSGAII	There is increasing complexity when multiple objectives are included. The trade-offs between objectives can be non-linear and increasingly complex as more objectives are considered. Different optimisation algorithms have different efficiencies.

Galindo-Calderon et al., 2015	Urban area	Melendez catchment, City of Cali, Colombia	Identify most suitable placement of SUDS and SUDS type. Reduce peak flow	BR RG GR Infiltration trench PP Rain barrel Vegetative swale	SWMM V 5.1	NSGAII	Multiobjective optimisation has a good capacity to assess SUDS design. Potential application for ensuring systems are applicable to changing environmental conditions, such as those likely under future CC. There was substantial variation in peak runoff reduction and investment cost. With high investment costs corresponding to the greatest decreases in peak runoff.
Liu et al., 2016	Highly urbanised watershed	Crooked Creek watershed, Indiana, USA	Identification of optimal implementation of best management practices and low impact development. To reduce runoff and pollutant loads.	Retention pond Detention basin Wetland basin Rainwater harvesting Permeable surfaces GR Grassed swale Wetland channel BR PP	Long-Term Hydrologic Impact Assessment-Low Impact Development 2.1 (L-THIA-LID 2.1)	A Multi-Algorithm Genetically Adaptive Multiobjective (AMALGAM) combined with a multilevel spatial optimisation (MLSOPT) framework	Different catchment area features result in different optimal solutions. For scenarios with greater financial outlay, more types of SUDS are suggested to be implemented to attained desired management goals in comparison to lower financial outlay scenarios. Increasing expenditure beyond a certain level did not always result in decreases in runoff volume and pollutant load. The optimised SUDS implementation scenarios were found to have a higher success at achieving water management goals in comparison to randomised SUDS placement between 3.9 – 7.7 times improvements in reductions. To achieve similar reductions, randomised placement scenarios required significantly greater financial investment.

Giacomoni and Joseph, 2017	Generic urban area hypothetical catchment	Not Applicable	Identify the optimal placement of SUDS within an urban area	GR PP	SWMM	ε-NSGAII	SUDS located downstream in subcatchments are more effective at reducing peak flow. SUDS located upstream are more effective at reducing the hydrological footprint residence. Optimal placement location is influenced by a variety of hydrological factors in combination with the stormwater management goal.
Li et al., 2017	Highly urbanised areas	Beijing and Wuhan cities, China	Optimising SUDS whilst considering multiple trade-offs for rainwater harvesting, runoff control, economic cost and pollutant reduction.	GR PP Green lands	Systematic multi-objective optimisation model	NSGAII	Using the optimisation model could potentially increase the rainfall under control by 200% compared to the current system. There was a significant influence of the different objectives on the generation of the optimum solution. The economic costs of solutions were also found to be highly variable.
Vincent et al., 2017	Urban areas	Montevideo Municipality, Uruguay	Assessing the flood reduction capacity and ecosystem services benefits of SUDS.	GR Rain barrels	SWMM	NSGAII	The inclusion of ecosystem services when determining the cost of SUDS (in addition to flood reduction) means that the benefits are always greater than the financial costs. Rainwater storage in combination with SUDS provides greater benefits in terms of flood reduction potential and is more cost-effective than SUDS without storage.
Eckart, McPhee and Bolisetti, 2018	Urban sewershed	Windsor, Ontario, Canada	Low impact development for managing stormwater	Rainwater harvesting Infiltration trench	SWMM	Borg Multiobjective Evolutionary	Infiltration trenches were found to be the most cost-effective option in the modelled scenario for reducing peak flow.

			drainage to minimise peak flows, reducing total runoff and minimising cost.	BR PP RG		Algorithm (Borg MOEA)	In terms of cost alone the SUDS may not represent the most cost-effective solution when compared to traditional drainage systems, but this may change when considering the effect on water quality.
Macro et al., 2019	Highly urbanised area	Buffalo, New York, USA	Assessment of trade-offs between cost of SUDS and reduction in stormwater flows. Comparison of outputs using three different algorithms.	Rain barrels	Optimisation Software Toolkit for Research Involving Computational Heuristics (OSTRICH) in combination with SWMM.	Asynchronous Parallel Dynamically Dimensioned Search (ParaDDS) Simulated Annealing (SA) Real-Coded Genetic Algorithm (RGA)	The three algorithms generated different optimal solutions for rain barrel placement. The ParaDDS was found to be the best performing algorithm in terms of a solution that provided the best compromise between conflicting objectives.

Overall, ten studies in Table 2-8 were identified and reviewed that investigated the modelling and optimisation of SUDS in the urban environment. Based on each category:

1- The majority of studies took an approach that incorporated use of the SWMM. It has been repeatedly proven through use in multiple studies as producing accurate and reliable outcomes.
2- It was found that the most commonly utilised algorithm was the NSGAII algorithm. Its use was justified by the authors as a proven algorithm that is suitable for use in the optimisation analysis of SUDS. However, this was not agreed upon by all authors, with Eckart et al., (2018) suggesting that the Borg MOEA algorithm is more suitable in this application than the NSGAII and the relative lack of use of Borg MOEA is only due to its relative novelty (Hadka and Reed, 2012). Similarly, Macro et al. (2019) suggested an alternative optimisation algorithm which, as with the Eckhart et al., (2018) study, was based on the use of multiple algorithms rather than a singular algorithm as in the case of NSGAII. Therefore, there is a need for continued research and development into novel algorithms to ensure that the optimisation analysis is robust.
3- The majority of studies investigated the modelling and optimisation of SUDS in terms of between one and three different objectives, but, whilst this prevents the model from becoming unwieldy due to multiple datasets, it does, however, promote questions regarding how the outcomes may influences other factors not included within the original objectives. It is for this reason that objectives are determined on a case-by-case basis and take into account the local conditions, as the primary objectives for one location may not be applicable to another. This highlights the importance of ensuring that all objectives are included in the optimisation analysis to ensure that the identified solution is applicable to the real-world scenario for which it is developed.
4- There is a tendency for modelled scenarios to be simplifications of real-world scenarios; however, it can potentially be problematic when considering the applicability of the outcomes for the real world. For example, Li et al. (2017) used only one input for annual precipitation, thereby not accounting for how the variability in annual precipitation across longer time scales may influence the functionality and outcomes of SUDS solutions. Similarly, when performing a cost benefit assessment, Eckart et al., (2018) only included the construction costs of SUDS, not the lifetime costs, which can potentially add substantial variations to the overall cost of different SUDS solutions (Berwick, 2016). Thus, it can be

seen that the outcomes of modelled scenarios are only as robust as the data included within them.

5- The number of potential SUDS solution was also highly variable between studies (range between 2:16) (Table2-8). This is due to predeterminations that the selected SUDS were either the most frequently implemented within their case study area or were the most likely to be applicable to area under study. There is the potential that the restriction of the SUDS solutions may lead to the overlooking of SUDS options that could potentially provide a more viable solution than those that have been included. It is suggested that restriction of SUDS options within a given scenario should only occur after all potential options have been considered within the modelled scenario.

6- The majority of the studies identified were focused on climates that are described as temperate or tropical; only one study was identified that investigated the modelling and optimisation of SUDS in an arid climate. It is likely that this stems from the limited application of SUDS in arid climates; however, it also represents a substantial gap of knowledge.

2.9 Optimisation in Stormwater Management

2.9.1 Overview

The process of selecting the optimal set of SUDS solution for urban stormwater drainage can potentially be a complex undertaking. This is due to the fact that there are multiple variables involved that will have differing degrees of influence over the final scenario outcome. This includes multiple SUDS options which can be implemented, with the complexity further enhanced when considering the number and size of these controls that should be implemented, the location of controls within the urban catchment area and the interactions between different controls. Each of these variables will need to be considered to enable a solution to be developed that provides the maximum benefit in terms of controlling stormwater drainage, i.e. the greatest reduction in peak flow and volume considering the financial constraints. It should also be considered that it is not only the control methods that are selected that will influence stormwater drainage, but also the characteristics of the catchment area within which they are placed, such as slope degree, which will have an additional influence on the performance of the implemented solution. Thus, the relevance of optimisation to the selection of a SUDS solution to urban stormwater drainage.

2.9.2 Multi-Objectives of Optimisation and the Application in Stormwater Management

If the focus of the study was to only consider a reduction in the peak stormwater flow of the urban drainage system (for example), then this would be described as a single-objective optimisation scenario (Makropoulos et al., 2008). The ultimate outcome would be to find the optimum solution for that one factor. This is a relatively straightforward optimisation process, given the need to consider only one variable outcome. In comparison, multi-objective optimisation requires that more than one factor is considered as influential in the variable outcome (Deb, 2011). Thus, it requires that all considered factors are optimised simultaneously to produce the desired outcome (Deb, 2011). The consideration of several factors under multi-objective optimisation scenarios typically results in the generation of more than one solution which can be defined as optimal (Chow et al., 2014). The identification of which of the determined solutions is the most appropriate and advantageous for the scenario can be calculated by determining the dominance of the solutions (Deb, 2011). The most dominant solution is the one which is most likely to present the solution with the least number of trade-offs between the multiple objectives.

In simplistic terms, the determination of dominance can be conducted by the following. Given two solutions, x and y, solution x will dominate solution y if solution x is identified as no worse than solution y when across all objectives and solution x performs better than solution y in at least one objective (Deb, 2011). Thus, in this situation, solution x would be described as dominant to solution y and, therefore, provides the more desirable solution scenario (Deb, 2011).

However, it is not always the case that a dominant solution can be identified and, thus, a set of alternative solutionsis generated which all meet the multiple objective requirements without one solution dominating; this set of solutions is referred to as the Pareto optimal set (Ikeda et al. 2001). The Pareto optimal set contains all the identified scenarios that will produce the best trade-off between the potentially competing objectives (Ikeda et al. 2001) and can be mapped, producing what is referred to as the Pareto front, Pareto surface or Pareto-optimal front (Goel et al., 2007). The optimal solutions will be as close as possible to the boundary that is defined by the Pareto-optimal front, with the trade-offs between objectives illustrated by its shape. Thus, the goal of a multi-objective optimisation becomes to identify solutions that are as close as possible to the Pareto-optimal front (Deb and Gupta, 2005). An additional objective

that can be considered within multi-objective optimisation is to find solutions that are close to the Pareto-optimal front, but also diverse in nature. This ultimately provides decision-makers with a varied range of potential solutions that hold in commonality their closeness to the Pareto-optimal front (Deb and Gupta, 2005) (See Figure 2-12).

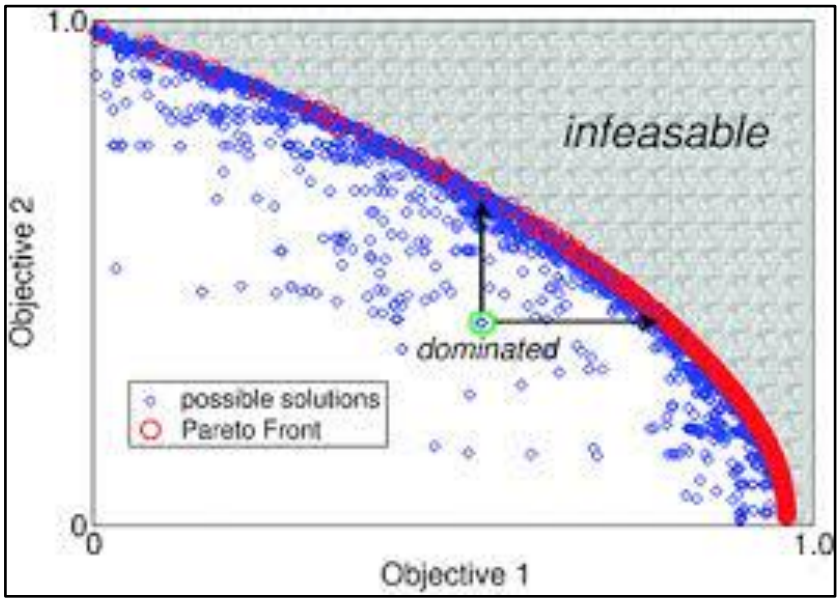


Figure 2-12 Example of Pareto-optimal front. Adapted from (Fingerhut et al., 2010)

There are multiple methods which have been developed to solve multi-objective optimisation problems and these include traditional approaches, such as the use of the weighted sum method, the ε-Constraint method and the weighted metric method (McCall, 2005). However, the complexity of the problem presented by multi-objective optimisation is such that methods of solving these problems have become increasingly focused on the use of specifically developed algorithms, in particular the use of evolutionary algorithms, such as genetic algorithms, has become increasingly frequent when approaching stormwater drainage challenges with multiple objectives (McCall, 2005).

2.9.3 Genetic Algorithms

Arguably the primary reason for the use of genetic algorithms as opposed to traditional calculation methods (cited in the previous Section 2.9.2), is that, whilst traditional optimisation methods operate on the basis of identifying one candidate solution, genetic algorithms operate on the principle of identifying a set of candidate solutions. This is unsuitable for meeting the goals of multi-objective optimisation, as it is an inherent characteristic of multi-objective

problems that all objectives are important and that, when deriving the optimal solution, no one objective can be placed above others in terms of importance. When using a traditional optimisation method focused on a single candidate solution, it is an almost certainty that the identification of a single solution will have an inherent bias promoting the attainments of the goals of one objective above the others (Cvetkovic and Parmee, 1998). In comparison, the ability of genetic algorithms to identify a set of candidate solutions is in keeping with the aims of multi-objective optimisation, thereby identifying a Pareto optimal set of solutions. Additional benefits of the use of genetic algorithms in this context is that derivative information is not needed and genetic algorithms possess an inherent flexibility whilst still remaining relatively simple to apply and sets of solutions are processed in parallel, which enhances the suitability for large-scale optimisation problems (Deb, 2001).

The developmental principle behind genetic algorithms is the adherence to an evolutionary approach, namely the use of a stochastic search technique which attempts to imitate the process of natural selection (Deb, 2001). These types of genetic algorithms can be further divided into those classified as non-elitist and elitist multi-objective optimisation evolutionary algorithms (MOEA: Coello et al. 2006). For the purposes of this study, only elitist MOEAs are considered going forward.

The operational principle of an elitist MOEA is that it examines scenarios in generations. The first set of scenarios is run and the highest performing (i.e. elite) solutions are preserved and carried through to the next generation. This is then repeated with the ultimate outcome being that the genetic algorithm converges upon the most optimal solutions based upon the multiple objectives. Thus, the final solutions set is based upon the evolutionary principle of fitness.

In order to regulate the process of generational selection and to ensure that convergence does not occur, two operators are applied to regulate the process; crossover and mutation regulators, which are applied to the identified solutions of each generation to create the child generation solutions.

2.8.3.1 Crossover

The crossover is a reproduction operator, which is applied to identified solutions in each generation to provide the potential solutions to be tested in the next generation. During this

process, two solutions are combined to produce one new solution, thereby creating copies of the 'good' aspects of solutions without creating entirely new solutions. An example of a single crossover whereby two child solutions are created from two parent solutions is given in Figure 2-13. The continued application of the crossover reproduction operator will produce improved offspring (Sivanandam and Deepa, 2007). There is more than one method of achieving crossover reproduction operations and a commonly used one is single-point crossover, whereby two individual solutions exchange a portion of their binary strings to result in the offspring with a random selection process applied to the selection of the portion to be exchanged (Sivanandam and Deepa, 2007). After the crossover reproduction operator has been applied, the mutation process is undergone.

	WW1	WAREA	WW3	WSLOPE	WW5
Parent 1	95	480	20	0.0545	0.0432
Parent 2	86	484	19.8	0.041	0.0344
Child 1	95	480	19.8	0.041	0.0344
Child 2	86	484	20	0.0545	0.0432

Figure 2-13 An example of two parent solutions undergoing single genetic crossover to create two child solutions, where WW1, WAREA, WW3, WSLOPE and WW5 represent the sensitive runoff parameters that are being altered (Wan and James, 2002, p.94).

2.9.3.2 Mutation

The purpose of the mutation process is predominantly to prevent solutions from convergence upon a local minimum. Essentially, the purpose of the mutation operator is to ensure that all potential solutions are considered equally following the evolutionary principle of maintaining genetic diversity within a community and implementing random genetic mutations (Sivanandam and Deepa, 2007). An example of a mutation is shown in Figure 2-14. The candidate strings can be represented either by a binary string or by the finite decimal representation of real numbers (Gaffney et al., 2010). If the parameter variables are directly utilised within the genetic algorithm, then it will not be possible to use binary-coded crossover operators, instead real number operators must be used (Deb and Kumar, 1995).

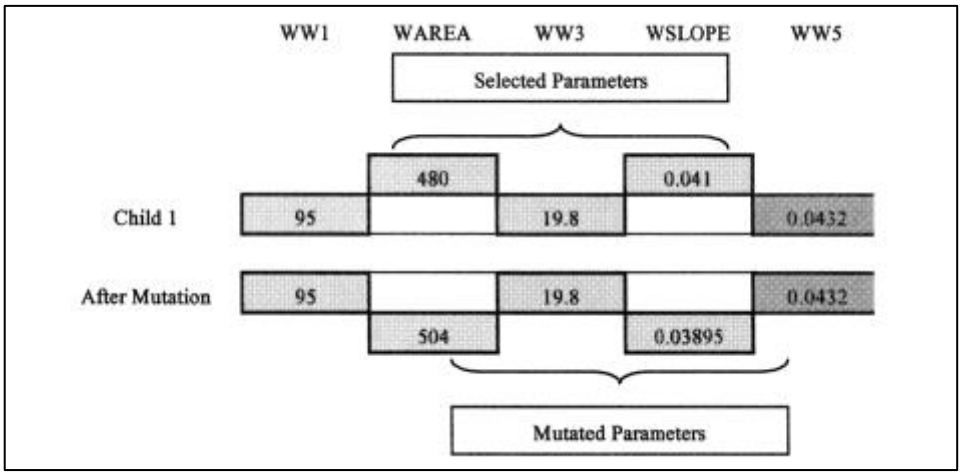


Figure 2-14 An example of a mutation operation whereby a child solution undergoes mutation to create a new solution., where WW1, WAREA, WW3, WSLOPE and WW5 represent the sensitive runoff parameters that are being altered (Wan and James, 2002, p.96).

In the following sections, two types of genetic algorithms that have been identified as highly applicable to the problem of urban stormwater drainage management are examined in more depth (Zhen et al., 2004).

2.9.4 The Non-dominated Sorting Genetic Algorithm-II (NSGAII)

The NSGAII uses a combination of two strategies, an explicit diversity-preserving strategy and an elite-preservation strategy (Cao et al., 2011). The use of both of these strategies is advantageous as it ensures that the diversity of the non-dominated solutions is preserved with the need for additional protocols to maintain diversity and the elite-preservation strategy ensures that any solutions identified throughout the process as Pareto optimal solution are preserved throughout the process and, therefore, are not discarded (Cao et al., 2011).

The ε-NSGAII algorithm operates on the basis of solution ranking. This process ranks the solutions on the basis of dominance (see Section 2.9.1 for a description of dominance determination; Dumedah et al., 2010). Once the solutions have been ranked, a two-step crowded binary tournament selection is conducted on the basis of the determined fitness value carried by each solution. The first step in the binary tournament selection is to include the most widely spread solutions by calculating the crowding distance values, followed by the creation of the child population using the crowded tournament selection, crossover operators and mutation operators. During this process, solutions that have a lower rank are preferentially selected; if two solutions are found to have the same rank then crowding distance values will be used to

determine which should be discarded (the solution with the larger crowding distance remains for inclusion). An overview of the NSGAII process is shown in the flow chart in Figure 2-15.

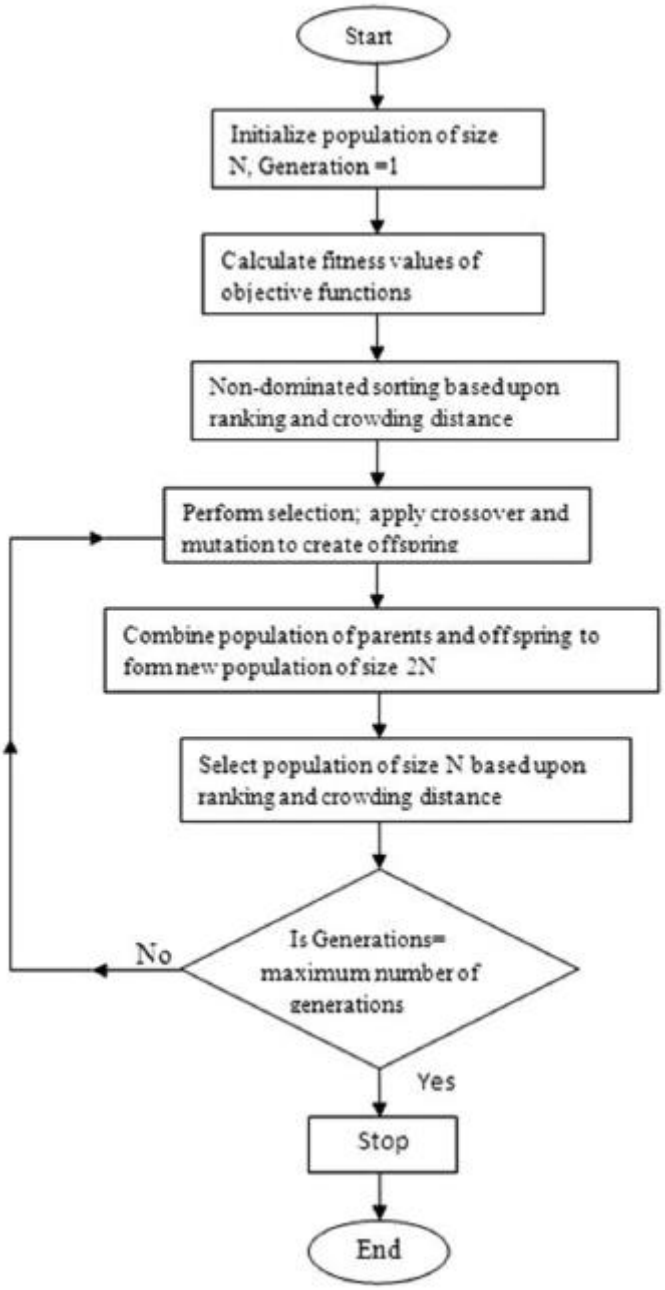


Figure 2-15 A flow chart of the NSGAII process (Garg et al., 2012, p.1998)

ε-NSGAII differs from NSGAII in that the former algorithm includes adaptive population sizing, ε-dominance archiving and automatic termination to the solution identification process (Kollat and Reed, 2005). This is a beneficial adaptation to the original algorithm as it provides the user the ability to specify the degree of precision with which

solutions are tested against the objectives. The greater the ε value, then the greater the permitted distance from the objectives potential solutions are permitted to be. However, whilst this can potentially increase the rate of solution return, it will also decrease the degree of closeness to the optimum that return solutions are permitted to be.

Multiple studies have applied the ε-NSGAII algorithm to the issue of urban stormwater drainage management from the perspective of implementing SUDS (Zhang et al., 2013; De Paola et al., 2018). This algorithm has arguably become the most widely utilised algorithm for multi-objective optimisation problems in this area. However, some studies have highlighted that one of the disadvantages of using a genetic algorithm, such as ε-NSGAII, is that, as the number of objective increases, then the proportion of locally Pareto non-dominated solutions can become disproportionatley large (Hadka and Reed, 2013). This can ultimately lead to a situation where it is difficult to produce child solutions that dominate the poorly performing (but still non-dominated) solutions, termed dominance resistance (Hadka and Reed, 2013). This has led researchers to develop novel algorithms to overcome this issue, such as the Borg MOEA.

2.9.5 Borg MOEA

The Borg MOEA has been developed specifically to address the problem that has occurred with previous algorithms when the number of objectives becomes greater than four (for an in-depth discussion of why objectives greater than four are an issue see Hadka and Reed, 2013). Multiple studies have identified that other algorithms, such as ε-NSGAII, do not produce Pareto optimal solutions when presented with a relatively high number of objectives (Hadka and Reed, 2013). Even when the objectives number is less than four, studies have shown that the optimisation undertaken by the Borg MOEA produces Pareto optimal solutions (Hadka and Reed, 2013). In order for current and future design and development scenarios to be attained, it has become clear that it is necessary to develop algorithms that can successfully incorporate the multiple objectives that will be necessary to ensure that solutions reflect the multiple objectives of sustainable development. The Borg MOEA is an example of an algorithm that can cope with the optimisation of multiple objectives and the characteristics that enable it to do so are reviewed in the following sections.

2.9.5.1 Borg MOEA Characteristics

Dominance resistance is a factor that contributes to the failure, by not selecting the most optimal solution, of many optimisation algorithms. Dominance resistance occurs when a less than optimal solution fails to be replaced by more optimal solutions. It can potentially exacerbate deterioration and result in the selection of less than optimal solutions. This is the primary difference between the Borg MOEA and the ε-NSGAII, wherein the former includes coding to overcome dominance resistance. The ϵ-Dominance archive has been developed to solve the issue of dominance resistance whilst also maintaining the guarantee of a varied set of Pareto optimal solutions (Hadka and Reed, 2013). Thus, the solutions determined by the Borg MOEA algorithm will simultaneously have convergence and diversity. The value of ϵ can be specified by the user and can be varied for each objective. Once a solution has been determined to be dominant, it is included within the ε-box. Thus, the Borg MOEA algorithm follows the principles of other elitist genetic algorithms.

A solution is added to the population within the ε-box if it can be proven to dominate at least one member of the population already within the ε-box. If a solution is proven to dominate, it replaces the dominated solution. Additionally, it is possible for a solution to dominate more than other solution held within the ε-box. All solutions that are found to be dominated are removed. It is the criteria for inclusion within the ε-box that prevent additional solutions from being added which are similar to already identified solutions, thereby preventing clustering and dominance resistance. To provide child solutions for each generation, one solution is chosen from within the population of the ε-box and one solution is selected from the wider population. The number of solutions that are selected from within the wider population is variable and is adapted depending upon the population size. This, therefore, means that selection pressure is maintained and also functions to ensure that, if a non-dominated solution is selected from within the wider population, it will not be dropped (Hadka and Reed, 2013). This is the same adaptive population sizing strategy that is used within the ε-NSGAII algorithm with the additional feature within Borg MOEA that the population to archive ratio is kept constant throughout the simulation (Woodruff et al., 2012). Thus, if the population to archive ratio varies by more than 25%, then the population size is adapted to remain similar (Hadka and Reed, 2013). The difficulty of the problem that the Borg MOEA is being applied to is reflected in the population size, thus, the more complex the problem, then the greater the population size.

To generate child solutions from the selected parent solutions, Borg MOEA uses an adaptive multi-operator recombination process, which named AMALGAM (Vrugt and Robinson, 2007). The operating principle of AMALGAM is that a feedback loop is established whereby the operators that produce the most successful offspring are prioritised in future offspring production and, therefore, produce more offspring. The Borg MOEA can be run for either a pre-determined fixed number of iterations or it can be chosen to allow the program to run until a point is reached where further runs do not result in improvements to the population, thereby signifying that the optimal solutions have all been generated.

It can, therefore, be seen that the Borg MOEA algorithm is an improvement upon previously utilised genetic algorithms such as ε-NSGAII. The improvements that are included within the Borg MOEA means that dominance resistance will not occur and it is, therefore, more likely that the outcome of utilising the Borg MOEA will be the correctly identified Pareto optimal set of solutions to the scenario. For these reasons, it was determined that the use of the Borg MOEA algorithm was the appropriate solution for the multi-objective optimisation necessary for this study.

2.10 Summary and Key Gaps in Knowledge

This chapter reviewed the inherent challenges and barriers to the use of SUDS solutions in tandem with considering the potential benefits and advantages of this approach to urban stormwater management. The review also included the stormwater management tools that help to simulate various scenarios of hydrologic process and SUDS practices applications, examining the process of selecting an appropriate software tool for this study from the many available. In addition, the current studies on modelling and optimisation of SUDS selection and placement were also considered in detail. This included consideration of the location of studies, the type of SUDS simulated, the stormwater management tools used, the optimisation techniques and the main findings. This is considered as one of the most important aspects that impart a comprehensive overview of the topic. Finaly, optimisation algorithm were also considered in this chapter.

The review showed that SUDS can be highly varied in terms of scope and the effect of the approach on the runoff volume, peak flows and the pollutant load. There are multiple factors that can potentially influence the relative success of SUDS and these will vary with locale and

the climatic conditions. What is evident is that the use of SUDS solutions for stormwater management in urban environments has significant advantages over the use of grey infrastructure. However, there is a lack information regarding the implementation of SUDS solutions in ASARs and, consequently, challenges to selecting the most appropriate SUDS solutions as a result. Thus, one of the focuses of this study is to gather novel information through the conduction of a questionnaire survey which aims to provide the information needed, which cannot be gathered from secondary data resources, regarding both the suitability of SUDS solutions for Jeddah City and their financial cost.

The review of the currently available software tools for modelling stormwater management in an urban environment highlighted that there are multiple tools available; however, the capabilities and limitations of each tool were highly variable. The review identified the SWMM as that which has been used in multiple studies to produce reliable and accurate outcomes and having sufficient flexibility and capacity to accurately simulate the scenario in question.

The review highlighted that, whilst the use of modelling and optimisation is a well-established method for identifying appropriate SUDS solutions to urban stormwater management problems, there are still substantial knowledge gaps which may negatively influence the performance and accuracy of these approaches to SUDS selection. It was identified that there are relatively novel algorithms being developed that may potentially be more robust than the most commonly used NSGAII algorithm; however, more research is needed to substantiate or disprove this. Additionally, it was noted that there are limited modelling and optimisation studies that have been conducted in arid and semi-arid climates and further research is needed in this area to quantify the applicability of the existing modelling and optimisation protocols for this climate type. Concerns were also identified regarding the potential impact of modelling and optimisation oversimplification on the real-world functioning of the SUDS solution identified as optimal. Thus, to overcome all of these challenges, a robust DSS is necessary, one which will provide valuable information to decision-makers, thereby enabling them to make sustainable; and effective SUDS solution selection and placement for stormwater management in ASAR urban environments.

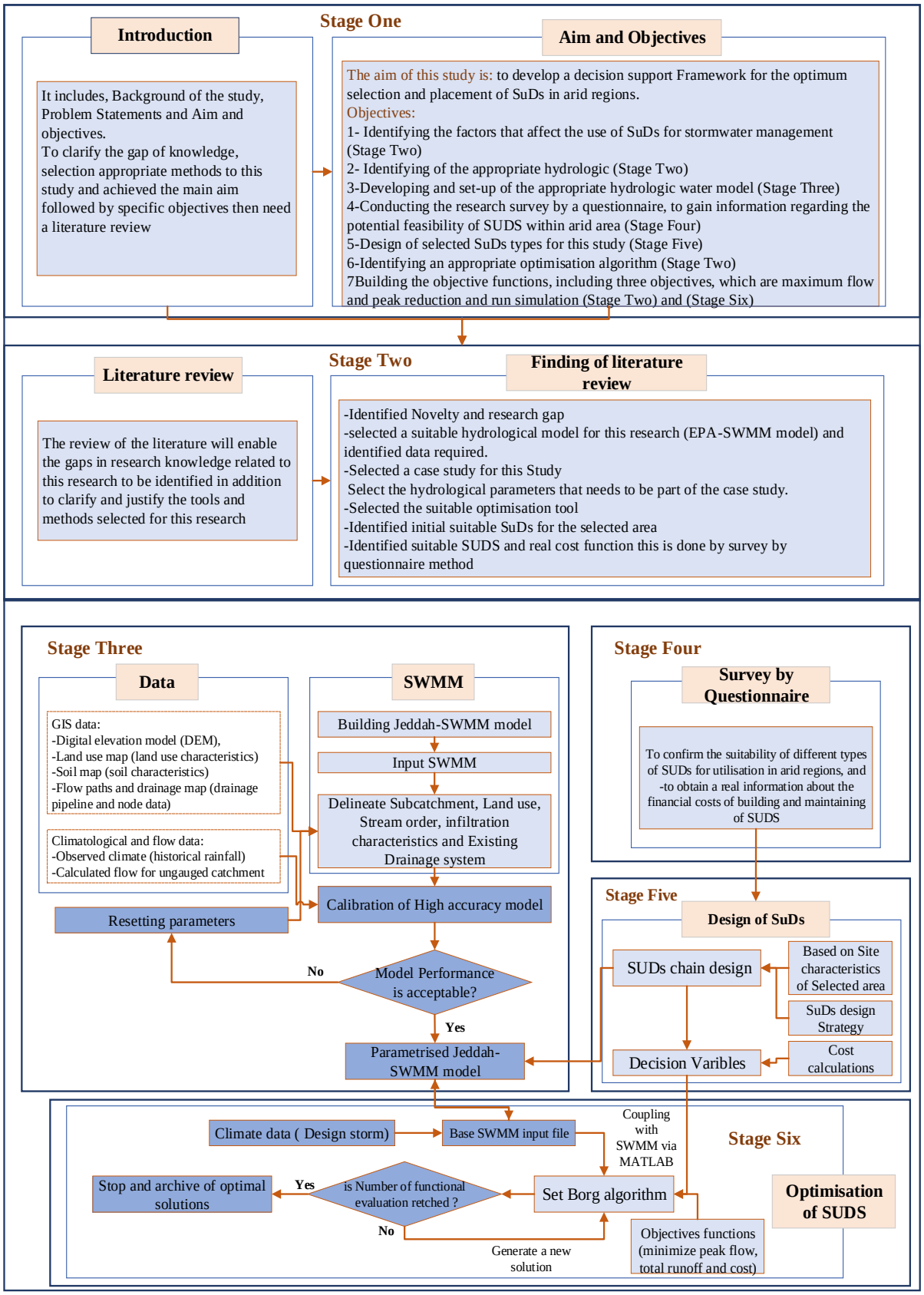


Figure 2-16 gives an overview of this study, including all processes.

Chapter Three: Study of Watershed within Jeddah City

3.1 Introduction

An urban watershed within Jeddah City in the Kingdom of Saudi Arabia (KSA) was selected as the study watershed for this research. In the following sections, an overview of Jeddah City is presented. This includes background information on Jeddah City characteristics and a review of the issue of stormwater management.

3.2 Background for Jeddah City

Jeddah city is the second largest urban area in the KSA (Aljoufie et al., 2013a). It is located in the western area of Saudi Arabia, bordering the Red Sea to the west of the City and the Hijaz mountains to the east (Figure 3-1). Jeddah is highly important as it is considered the gateway to Makkah and Medina, the two holy Islamic cities that host Millions of visitors annually (Abdu et al., 2002). As with many urban areas globally, Jeddah City has experienced a substantial and rapid growth in the population , the most recent population survey conducted in the Kingdom of Saudi Arabia placed the Jeddah City population at 4.69 million in 2017 (Al-Shutayri and Al-Juaidi, 2019). The rapid growth in the population has been primarily due to an influx of inhabitants from rural areas (Aljoufie et al., 2013b). The population in Jeddah City has continued to increase, with estimates suggesting the population growth rate is approximately 3.3% - 3.5% annually (Almazroui et al., 2017; Al-Shutayri and Al-Juaidi, 2019). If the population of Jeddah City continues to increase at the rate of 3.3% annually, this would mean a population of approximately 12.8 million in the next 30 years. This has corresponded with an increase in the land area coverage of the urban area, from 700 square kilometres in 1962 to over 5,000 square kilometres in 2012 (Momani and Fadil, 2013).

Jeddah City is located between the Hijaz mountains and the Red Sea, meaning that the drainage route for multiple watersheds is via the urban area (Figure 3-2). In the mountainous areas, the slope is approximately 40% and it decreases towards the coastal plain (where Jeddah City is located) to an average slope of 10% (Sunyani, 2012).

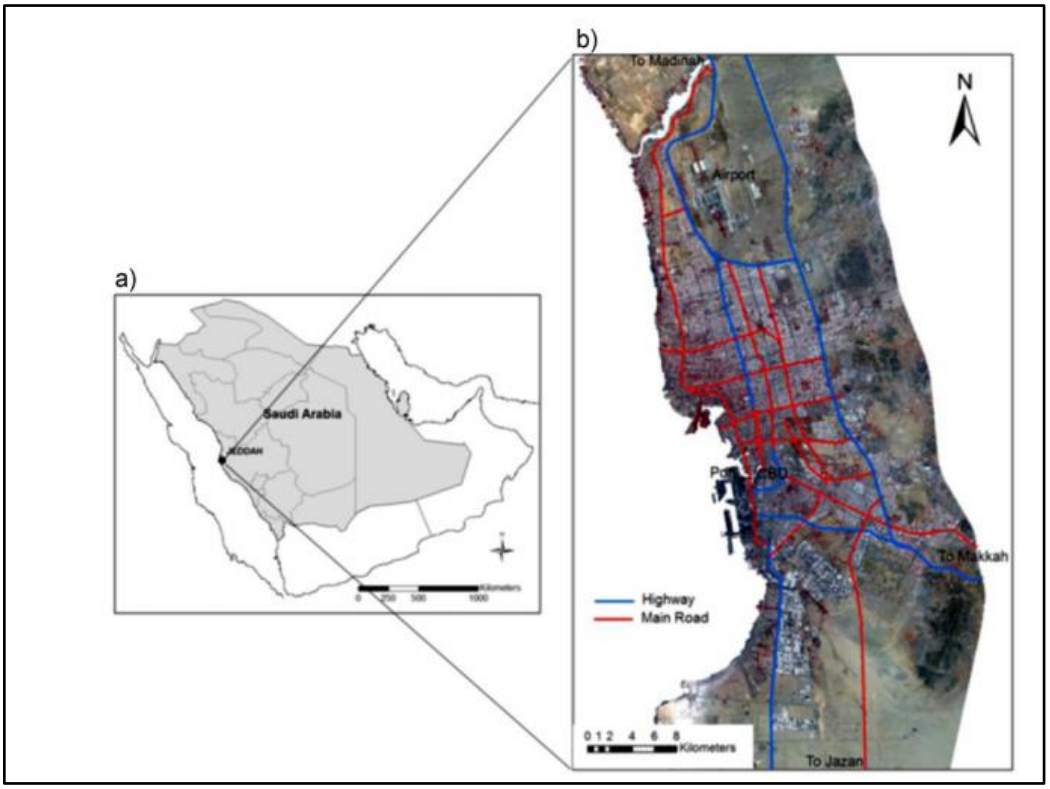


Figure 3-1 The geographical location of Jeddah City and b. Jeddah City with primary road networks (Alijoufie et al., 2013a, p.495).

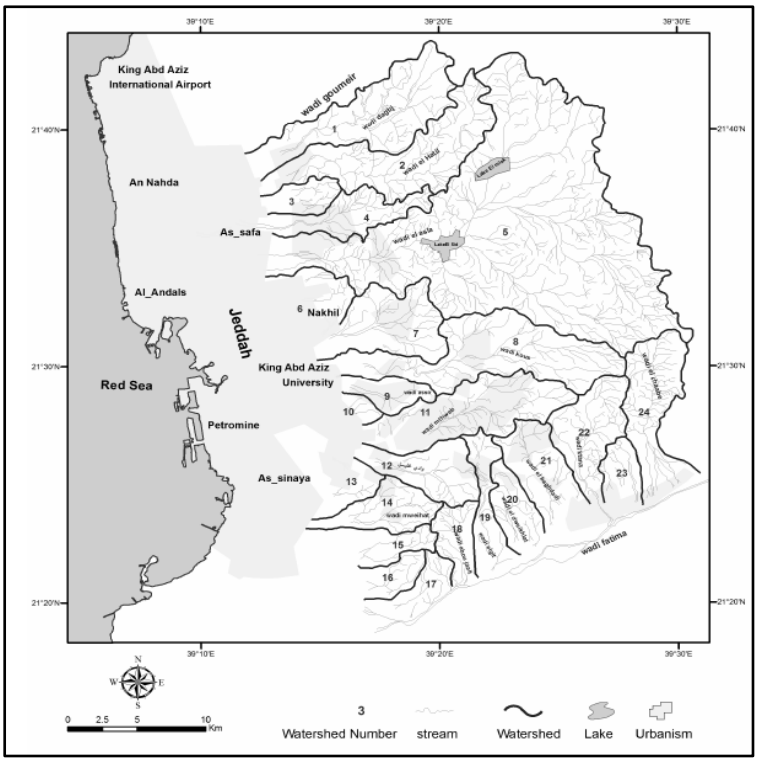


Figure 3-2 The watersheds and sub-watersheds draining into the urban area of Jeddah City (Al Saud, 2010).

It is this topography which causes rapid water flow during precipitation events from the mountainous area to the coastal area. A study conducted by Subyani (2012) identified both the watersheds and the slope as contributory factors to flood hazards in Jeddah City. Additionally, the floodplain and the rapid expansion of the urban area have also been identified as contributory factors (Subyani, 2012). The rapid expansion of the urban area of Jeddah City has increased the area of impervious surfaces, this, in combination with a poorly planned and implemented drainage system, which is not of a sufficient capacity, has resulted in a substantial increase in the occurrence of pluvial flooding events (Youssef et al., 2016).

In 2009, and again in 2011, devastating flash floods events occurred in Jeddah City. These events were characterized by rainfall values of 80mm within 3 hour and 124 mm within 4 hour, respectively, recorded by rain gauge station called "Jeddah J134" (Yousef et al., 2016; AECOM, 2014). In the 2009 event, 123 individuals perished, approximately 20,000 families were displaced from their homes and Millions of dollars' worth of damage occurred (Figure 3-3). A study conducted by Momani and Fadil (2010) subsequent to the 2009 flooding recommended that action strategies needed to be implemented based on increasing the resilience of the urban area and developing policies and procedures to facilitate the decision-making process to improve the response to natural and manmade disasters within Jeddah City in the future. However, it is evident by the continued occurrence of flooding in Jeddah City that the recommendations of Momani and Fadil (2010) were either not sufficient or were not implemented. This inference is supported by the findings of Absoliman et al. (2014) who investigated the perception of the response to the 2011 flooding event. The predominant opinion expressed by those consulted for the study was that there was a lack of development of emergency response planning, including a lack of development of infrastructure and overall policy (Absoliman et al., 2014).



Figure 3-3 Illustrates the Jeddah flood 2009-2011 respectively (Arab News, 2012; Fatlemaeus, 2011)

The prevention of flooding in Jeddah City has become a key priority for the governing body. In the following sections, the study area will be reviewed and an examination of the factors contributing to flooding events in this area conducted, including geomorphological characteristics of the area, land cover, soil type, climate and the existing stormwater drainage system.

3.2.1 Climate

The climate of the KSA is categorised as hot, arid desert according to the Koppen-Gieger classification system for world climates (Peel et al., 2007). In general, hot, arid desert climates are characterised by warm winters and hot summers and precipitation is generally scarce (Peel et al., 2007). Jeddah City experiences rainfall that typically occurs during the wet season running from November until April; however, precipitation events have been recorded infrequently during the months of October and May. The annual rainfall in jeddah, ranges from 50 to 100 mm, with a maximum rainfall of 284mm occurred in 1996. Rainfall patterns in Jeddah City are not spread across the annual wet season, instead they are characterised by intense, short duration rainfall events (Almazroui, 2011; Al Saud, 2010; Youssef et al., 2016). The spatial variations in rainfall patterns can be explained by the difference in elevations, with the highest rainfall rates (on an annual basis) occurring in the highest elevations, i.e. the Hijaz mountains and surrounding foothills. Al-Sefry et al. (2004) attribute the relatively intense rainfall in the Hijaz mountains to the frontal weather conditions during the wet season. However, some researchers have proposed alternative explanations, for example, Wheater (2002) suggests that

the intense rainfall events leading to floods within arid regions are attributable to the extremely localised nature of storm cells.

3.3 The Study Area

The study area selected for this research project was chosen from the 17 planning areas of Jeddah City identified by AECOM, who were commissioned by Jeddah Municipality to undertake the Jeddah Stormwater Drainage Program AECOM (2014). Figure 3-4 shows an overview of the 17 planning areas of Jeddah City. For this study, an urban watershed within planning area D was chosen to be studied. The following sub-sections provide the rationale and justification for the selection of the study watershed.

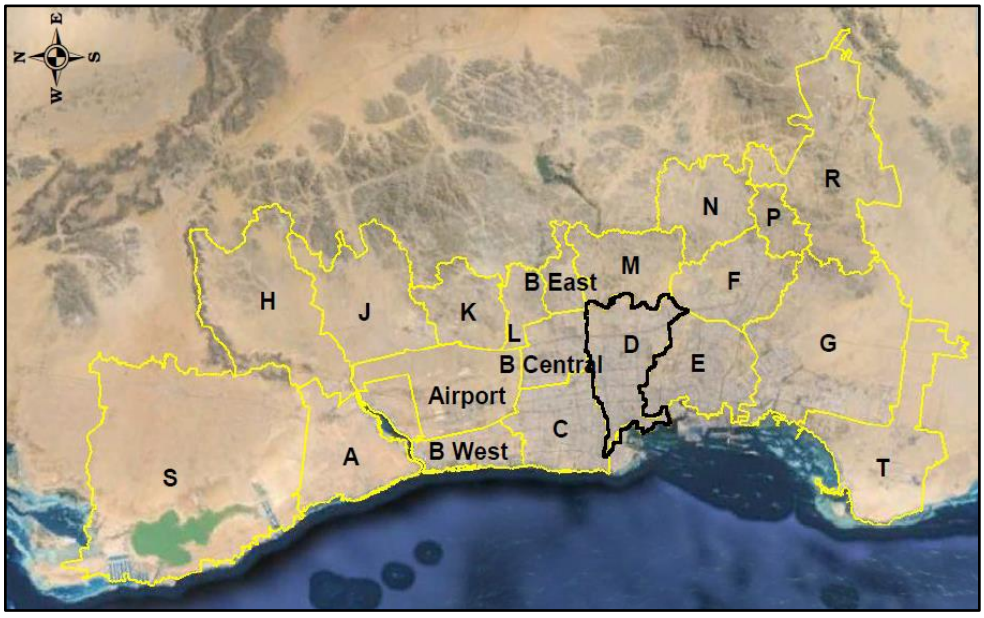


Figure 3-4 The planning areas of Jeddah City and the surrounding rural area as described by AECOM (2014). The study site, area D, is delineated in black.

3.3.1 Overview of Planning Area D

Planning area D is approximately 75 square kilometres in area and is located in the central area of Jeddah City, with a distance of approximately 8 kilometres from north to south and approximately 12 kilometres from east to west. The area is bounded by Al Rawdah Street to the north, foothills to the east, the Red Sea to the west and by the Al Falesteen, Bani Malik, Prince Majid and King Abdullah roads to the south. The urban composition of planning area D is primarily comprised of high-density construction with both high- and low- rise buildings. At the current time, there are areas of little to no development located to the east of Haramain

Highway; however, there are development plans for this area which predominantly consist of industrial developments (Figure 3-5; AECOM, 2014). An examination of satellite images on Google.maps suggests that the majority of the proposed planning outlined in Figure 3-5 has been completed.

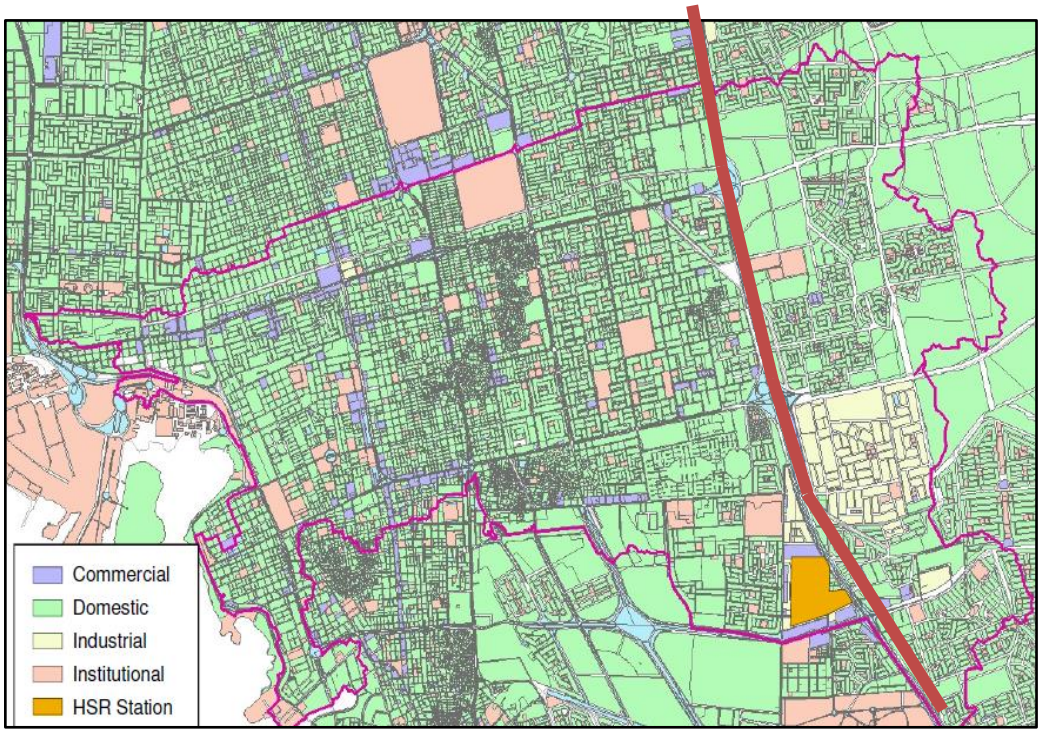


Figure 3-5 The future composition of planning area D (outlined in purple) according to current development plans. The Haramain highway is indicated by the red line (AECOM, 2014).

Part of the AECOM (2014) assessment study involved the identification of flooding hot spots, as shown in Figure 3-6, for area D. It is clear that a number of flooding hot spots are identified within planning area D, particularly in the regions neighbouring the Red Sea. The frequent flooding in this area is suggested to be due to the land slope of the area and the design of the urban drainage system which outflows into the Red Sea in this area. The frequent occurrence of flooding and multiple flooding hot spots mean that planning area D is a suitable area from which to select the study site for this research.

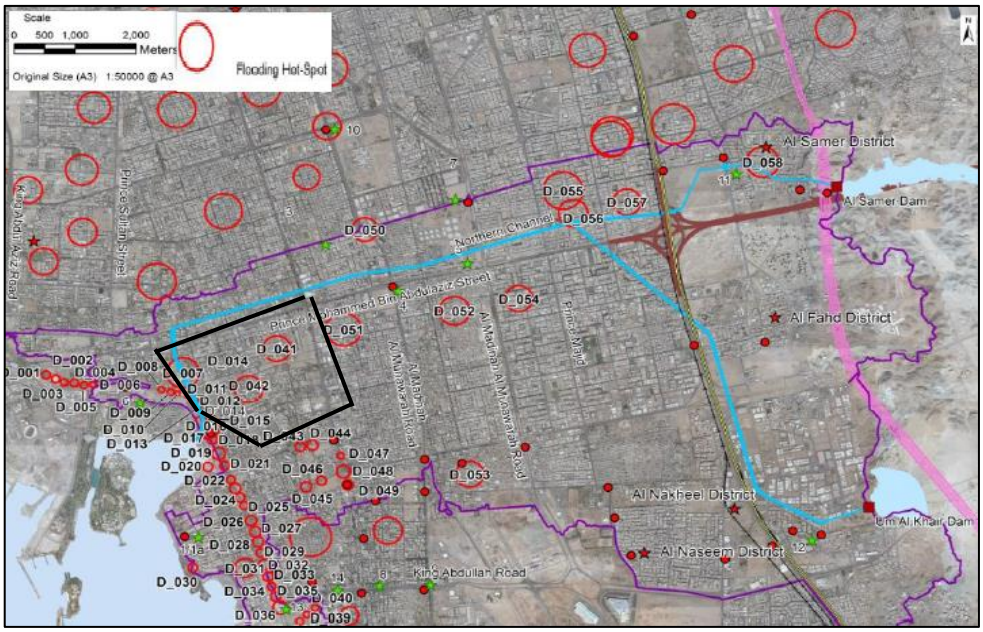


Figure 3-6 Flooding hot spots in planning area D. Planning area D is outlined in purple and the flooding hot spots are indicated by red rings, the larger the ring the more prolific the flooding in the past. The blue line indicates the Northern Channel. The numbers refer to IDs of suggested stormwater system (Pipes). The selected study site within planning area D is approximately indicated by the black line. (AECOM, 2014).

Due to the size of planning area D, it was not possible to investigate the entirety of the planning area for this study. Therefore, a sub-area watershed was selected from within planning area D. This sub-area is approximately five square kilometres in size and is located within the districts of Alhamra and Alandlus. These districts are situated in the northeast of planning area D, bordered on the west by Almadina Street, on the east by Prince Sultan Road, on the south by Non-name and on the north by Alraudh Road (Figure 3-6). The composition of the selected study site is mixed, with commercial buildings, businesses, educational sites, residential compounds, residential buildings and government services. The mixed composition of the construction within this area was one of the reasons for selecting this area for the study site. This is because the variety of buildings within a mixed-use area adds a degree of complexity to the development and implementation of reliable and effective stormwater drainage design. The number of flooding hot spots within the selected study area indicates that flooding has been an ongoing issue in the area, and effective stormwater drainage is needed. This further strengthens the justification for selecting this area as the study site.

When considering future drainage options, the selected site is potentially optimum for applying alternative drainage options within it. This is due to the space that is available within

the urban construction, meaning that it should be possible to implement solutions. Additionally, the relatively small size of the study area is manageable, limiting the unwieldiness of data inputs that will be needed to determine the optimal selection and placement of SUDS. In the following sections, further characteristics of planning area D are outlined as they pertain to the research study conducted.

3.3.2 Soil and Slope

The topography of planning area D is one of a gradual downwards slope towards the coast (Figure 3-7). Around Al Haramain Road, the elevation is approximately 35m above sea level. From the road, the topography slopes down to a low of less than 1m in the urban area circumventing the Red Sea (Figure 3-7).

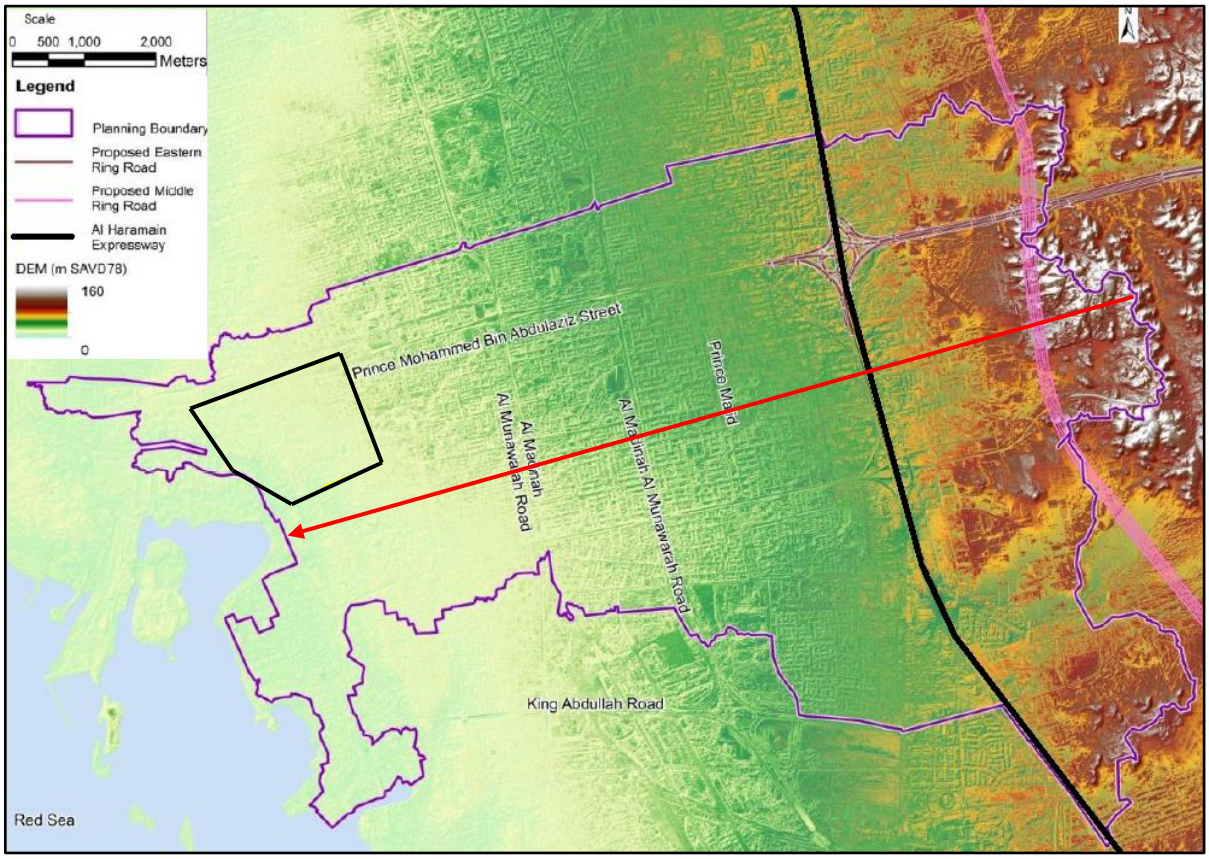


Figure 3-7 The topography of planning area D. The red arrow indicates the general direction of the slope within the area. The black trapezoid outlines the approximate area of the study site and the black line indicates Al Haramain Road (AECOM, 2014).

Within the selected study site, the topography ranges from an elevation of 17m at the highest point on the western boundary of the study site, to a low of 2m on the eastern edge. As with the rest of planning area D, the direction of the slope is generally from west to east (towards the sea) and it is generally characterised by flat terrain throughout.

The geology within planning area D is primarily comprised of quaternary deposits within the western areas and igneous rock of the Dighbjj complex in the wadis to the east; these are outlined in further detail in Figure A-1, Appendix A. In the northwest section of the planning area predominant strata are found, consisting of both reef limestone and sabkha soils. The composition of the sabkha soils is varied, including clays, sand and silt that are characterised by dolomite, calcite gypsum and aragonite presence (Fookes, 1978). The sabkha soils that are located in the coastal portion of the planning area contain extremely high concentrations of salt. Whilst these are the underlying geological structure of the area, it is not clear whether the process of development has had any significant impact on the characteristics of these soils (Fookes, 1978).

In planning area D, the groundwater table is relatively high, only a few metres below the surface within the sabkha and the reef limestone soils (the area near to the sea). The relatively high groundwater tables are likely to contribute to flooding events as the soils will become saturated at a faster rate than soils where the groundwater is at greater depths, thereby impeding the infiltration rate and contributing to increased surface runoff.

3.3.3 Existing Drainage System

The existing drainage system in planning area D needs to account for three different types of drainage; watershed runoff, stormwater runoff and groundwater (AECOM, 2014). The watershed runoff is that which originates from two wadi catchments, the Bani Malik catchment, 292 square kilometres in size, and the Mraikh catchment, 38 square kilometres in size. The existing drainage management system accounts for the watershed runoff from these two catchments, predominantly through the use of a series of dams and intercepting channels. There are two primary dams that protect planning area D, the Samer Dam to the northeast and the Um Al Khair Dam to the southeast. The discharges from both of these dams flow directly into the Red Sea via the Northern Channel. The management of watershed runoff prior to entry into the urban area means that, typically, the urban drainage system does not need to manage this runoff.

Therefore, within the urban area, the drainage system is designed solely to account for runoff originating from the urban area itself. To the east of the Haramain Highway there is very little drainage infrastructure. The predominant form of runoff management in this area is conducted by the Northern Channel via surface runoff. To the west of the Haramain Highway, the urban area is comprised of high-density construction, requiring surface runoff management. This is achieved through two drainage networks, both of which discharge into the Red Sea.

In some areas, drainage infrastructure has been implemented to reduce the level of the groundwater table. This is due to the relatively high groundwater table impeding stormwater management on account of the water table being commensurable with the surface level, resulting in surface water ponding. Where the groundwater drainage system has been implemented, it connects into the two existing surface water runoff drainage systems (AECOM, 2014). The location of the dams, wadis and stormwater drainage network within planning area D are detailed in Figure 3-8.

It is evident that the existing stormwater management system is insufficient, as indicated by the frequency of flooding and the lack of coverage of some areas by a drainage network (Figures 3-6 and 3-8). Also, Jeddah's current stormwater management projects are based on grey infrastructure that increases impervious surfaces and does not contain any sustainable urban drainage system (SUDS), despite its multi- environmental benefits. Thus, there is an urgent need for the stormwater management options for Jeddah City to be re-evaluated and implemented. Existing drainage system data were obtained from AECOM in the form of belgon maps. Information related to existing drainage system data can be found in Table A-9, Appendix A.

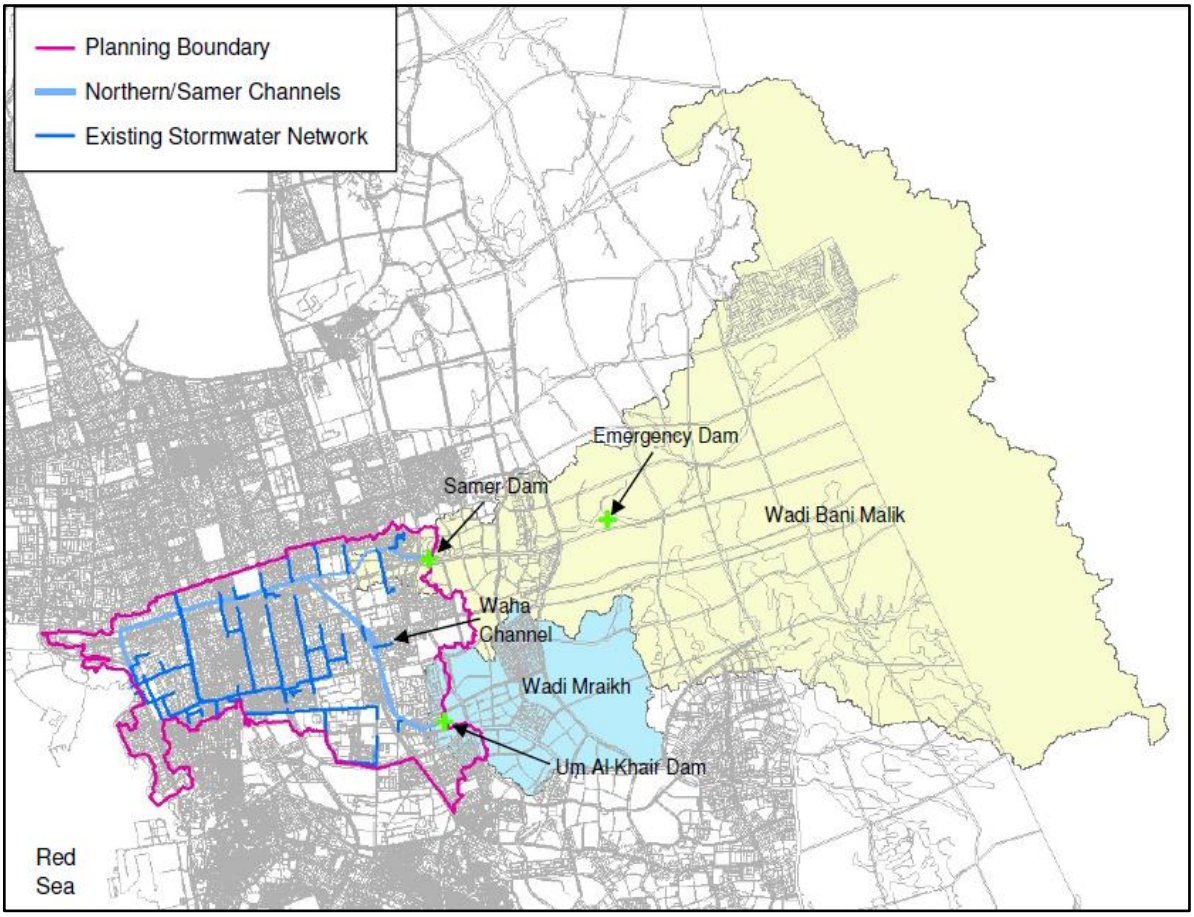


Figure 3-8 The surface runoff management infrastructure for planning area D (boundaries indicated by purple line). The locations of dams are indicated by the green crosses, the surface drainage channels are indicated in light blue and the subsurface drainage network is indicated by dark blue lines (AECOM, 2014).

3.4 Available Data

3.4.1 Topography, Geology and Existing Infrastructure Data

For this study, different topography, geology and existing infrastructure datasets were used, as shown and detailed in Table 3-1. To generate these data for data interpretation and analysis, a geographic information system (GIS) was utilised.

Table 3-1 Shows available topography, geology and existing infrastructure data. DEM is the Digital Elevation Model with units in metres.

Data	Type/format	Description	Source
Land use and land cover map	Raster (grid)	Applied to analyse SUDS site suitability and characterise the hydrologic properties of watershed / sub-watersheds (Scale 1:250000)	AECOM consultant company, represented Jeddah's municipality
DEM	Raster (grid)	Used to calculate the drainage slopes, elevation and drainage areas (Resolution 5m)	AECOM consultant company, represented Jeddah's municipality
Soil map	Vector (polygon)	Used to provide soil properties, for instance hydrologic soil groups or infiltration	Saudi geological survey and AECOM
Storm drainage network	Vector (point, polyline)	Used to develop stormwater networks in modelling	AECOM consultant company, represented Jeddah's municipality
Satellite images		Utilised for defining the physiography of selected area. (Resolution 1m)	AECOM consultant company, represented Jeddah's municipality

3.4.2 Rainfall Data

3.4.3.1 Rain Gauges

In the urban environment of Jeddah City, there are five rain gauges, which are Jeddah Airport (No.41024), Jeddah J134, KAU Weather Station and two stations managed by Saudi Geological Survey (SGS1 & SGS2) (Figure 3-9). Only two of them can deliver records that can be said to be long term (recorded). These are gauges No.41024 and J134. These two gauges comprise the complete record of observed daily rainfall, but station No.41024 also has hourly rainfall data for the last eight years (obtained from Saudi metrological data). The record for two Saudi Geological Survey (SGS) stations comprise of one-minute observations and they were inaugurated in 2010 (Al Saud, 2010; Youssef et al., 2016). Judging by the AECOM (2014) review, recording one minute of rainfall is not sufficiently accurate for meaningful analysis. Therefore, it was not included in the analysis of design rainfall depth for Jeddah. None of the rain gauges are located in the selected study watershed; the closest ones (from the centre of the selected area) being J134 to the south, 41024 to the north and SGS1 (see Table 3-2 and Figure 3-9).

Subyani (2009) claims that fluctuations in rainfall occur because of topographic shifts over Jeddah and its environs. The narrow region of the coastal plain, in the west, sees the lowest amount of rain, but, as the land rises into the Hijaz mountains in the east, it increases. Consequently, areas in which it has been possible to set rain gauges of a long enough recorded term and a sufficient fluctuation of rainfall have been used.

This study has chosen to use data from the J134 and 41024 gauges. However, Station No.41024 has sub-daily rainfall data (hourly) which is required for this study. The drawback of using daily rainfall data is that, for example, if using the SWMM model, if the inputted daily rainfall figure is 48mm, SWMM will translate this as 2 mm/hr, which is incorrect. In order to achieve good rainfall data, the proper recording time interval should match the catchment area response time. Therefore, Station No. 41024 and the relevant historical rainfall data have been chosen for this study.



Figure 3-9 Rain gauges within the Jeddah urban area (AECOM, 2014)

Table 3-2 Rain Gauges within the Jeddah Urban Area and its location to selected area

Rain gauge name	Period of Record	Operating Agency	Location	Distance To watershed km
Jeddah Airport 41024	1970- 2011	Presidency of Meteorology and Environment	latitude 21° 30’ and longitude 39° 12’	13km
Jeddah J134	1970-2009	Ministry of Water and Electricity	latitude 21° 30’ and longitude 39° 12’	10Km
SGS-1	Dec 20 10-2011	Saudi Geological Survey	latitude 29° 38’ and longitude 48° 19’	11km

In addition, to validate that the selection of station No. 41024 and the relevant rainfall data are correct for this study, it was checked to determine whether both stations have the same effect to the selected area. Thus, analysis of statistics and comparisons has been made among rainfall data gleaned from Gauges J123 and No.41024, which have long-term records, and their data are available (Figure 3-10). The period covered in the analysis includes the sudden and devastating flash floods in 2009 and 2011; 665 days have been compared over two years.

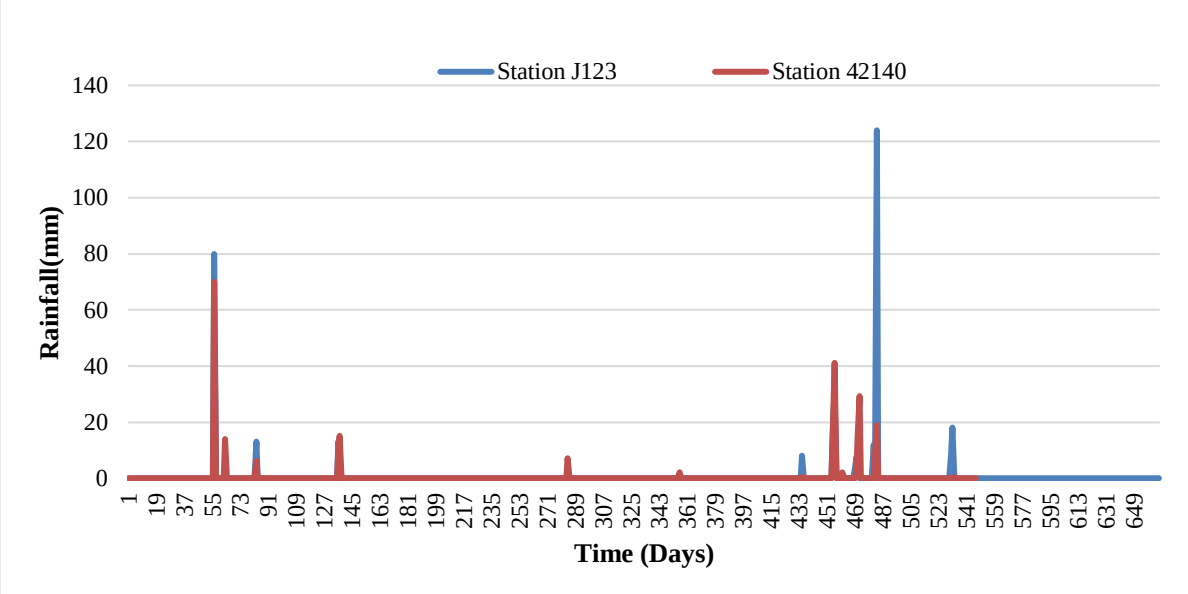


Figure 3-10 Hyetograph for daily rainfall for Stations J134 and 41024

As the figure shows, the difference between the gauges is not big; J134 is slightly larger than No.41024, and the biggest rainfall recorded for Jeddah. J134 and 41024 both have almost the same distance to the area of study. Therefore, Station No. 41024 and the relevant historical rainfall data have been chosen for this study.

3.4.3.2 Selected Event

Due to Jeddah having suffered massive floods in 2009 and 2011, all this period's major rainfall events were chosen from Station No.41024 (Table 3-3). The selected rainfall events are considered as the most important events, historically, that have been recorded by Station 41024. Therefore, it has been used for the purpose of flow estimation calculations (Section 3.5.1). In addition, it has been used as input to a SWMM model for calibration and verification for the case study watershed (Section 4.2.1, Chapter Four).

Table 3-3 Historical rainfall events selected and used for this study

Rainfall Event	Duration (hours)	Total depth (mm)
25/11/2009	3	70
29/12/1010	2	24
30/12/2010	3	41
14/01/2011	1	15
02/12/2009	1	14
15/01/2011	5	29.2

3.4.3 Flow Data

3.5.3.1 Flow Estimation for the Case Study Watershed.

As mentioned, earlier (Section 2.7.1 and 2.7.2) there are no recorded flow data from the catchments in the Jeddah study area. Therefore, the Soil Conservation Service Curve Number method (SCS-CN) and the production of Synthetic Unit Hydrographs (SUHs) were selected and used to estimate the flow patterns in the Jeddah watershed (SCS-CN and SUHs methods are detailed in Section 2.7.2.1). SUHs are dimensionless and produce a single smoothed peak, which simulates the rainfall-runoff flow attributed to one unit of runoff volume. The actual

hydrograph (rainfall-runoff flow) was then calculated and drawn by applying all selected historical rainfall events (Listed in Table 3-3) (The full techniques and procedures for calculations of flow estimations are detailed in Section A-3, Appendix A).

The results of flow estimation calculations (runoff flow and peak flow) for each subcatchment for each historical rainfall event applied , are listed in Table 3-4, the location of each of the subcatchments is given in Figure 3-11, and the runoff hydrographs of the 25/11/2009 rainfall event are shown in Figure 3-12. Full hydrographs of other historical rainfall events are attached in Section B-1, Appendix B, within calibration results. These estimations flows are considered as "observed flow" for the selected case study watershed, and will be compared with runoff hydrograths generated via the SWMM model for the purpose of calibration and verfication of the model in Chapter Four.

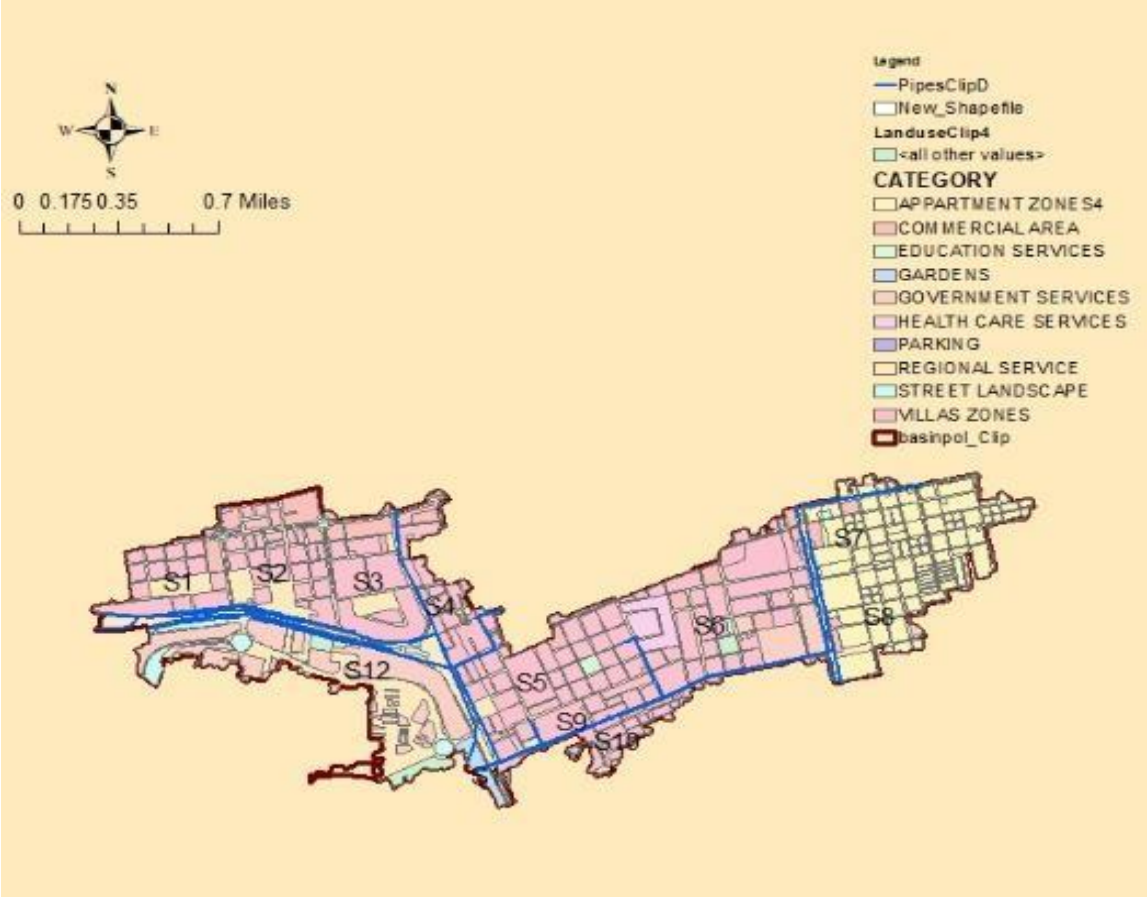
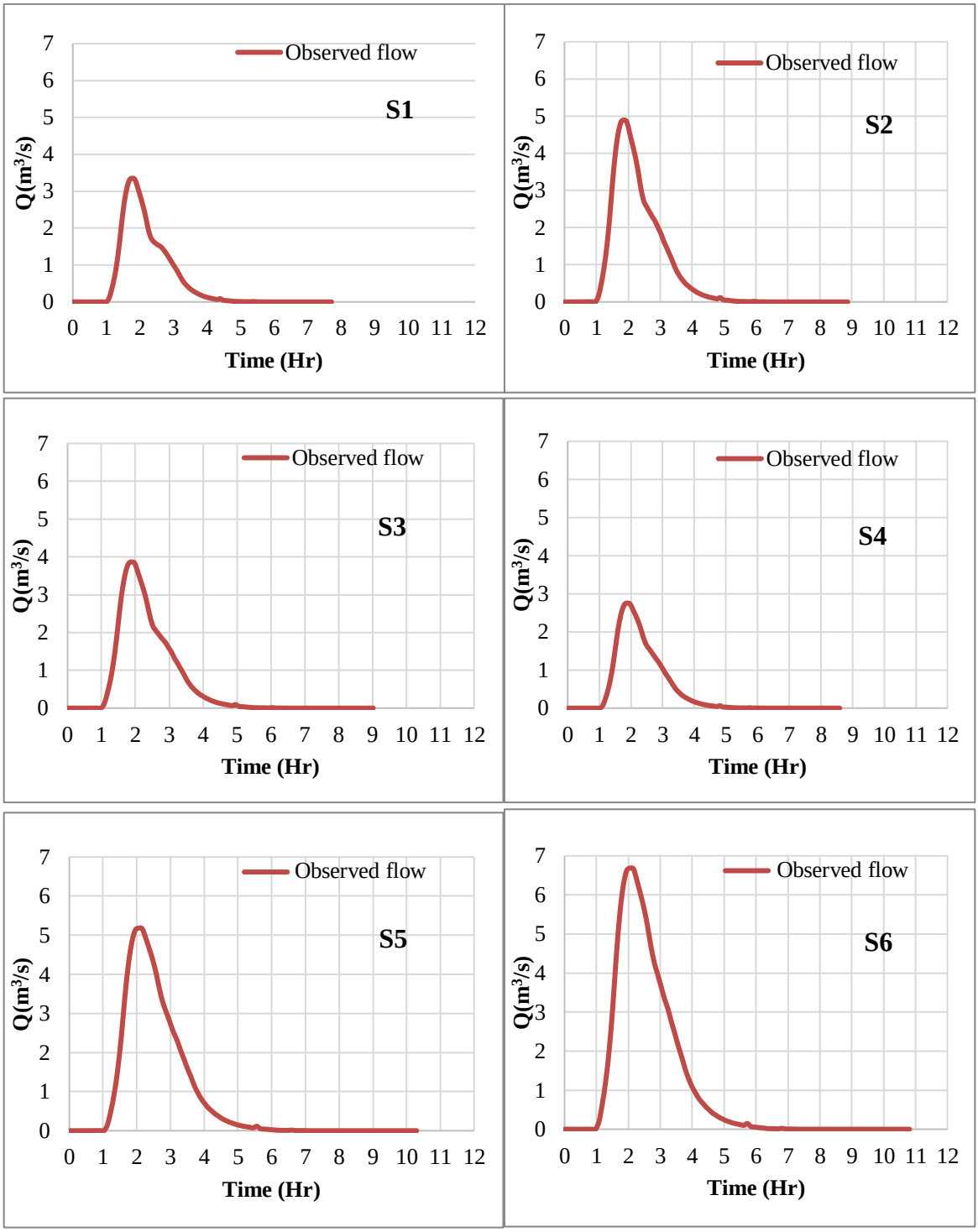


Figure 3- 11 The land use and land cover for the selected study site including the existing stormwater drainage system.

Table 3-4 Shows estimation flow data (considered as observed data)

Historical Rainfall Events	Total duration (hr)	Rainfall depth (mm)	Runoff conditions	Subcatchments of the case study watershed											
				S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
25/11/2009	3hr	70	Runoff volume(m^3)	19646	28357	22486	16057	30076	39215	25715	30295	10859	11507	3503	39187
			Peak flow (m^3/s)	3.4	4.9	3.9	2.8	5.2	6.7	4.5	5.3	1.9	2	0.6	6.9
29/12/2010	2hr	24	Runoff volume(m^3)	4209.8	6964.0	5248.6	3681.5	7199.6	8384.2	6667.0	7811.2	2642.4	2638.4	685.7	8794.0
			Peak flow (m^3/s)	0.5	0.8	0.6	0.4	0.9	1.2	0.8	1.1	0.3	0.3	0.1	1.4
30/12/2010	3hr	41	Runoff volume(m^3)	9614.8	14630.5	11375.3	8066.9	15364.7	19175.4	13548.5	15927.4	5582.7	5781.3	1748.4	19524.6
			Peak flow (m^3/s)	1.3	2.1	1.6	1.1	2.2	2.6	1.9	2.3	0.8	0.8	0.2	3.0
14/01/2011	1hr	15	Runoff volume(m^3)	1766.1	3277.9	2368.0	1636.2	3317.4	3510.6	3282.2	3828.0	1234.3	1172.6	254.2	3838.0
			Peak flow (m^3/s)	0.4	0.7	0.5	0.3	0.7	0.7	0.7	0.8	0.3	0.2	0.1	0.8
15/01/2011	5hr	29	Runoff volume(m^3)	5791.2	9249.9	7063.2	4977.2	9626.0	11541.2	8732.6	10245.8	3513.5	3556.4	898.0	11954.9
			Peak flow (m^3/s)	0.9	1.3	1.0	0.7	1.4	1.8	1.2	1.5	0.5	0.5	0.1	1.9
02/12/2009	1hr	14	Runoff volume(m^3)	1530.5	2903.6	2080.9	1433.7	2926.8	3041.0	2931.7	3416.3	1091.8	1027.5	217.7	3351.4
			Peak flow (m^3/s)	0.3	0.6	0.4	0.3	0.6	0.6	0.6	0.7	0.2	0.2	0.0	0.7


Observed flow
S1
Q(m³/s)
Time (Hr)
Observed flow
S2
Q(m³/s)
Time (Hr)
Observed flow
S3
Q(m³/s)
Time (Hr)
Observed flow
S4
Q(m³/s)
Time (Hr)
Observed flow
S5
Q(m³/s)
Time (Hr)
Observed flow
S6
Q(m³/s)
Time (Hr)

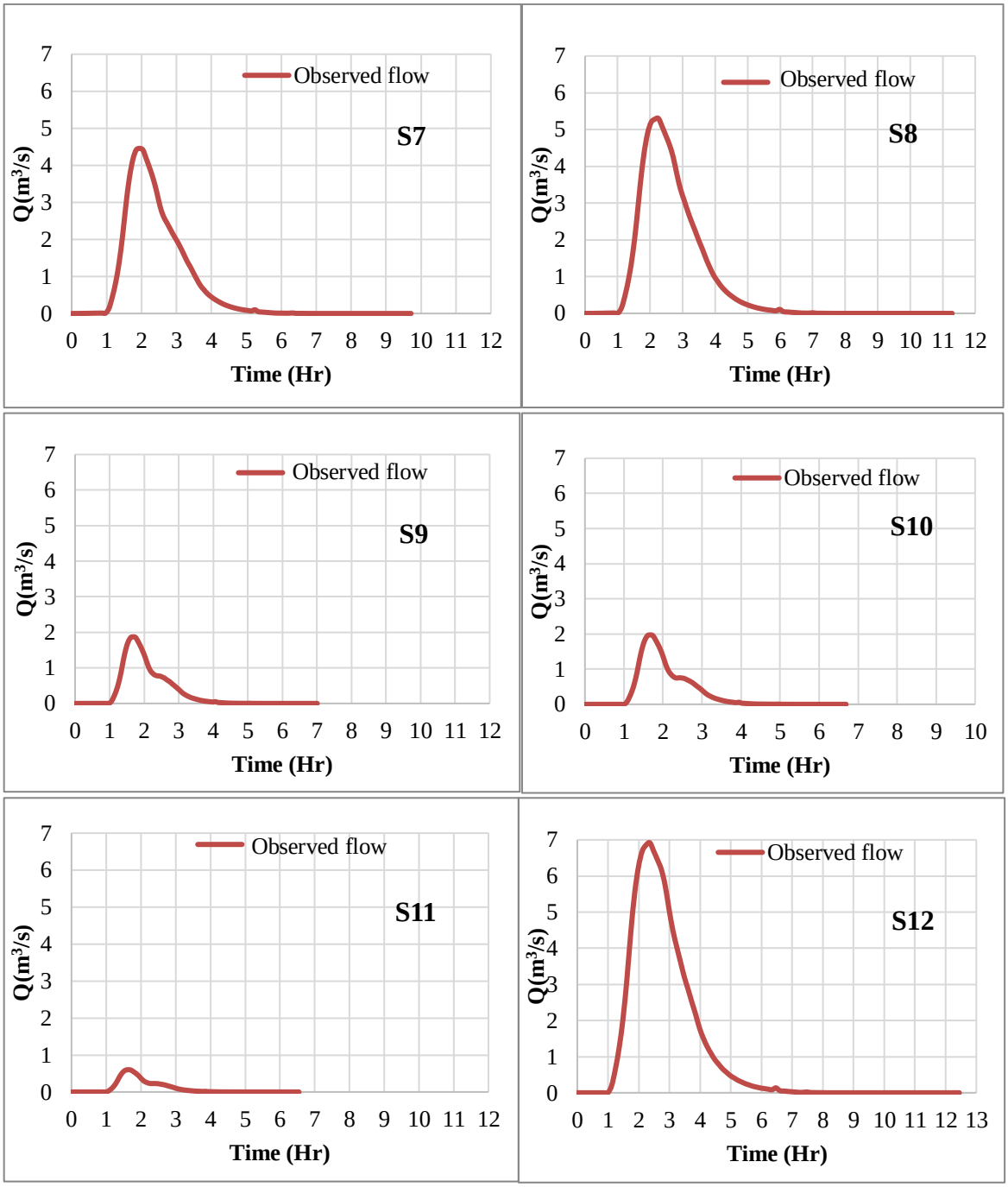


Figure 3-12 Estimation flows, which are considered as "observed flow" of the 25/11/2009 event at each subcatchment outlet

Chapter Four: Development of Jeddah-SWMM Model

4.1 Introduction

The current urban stormwater drainage system in Jeddah City has been noted as unsuitable for purpose, primarily due to the inability of the system to manage the periodic high intensity rainfall events, resulting in significant flooding in the urban area (Youssef et al., 2016). In line with current concerns regarding urban growth and climate change (CC), it was determined that implementation of SUDS could present a potential solution to both the issue of flooding and addressing environmental concerns, such as water quality and urban heat zones, within Jeddah City. Therefore, an SWMM model of the selected study site (introduced in Chapter 3), hereafter called the Jeddah-SWMM model, was developed to model and assess the potential for application of SUDS for stormwater management in the city of Jeddah.

In this chapter the processes that were applied for developing the Jeddah-SWMM model are outlined. The first section (4.1) outlines how the model was developed, including the delineation of drainage area and stormwater system representation; and the default parameter values of the Jeddah-SWMM model. The second section (4.2) details the process of model calibration and verification, and finally, Section 4.3 discusses the results and conclusions.

4.2 Building the Jeddah-SWMM Model (Model Development for Jeddah City)

The Stormwater Management Model (SWMM) (version 5.1) was selected to be used for this project as it has several aspects that make it more suitable than other comparable modelling software for the intended application (see Section 2.5 and 2.8). Most importantly, it has multiple types of SUDS already coded for within the software, thus it is relatively easy to incorporate SUDS within the model. The overall aim of this section is to describe the methodology behind building and parametrising an SWMM hydrologic model for the study site. This model will, in turn, be used to assess the potential for SUDS to be implemented in Jeddah City. Specific objectives are to set up a default SWMM model and calibrate it with reasonable accuracy. To achieve this, SWMM was used in combination with GIS data to identify the site characteristics and existing stormwater drainage network. An overview of the methods followed is given in Figure 4-1.

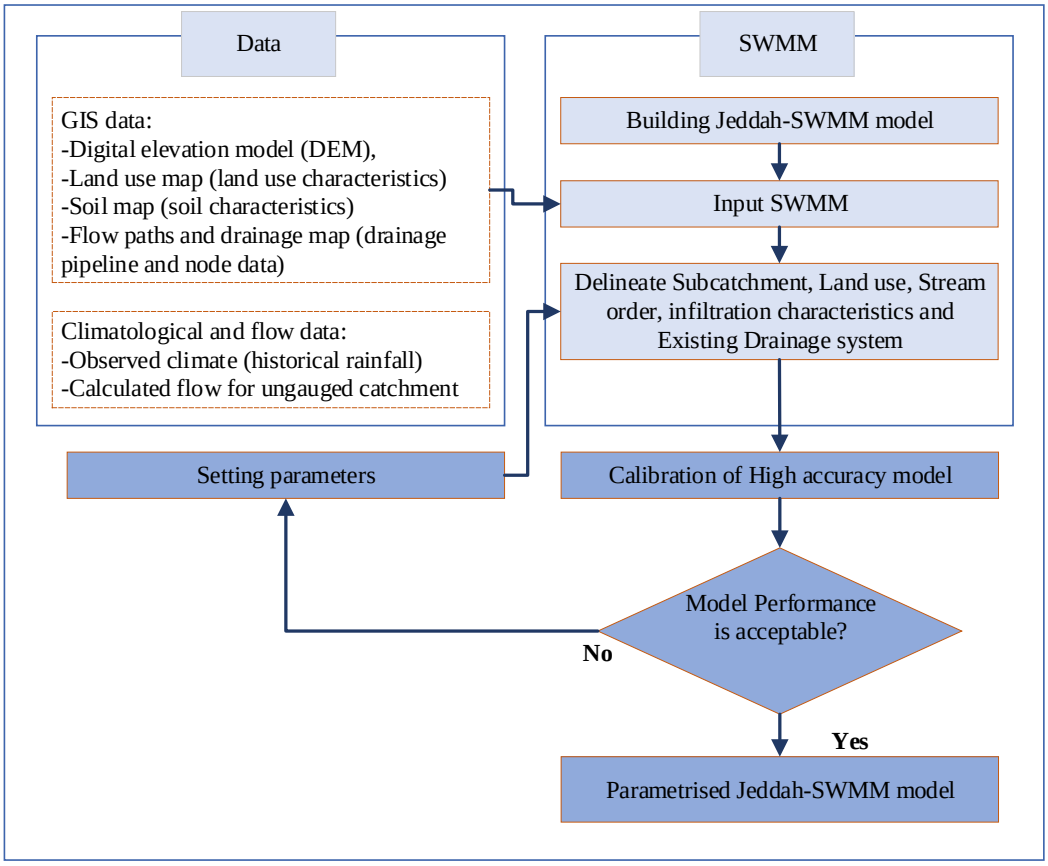


Figure 4-1 A flow chart overview of the methodology and process used in this chapter.

4.1.1 Delineation of Drainage Area and Stormwater System Representation

4.1.1.1 Delineation of Subcatchments

The first step in the process involved dividing the selected study site watershed within the Jeddah City into subcatchments for inclusion in SWMM. This was carried out by the use of GIS tools to identify critical parameters, such as ground slope (an overview of the GIS data used is presented in Table 3-1 in Chapter Three). The first undertaking was to use the ArcGIS 10.4 Spatial Analyst Hydrology tool on a digital terrain model (DEM) that had a 5m resolution (Figure 4-2). The elevation of the area is important to the delineation of the subcatchments as ground elevation will impact the slope and will, therefore, be highly influential on the surface water flow paths of the area. Therefore, the determination of the elevation of the area will allow the topography to be understood in relation to water flow paths from upstream to outlet to ensure that the edge of the subcatchment is defined correctly. Thus, the DEM was used to calculate the direction of water flow within the watershed area. Additionally, it was also necessary to outline the stream network of the area, within which the flow will accumulate. For the urban area of Jeddah City, the stream network is defined by the existing stormwater drainage system. The

stream network map was drawn based upon surveys and maps that were provided by the municipality of Jeddah City (Figure 4-3). Using ArcGIS 10.4 Spatial Analyst Hydrology tool, both the slope and the flow direction (using the six-direction flow model) of the catchment area were calculated. This then enabled the selected case study area to be divided into 12 subcatchments based on both natural water flow pathways (by DEM) and existing stormwater drainage system within the area.

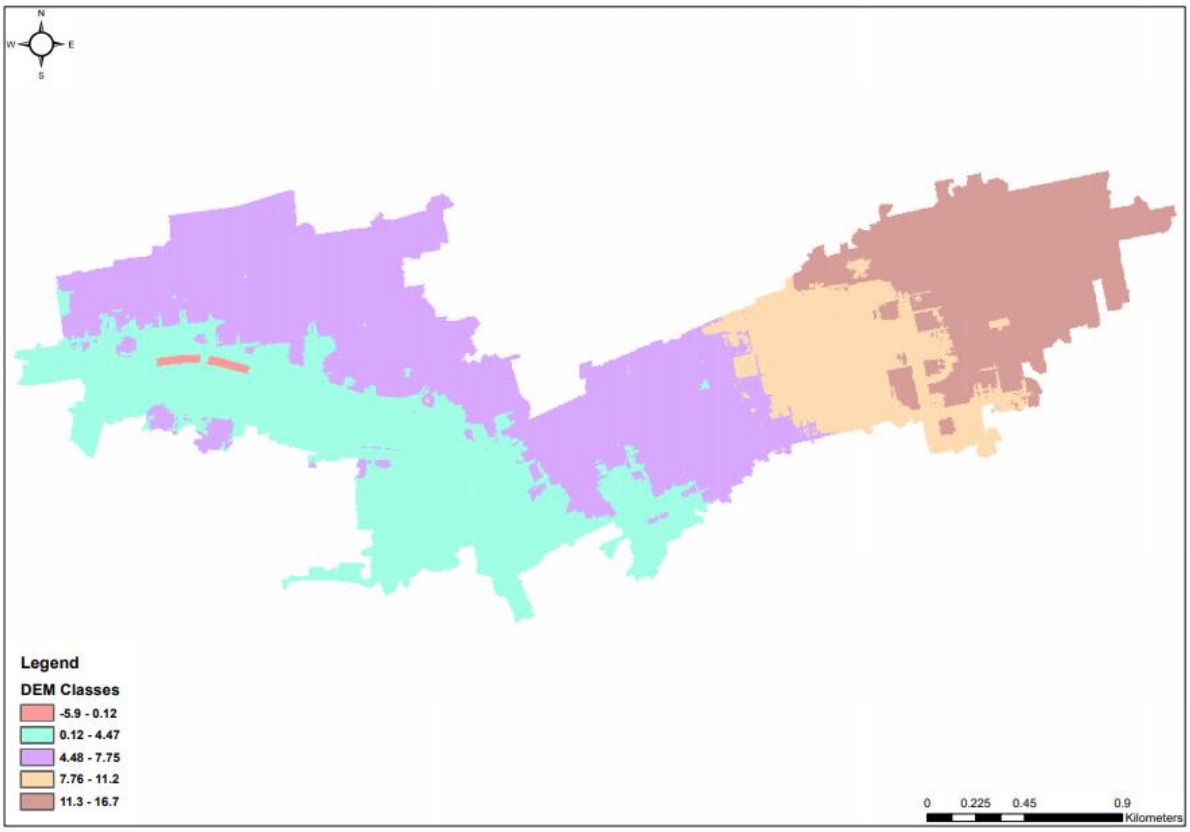


Figure 4-2 The ground elevation within a digital terrain model of the selected study site within Jeddah City at a resolution of 5m.

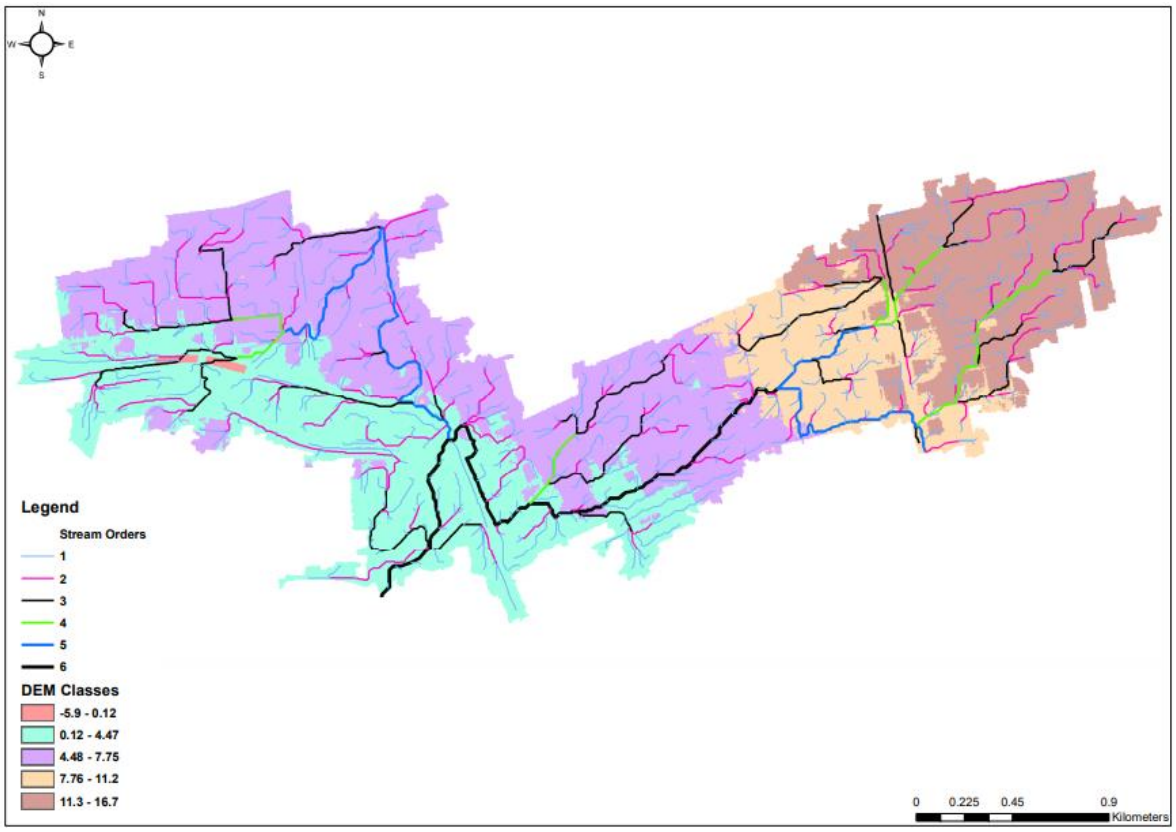


Figure 4-3 The stream network diagram utilised to develop the stream network for the Jeddah-SWMM model. In the legend, 1 represents the highest elevation stream and 5 the lowest, hence water flow is from streams 1 to 6.

Once analysis of the study watershed was completed, GIS layers were used to identify the additional characteristics required for a thorough analysis within the SWMM model. These characteristics included: land use and land cover, existing stormwater systems, slopes for each subcatchment, flow baths and direction, the percentage of surface layer imperviousness and the soil type and are summarised in Table 3-1.

Table 4-1 summarises the land use information for the entirety of the selected study area. This table quantifies the extent of each land type and how each type contributes to the impervious/pervious surface areas within the selected area. As seen from the table, the average percentage of impervious surface area is obtained as 83.2%. The high impervious surface area substantiates the categorisation of this area as highly developed. The distribution of the different land use and the land cover types are shown in a spatial format in Figure 4-4. It is clear that there is a spatial variation in the land use and land cover types which was taken into account when delineating the subcatchment areas.

Table 4-1 The land use and land cover details for the entirety of the selected study site.

Land Use Information For the Selected Watershed													
Land use type	**ID (Symbol)**	**Average % Impervious Area**					**Average % Pervious Area**	**Quantity (n)**	**Area (m^2)**	**Quantity of Developed Area (n-d)**	**Area (n-d)**	**%Area (n-d)**	**Area(m^2) impervious**
		Total	**Roof**	**Parking**	**Road**	**Space**	**Green Space**						
Apartment Zone	AZ	95	70	13	8	4	5	131	756330	129	742031	15	704930
Commercial Area	CA	95	60	25	5	5	5	27	235346	25	213375	4	202706
Education Services	Ed	90	50	25	15	0	10	6	31551	6	31551	1	28396
Govt. Services	GS	90	50	25	15	0	10	9	556384	8	477339	10	429605
Gardens	G	20	0	20	0	0	80	5	63895	5	63895	1	12779
Mosque	M	75	50	20	0	10	20	9	32435	9	32435	1	24326
Healthcare	HC	90	50	25	15	0	10	9	156303	9	156303	3	140673
Roads	R	100	0	0	100	0	0	-	831758	-	831758	17	831758
Street Landscape	SL	50	0	0	0	50	50	74	192769	74	192769	4	96384
Parking	P	80	0	80	0	0	20	5	12999	5	12999	0	10399
Villa Zone	VZ	90	65	13	8	4	10	213	1953527	203	1699918	35	1529926
Regional Services	RS	90	50	25	15	0	10	3	822	3	822	0	740
							Total	491	4824119	476	4455195	92	4012623
											% imperviousness		**83**

Note: Most information on different land usage types in Table 4-1, were extracted from GIS because it was available in the GIS maps and databases. Only calculations of Road area were conducted in GIS.

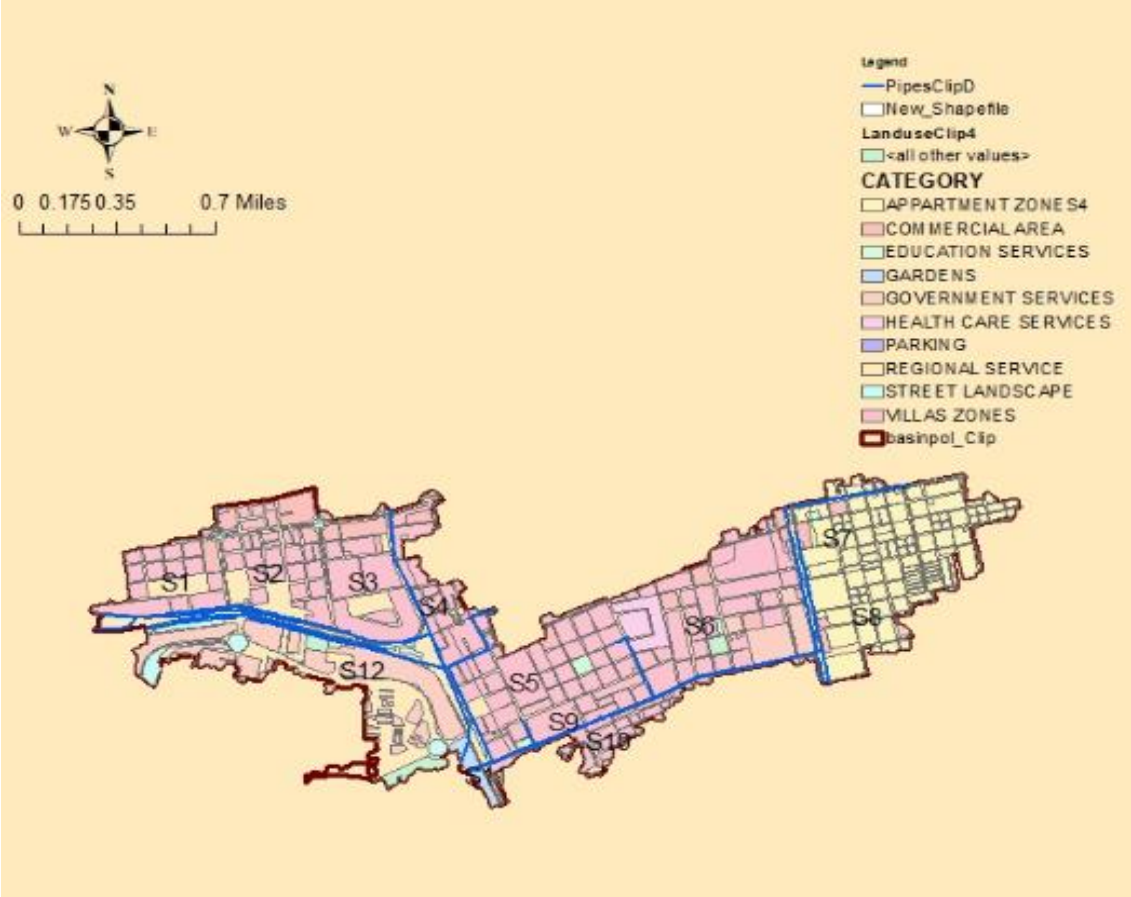


Figure 4- 4 The land use and land cover for the selected study site including the existing stormwater drainage system.

In Figure 4-4 it can be seen that the subcatchments S1, S2, S3, S4, S5, S6, S9 and S10 are primarily comprised of villa zones (areas comprised of residential villas) with some government services and healthcare services within S6. Subcatchments S7 and S8 are primarily comprised of apartment buildings, with some small areas of commercial zones. Subcatchment S11 is comprised of approximately two-third garden area with approximately one-third commercial area. Subcatchment S12 is the subcatchment which has the greatest degree of mixed use, with government services, regional services, education services and a small area of gardens occurring within this catchment. The different types of land use and land cover are important to understand as they will influence the type of SUDS that could potentially be implemented, for example, a high proliferation of apartment buildings provides an opportunity for the application of green roofs (GRs).

4.1.1.2 Stormwater System Representation

The stormwater system representation was based on the existing drainage network incorporated into the selected study area. The pipe inlets and manholes were represented within the Jeddah-SWMM model as junction components; these are represented as the blue solid circles in Figure 4-5 obtained from the stormwater drainage system maps from AECOM (2014). In total, there were 21 water inflow points and two outlets identified and incorporated into the model. The conduits that comprise the selected study are stormwater drainage system and were all identified as pipes, all of which were circular in shape, except for one which was determined to be rectangular in shape. There were found to be differences in the diameters of the conduits with subsequent differences in the designed flow rate of each conduit (details of the conduit properties are summarised in Table A-9, Appendix A).

4.1.2 The Default Parameter Values of the Jeddah-SWMM model

The Jeddah-SWMM model was comprised of three distinct model components, the subcatchments, junctions (nodes) and pipes (conduits). Each of these model components has several default parameter values that need a setting. The details of these parameters and the procedure for them are discussed in the following sub-sections:

A) Junctions

The input parameters for the junctions represented in the model were the invert elevations and the maximum water depths for the pipe inlets and manholes that corresponded to the junctions. These were calculated from the stormwater system maps with information obtained from AECOM (2014).

B) Pipes

The pipe (conduit) input parameters which were included are the diameters of the pipes, the slope of the pipes and Manning's roughness coefficient (n). The first two parameters were obtained from the stormwater system maps and information that was obtained from AECOM, 2014 (details of pipe parameters can be found in Table A-14, Appendix A). The default parameters for (n) were obtained from SWMM's manual (Rossman, 2015), a value of 0.01 was used for conduit, as the pipes were found to be constructed of concrete (Table A-12, Appendix A). Whilst it is possible that the Manning's coefficient of the existing pipes may vary from the

identified standard Manning's coefficient for concrete, due to the age of the pipes, it is not possible to quantify this within the scope of this study, therefore a standard Manning's coefficient was selected.

C) Subcatchment

The default parameters necessary for the subcatchment components are more numerous than for the junctions and conduits. The default parameters that are required are; subcatchment area (A), subcatchment width (b), pervious depression storage (Dstore-perv), impervious depression storage (Dstore-Imperv), *n* pervious, *n* impervious, percentage zero (% Zero)and the curve number (CN). A summary of the default input parameters for each subcatchment is illustrated in Table 4-2.

Table 4-2 The input parameters used for each subcatchment in the Jeddah-SWMM model.

Subcatchment	Area (km^2)	Average Flow Length (m)	Initial Width (m)	Slope (%) (m/m)	Weighted CN0.20	Dstore-Imperv	Dstore-perv	% Zero
S1	0.28	818	347.3	2.33	93.8	1.2	8.4	15
S2	0.43	1088	398.8	1.50	95.7	1.2	9.2	15
S3	0.36	1101	327.6	1.53	95.0	1.3	8.8	15
S4	0.25	942	263.3	1.53	94.8	1.3	12.4	15
S5	0.54	1280	423.6	1.08	95.3	1.4	13	15
S6	0.80	1506	528.4	1.36	93.8	1.2	11.8	15
S7	0.42	1277	326.5	1.21	96.4	1.3	13.5	15
S8	0.57	1694	338.1	1.08	96.4	1.3	12.6	15
S9	0.13	465	283.8	1.45	95.6	1.3	13.5	15
S10	0.14	438	316.1	2.02	94.8	1.2	13.5	15
S11	0.04	295	139.7	1.54	92.9	1.2	8.3	15
S12	0.89	1817	489.0	1.05	94.5	1.6	9.2	15

- The initial width indicated in Table 4-2 is the characteristic which summarised flow width within the subcatchment. This was calculated by dividing the subcatchment area by the average maximum overland flow length (L) which is "the length of the flow path from the furthest drainage point of the subcatchment before the flow becomes channelized" (Rossman, 2015). To calculate this parameter, three different pathway lengths were measured using GIS from which the average was calculated (Table 4-2).
- Average slope for each subcatchment was calculated by using Zonal Statistics from the Spatial Analyst tool in ArcGIS.
- The Dstore-perv is the rainwater which has accumulated in the depression which is formed on a pervious surface. This rainfall represents a temporary accumulation and, therefore, does not behave in the same manner as surface water runoff. Instead, this rainfall accumulation will be lost through the processes of evaporation and infiltration. Conversely, the rainfall which accumulates within Dstore-Imperv can only be lost through the process of evaporation, as infiltration does not occur due to the surface being impervious. Depression storage calculations involved estimation of the CN, which is needed for calculating infiltration rates. The subcatchments are comprised of more than one land use/land cover in each subcatchment area; therefore, it was necessary to calculate an area weighted CN. SCS-CN method assumes that the initial abstraction is a fixed fraction of the maximum retention. By calculating an area weighted CN, it accounts for the potentially different infiltration rates caused by differences in the imperviousness of the different land use/land cover types. At the present time, the SWMM model is unable to account for multiple CNs within one catchment.
- The calculation of the CN was derived from an appraisal of the key hydrological characteristics of each subcatchment. For the Jeddah-SWMM subcatchments this was based upon the characteristics of the soils and the geological survey data described in Chapter Three (Section 3.3.2) and Section A-1, Appendix A. This was combined with the land use/land cover data identified in Section 4.1.1. Additionally, other factors were included, which were: an assessment of soil conditions based upon the location of Jeddah, known rainfall data and estimates of infiltration which also resulted in the production of an assessment of soil condition. The final weighted CNs for each subcatchment area are given in Table 4-2, (more details about SCS-CN method clculations can be found in Section A-3, Appendix A). The depression storage for both previous and impervious zones was assumed to be equivalent to the initial abstraction of the SCS-CN method.

- The *n* pervious and *n* impervious are the Manning's roughness coefficients for the respective pervious and impervious surfaces and were taken from the tables provided by Rossman (2015) (Table A-7, Appendix A). The Manning's coefficient was based upon typical coefficients used in other studies developed from the scientific knowledge pool. Thus, typically Manning's coefficients were selected which corresponded to the material type which was identified. The total area and the impervious surface area within each subcatchment were calculated based on the land use and land cover identified in each subcatchment (see Section 4.1.1). This then allowed the percentage of imperviousness for each subcatchment to be calculated and entered into the default model. The Manning's coefficients *n* that were used in this model were 0.0125 for impervious surfaces and 0.15 for pervious surfaces, due to the type of material that they were found to be comprised of.
- The percentage zero (%Zero) is a parameter which is defined as a measure of the impervious surfaces which will not store water on the surface and, therefore, have a potential water depth on the surface of zero resulting in the immediate undertaking of the process of surface runoff when rainfall begins. Percentage Zero was set as 15% due to its typical values ranged between 1% and 30% and, therefore, 15% represents a median of typical values (Balascio and Gao, 1998).

An additional requirement of the SWMM model is the use of equations to define flow routing and set-up time for the simulation. Kinematic wave routing was the method selected for use in the Jeddah-SWMM model. The justification for the selection of this routing method is that it is not as complex as dynamic wave routing, yet it incorporates a greater degree of complexity than the use of steady flow routing. The primary difference between kinetic wave routing and dynamic wave routing is that the latter allows for the inclusion of backflow within the model. However, it was decided that this is not a necessary function for the purposes of the Jeddah-SWMM model given that excess flow is either lost from the model or will pond at inlet nodes; therefore, it is not necessary to account for backflow and there is no need for the added complexity of using dynamic wave routing. It was determined that the time intervals for each routing step were to be set at 30 seconds and the overall reporting time interval at 30-minute increments. Thus, the rainfall interval and the hydrograph were also set at 30 minutes.

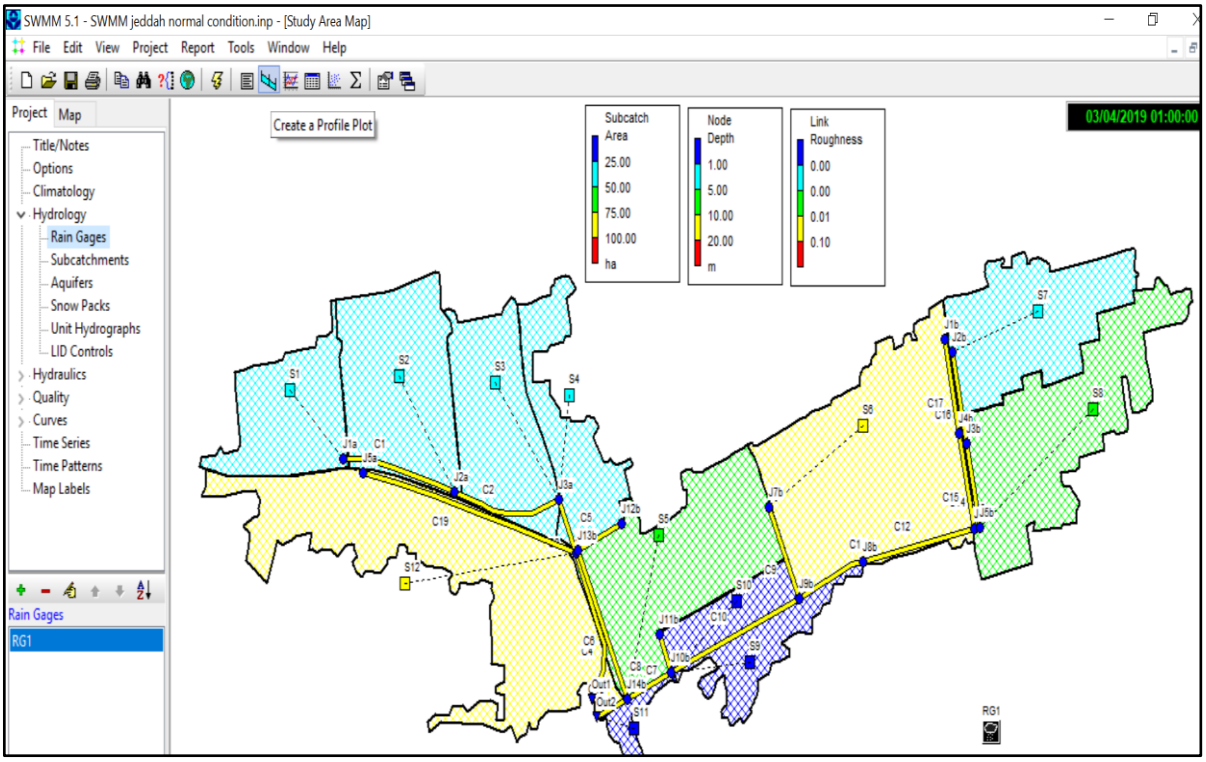


Figure 4-5 The SWMM model map of the selected study site within Jeddah City. The links are indicated by yellow lines and the nodes are indicated by blue circles.

4.3 Calibration and Verification of Jeddah-SWMM Model

The process of calibration of the constructed SWMM model is a highly necessary stage in the modelling procedure as it ensures that the model outputs are reflective of reality. This is achieved by tweaking the immeasurable parameters of the model until the outputs match observed measurements. To select a subset of parameters for calibration, a sensitivity analysis is often performed first.

4.3.1 Sensitivity Analysis

4.3.1.1 Selecting Subset of Parameters

The first step in calibrating a model with many parameters is to find the sub-set of parameters to which the model is most sensitive. For the selected test case (Jeddah City), these parameters will impact the final runoff predictions, which are calculated by the SWMM model due to the treatment of each sub catchment within the SWMM model as a non-linear reservoir (Wang and Altunkaynak, 2011). For the purposes of the Jeddah-SWMM model, it was determined that a sensitivity analysis should be conducted on the following subset of parameters to determine which are the most sensitive: Dstore-perv, Dstore-Imperv, *n* pervious, *n*

impervious, % Zero and CN. These parameters were selected due to their known substantial influence on the outputs of the hydrological and hydraulic models (in the underlying equations) incorporated within the SWMM model based on similar findings in other studies (see Balascio et al., 1998; Tsihrintzis and Hamid 1998; Zhang et al., 2013).

Some parameters that were selected for sensitivity analysis by other researchers in published studies were not selected for this study. For example, the percentage slope is a parameter that was included by Balascio et al. (1998) in their study utilising an SWMM model. However, it was not included as a sensitivity parameter for this study, due to Jeddah City was determined to be nearly flat; thus, there is little variation in the percentage slope between subcatchments used for the Jeddah-SWMM model. Therefore, the percentage slope was determined to be a parameter of limited sensitivity when considering the potential outputs of the model. This is because any change in the percentage slope would be relatively negligible and, therefore, of minimal effect upon the model outputs. This is an example of where the importance of the included parameter within the model is low, such that it can effectively be considered as a constant (Confalonieri et al., 2010).

4.3.1.2 Sensitivity Analysis: Method

A local method alters only one parameter at a time as opposed to the global method which alters all parameters simultaneously and, thus, accounts for interactions between variables (Kucherenko et al., 2009), while, in comparison, local methods do not. Whilst it could be suggested that this is a more limited method of sensitivity analysis, the use of a local method is a common occurrence for rainfall-runoff models (Mancipe-Munoz et al., 2014). The preferential use of local methods is primarily attributed to the relative ease of performing this assessment (in comparison to global methods), requiring minimal computational effort and the relative ease of integrating local methods into existing modelling software (Dotto et al., 2010). An additional benefit of altering individual parameters is that it increases the familiarity with the model for the researcher, thereby enhancing the understanding of how the model performs (Troutman, 1985).

The sensitivity analysis was performed manually; there were 144 permutations that were tested. This was due to two historical rainfall events being tested (the 25/11/2009 event and the 29/12/1010 event, see Table 4-3), over two subcatchments, which are subcatchments 2&12

(selected as they are varied in size and land cover in relation to each other), for each of the six parameters were selected for sensitivity analysis (see previous section). Each parameter was changed for each rainfall event in each catchment. Only one parameter was changed at a time. Each parameter was varied by increasing the parameter value incrementally by first 5%, then 10% and then 20% above the initial setting (which are the default parameters outlined in Table 4-2). The same procedure was then applied to decrease the parameter value from the initial value by the same percentage variations. The details of these parameter tweakings are given in the following sections.

4.3.2 Jeddah-SWMM Model Calibration and Selection of Rainfall Events for Calibration

There were two stages in the manual calibration process that was utilised for this study. The first stage of the calibration was to calibrate the model for the runoff volume. This was achieved by adjusting the parameters, which were found through sensitivity analysis using trial and error until such a point was attained where the runoff volumes predicted by the Jeddah-SWMM model were approximately the same as the observed volumes, which is the "observed estimates" determined by the SCS-CN method, as detailed in Section 3.4.3, Chapter Three. The second stage in the calibration was similar, but involved the varying of peak flow rates. To identify the difference between the predicted and the observed peak flow rates, the relative error (PF) was used. In addition, the relative error (RV) was used to calculate the difference between the predicted and observed surface stormwater runoff volumes. All aspects of these stages of calibration were repeated for each calibration event undertaken within each subcatchment. Subsequently, the calibrated parameter settings from each calibration event were summed and averaged to determine the Jeddah-SWMM model calibrated parameters, similar to methods which have been applied in comparable studies (Liong et al., 1991; Tsihrintzis and Hamid, 1998, Zahng, 2009). Finally, the calibrated model parameters were then verified with two separate rainfall events that were deemed suitable for calibration.

One of the factors that can potentially impact the effectiveness of the calibration is the number of points at which it is undertaken; the greater the number of calibration points within the watershed then the greater the potential accuracy of the model outputs. Thus, it was determined that 12 calibration points should be used, one within each subcatchment of the Jeddah-SWMM model. The calibrations that were undertaken within each subcatchment were undertaken independently of each other, it is suggested that this is an additional contributory

factor that could potentially increase the accuracy of the Jeddah-SWMM model based on the findings of similar published research studies (Zhang, 2009). Four historical events were selected to calibrate the Jeddah-SWMM model (shown in Table 4-3). These four events were selected to provide a range of rainfall duration and rainfall depth to further increase the effect of model calibration on the overall model accuracy by calibrating the model to a range of rainfall scenarios. Similar to calibration, two historical rainfalls were selected (see Table 4-3).

The use of manual calibration of the model could be argued as a more robust approach than the use of automatic calibration procedures due to the propensity for automatic procedures to calibrate to unrealistic values (Franchini and Pacciani, 1991). In-depth studies have suggested that automatic calibration alone would be insufficient for conducting a thorough and realistic calibration of a model; however, in comparison, the use of manual calibration can by itself provide an accurate means of calibrating a model with realistic variables selected for parameters. An additional benefit that can be gained from the manual conduction of calibration is that the researchers increase their familiarity with the model and its functioning, thereby ensuring that calibrated parameters are representative of values which are hydrologically realistic in relation to the other included parameters (Gan and Burges, 1990).

Table 4-3 Historical rainfall events that were used to calibrate and validate the Jeddah-SWMM model.

Rainfall Event	Duration (hours)	Total depth (mm)	Purpose
25/11/2009	3	70	Calibration
29/12/1010	2	24	Calibration
30/12/2010	3	41	Calibration
14/01/2011	1	15	Calibration
02/12/2009	1	14	Verification
15/01/2011	5	29.2	Verification

4.4 Results and Discussion

4.4.1. Sensitivity Analysis: Results

During the sensitivity test, it was found that, when the quantity of rainfall was increased, the magnitude of the water surface flow output also increased. This was also found to be marginally

influenced by the size of the subcatchment, i.e. the larger the subcatchment, the greater the degree of change. The higher the percentage variation, then the greater the change that was observed. However, this was not true for all parameters. Some parameters, such as *n* impervious and the CN, had a greater sensitivity to the model and, therefore, had a greater magnitude of change. Through observation and review of the outputs, it was determined that the parameters exhibiting the greatest sensitivity were the CN and then Manning's n for impervious area, thus, changes in these variables had the greatest measurable impact on the model outputs. However, it should be noted that all parameters were still included in the sensitivity analysis and selected as a subset of parameters for calibration.

One example of the outputs from the sensitivity analysis is given in Figure 4-6 where the outputs for variation in CN for subcatchment One (S2) and subcatchment Twelve (S12) are shown. It is clear from the comparison of the hydrographs generated that there is a slightly greater effect of varying CN for S12 than S2; this is due to the face that subcatchment S12 is greater in area and has different soil characteristics. All the sensitivity analyses were conducted in the same manner as the Figure 4-6 exemplar.

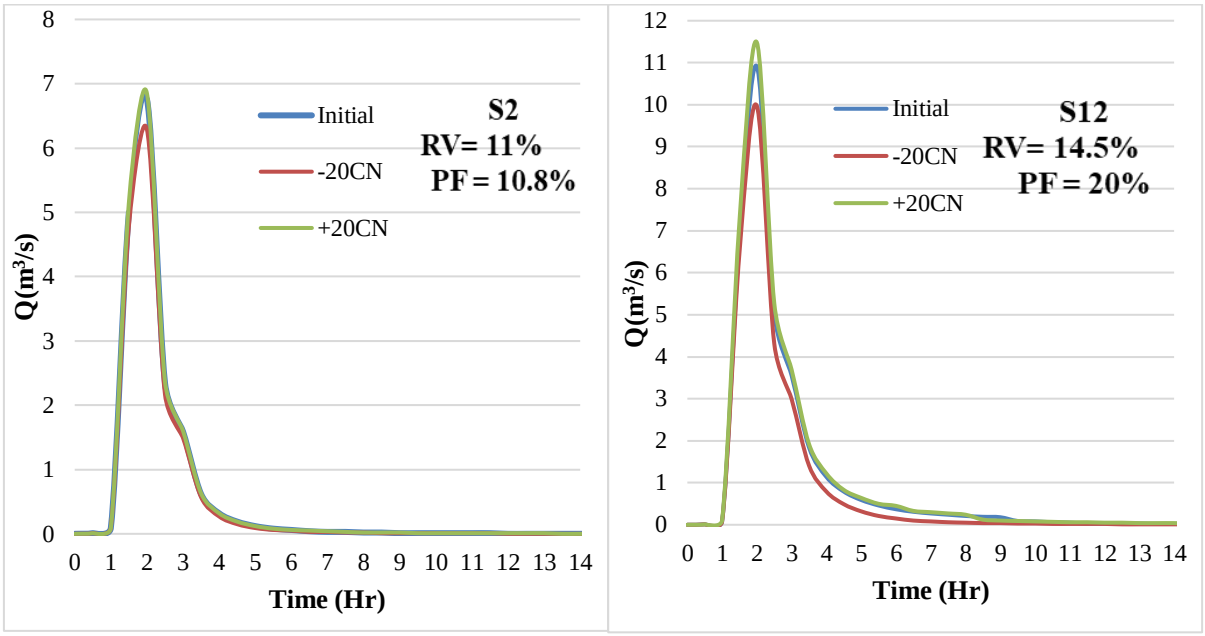


Figure 4-6 the sensitivity analysis of the Jeddah-SWMM model performed on subcatchments 2 & 12 for the parameter of CN, the sensitivity analysis output is given as the variation in the modelled hydrographs.

In the following sub-sections, each calibration event (corresponding to a different historical rainfall event) is examined and any notable points about the outputs highlighted.

4.3.2 Calibration for the 25/11/2009 Event

Default settings for the variable parameters used in the Jeddah-SWMM model were set to run the calibrations of the Jeddah-SWMM model and ultimately utilised to predict the surface stormwater runoff from the 25/11/2009 rainfall event (the default parameters are outlined in Section 4.1.2, Table 4-2). The runoff of the hydrograph observed (in Section 3.4.3) is compared with the hydrographs from the calibration events. The calibration was conducted for each output node within each subcatchment and the output graphs for each subcatchment, using the default parameter settings, as shown in Figure 4-7. The calculated differences in relative error peak flow (PF) were included in the graphs presenting the observed stormwater surface runoff peak flow rates and the predicted stormwater surface runoff peak flow rates. The difference in the total stormwater surface runoff volumes between the observed and the predicted rainfall surface water flows is indicated by the deviation relative error volume (RV) on each graph. In all but one of the subcatchments, the peak flow rate was overestimated by the Jeddah-SWMM model. This varied between 1.5% – 31.5% (see Figure 4-7 and Table 4-4) with half of the subcatchments having a difference of 30% or greater in the observed and peak flow rates for the 25/11/2009 event. Whilst the majority of the peak flow volumes were inaccurately predicted by the model for this event, the timing of the peak stormwater volume flow was more accurate. Overall, seven subcatchments had peak flow volume occurrence predicted slightly after the observed peak volume flow and five had predicted peak flow volume earlier than the observed.

Table 4-4 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 25/11/2009 event.

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Subcatchment	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr%	Observed	Predicted	FV-Erorr%
25/11/2009	3hr	70 mm	S1	3.4	4.2	19.5	19646	19170	2.4
	3hr	70 mm	S2	4.9	6.5	24.9	28357	30456	6.9
	3hr	70 mm	S3	3.9	5.1	23.9	22486	23940	6.1
	3hr	70 mm	S4	2.8	3.7	24.9	16057	16758	4.2
	3hr	70 mm	S5	5.2	7.6	31.8	30076	37008	18.7
	3hr	70 mm	S6	6.7	10.1	33.5	39215	48798	19.6
	3hr	70 mm	S7	4.5	6.1	27.0	25715	29322	12.3
	3hr	70 mm	S8	5.3	7.9	32.7	30295	39708	23.7
	3hr	70 mm	S9	1.9	2.4	22.9	10859	10692	1.5
	3hr	70 mm	S10	2.0	2.1	5.9	11507	9144	20.5
	3hr	70 mm	S11	0.6	0.6	3.1	3503	2772	20.9
	3hr	70 mm	S12	6.9	10.1	31.5	39187	54774	28.5

The calibration process was then conducted with a focus on reducing the total runoff volume and subsequently decreasing the peak surface stormwater runoff rate predicted by the model. This included increasing the depression storage (as a large reservoir delays and decreases the surface water runoff potential). The calibrated parameter values are given in Table 4-5.

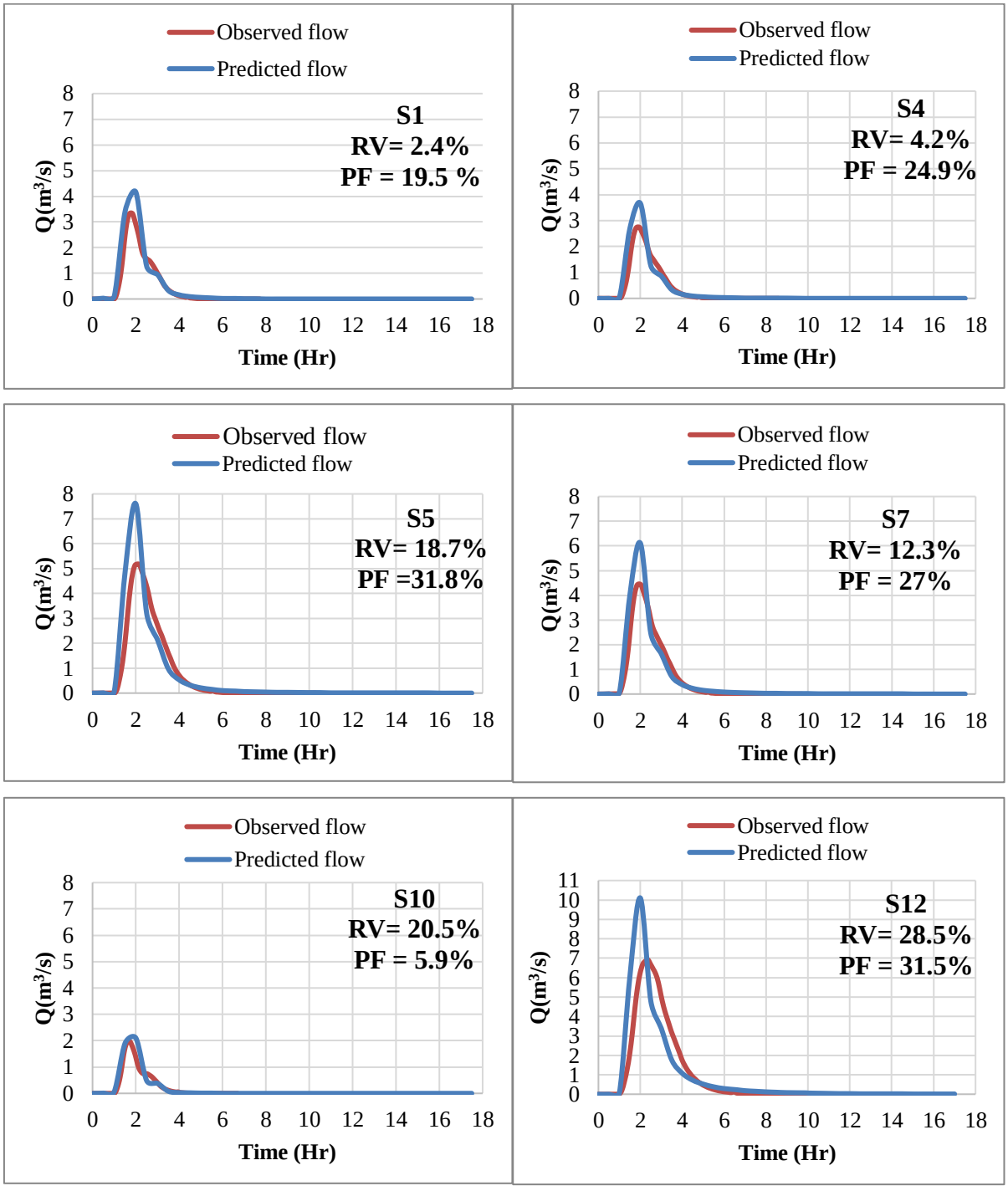


Figure 4-7 Calibration outputs of the 25/11/2009 event across six subcatchments using default parameter.

Table 4-5 The values of the calibrated parameters for the Jeddah-SWMM model for the 25/11/2009 event.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	90		S7	CN	91	
	Manning's n	0.013	0.19		Manning's n	0.015	0.13
	Depression storage (mm)	0.9	9.4		Depression storage (mm)	1.4	12.5
	%zero	20	NA		%zero	12	NA
S2	CN	91		S8	CN	91	
	Manning's n	0.015	0.16		Manning's n	0.015	0.13
	Depression storage (mm)	1.4	9.2		Depression storage (mm)	1.4	11.6
	%zero	15	NA		%zero	12	NA
S3	CN	90		S9	CN	89	
	Manning's n	0.015	0.16		Manning's n	0.013	0.15
	Depression storage (mm)	1.3	9.8		Depression storage (mm)	1.2	13
	%zero	15	NA		%zero	10	NA
S4	CN	89		S10	CN	90	
	Manning's n	0.015	0.15		Manning's n	0.014	0.15
	Depression storage (mm)	1.6	12.4		Depression storage (mm)	1.2	13
	%zero	10	NA		%zero	15	NA
S5	CN	89		S11	CN	91	
	Manning's n	0.015	0.15		Manning's n	0.015	0.2
	Depression storage (mm)	1.7	13		Depression storage (mm)	1.1	8
	%zero	10	NA		%zero	25	NA
S6	CN	88		S12	CN	91	
	Manning's n	0.01	0.2		Manning's n	0.015	0.2
	Depression storage (mm)	1.6	14.8		Depression storage (mm)	1.7	9
	%zero	15	NA		%zero	10	NA

4.3.3 Calibration for the 29/12/2010 Event

The differences between the predicted and the observed flow for the historical rainfall event of 29/12/2010 using the calibrated parameters are given in Figure 4-8. In comparison to the outputs shown in Figure 4-8, it can be seen that there is an even greater divergence between the observed and the predicted stormwater surface runoff flow patterns and volume. For all of the subcatchments (bar S12), the peak flow was predicted as significantly greater than the observed flow. The results of the Jeddah- SWMM hydrologic model for each subcatchment

includes the deviation in peak flow rate and flood volume for the 29/12/2010 event as shown in Table 4-6 below.

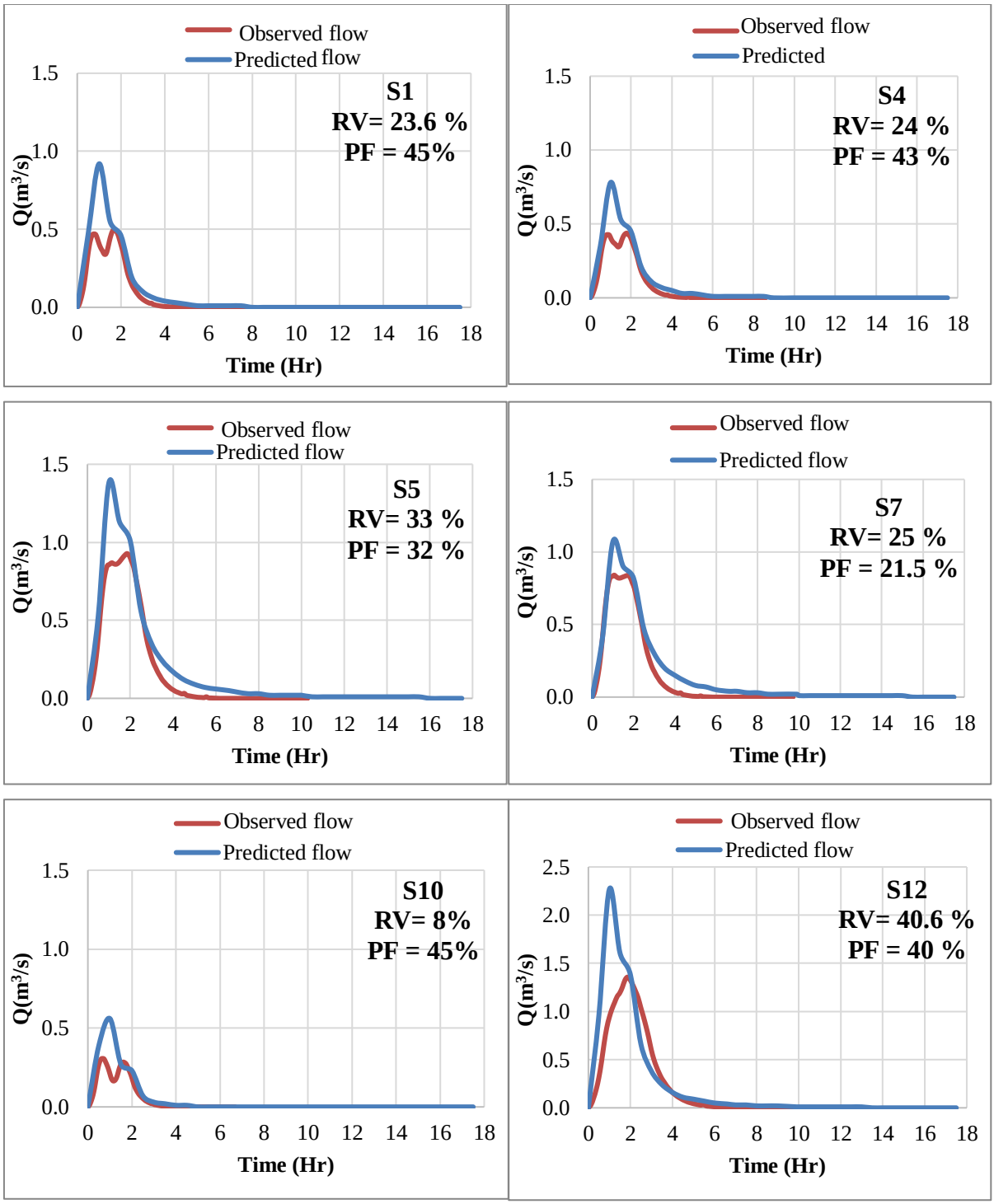


Figure 4-8 Calibration outputs of the 29/12/2010 event across six subcatchments using default parameter.

In some of the simulations the percentage difference between the observed flow and the predicted flow were found to have a difference of up to 45%. This is a point of some concern as it indicates that the model predictions are not reflecting the reality of the scenario which occurred. However, when compared to findings reported in the literature within similar studies it was found that it is not uncommon for there to be a high percentage difference between the observed and predicted water flows. For example, Barco et al., (2008) reported up to a 37% difference in the observed and predicted urban water flows in their application of SWMM. Similarly, Kourtis et al., (2017) reported up to a 35.1% difference between the observed flow volume and the predicted flow volume when calibrating SWMM.

Table 4-6 Results of the Jeddah- SWMM hydrologic model for each Subcatchment includes the deviation in peak flow rate and flood volume for the 29/12/2010 event.

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Subcatchments	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
29/12/2010	2hr	24 mm	S1	0.50	0.9	44.4	42098	52020	23.6
	2hr	24 mm	S2	0.84	1.2	30	69640	87660	20.6
	2hr	24 mm	S3	0.64	1.0	36	52486	66420	21.0
	2hr	24 mm	S4	0.44	0.8	43.9	36815	48420	24.0
	2hr	24 mm	S5	0.93	1.4	33	71996	108720	33.8
	2hr	24 mm	S6	1.19	1.7	30	83842	136620	38.6
	2hr	24 mm	S7	0.84	1.1	21.5	66670	88920	25.0
	2hr	24 mm	S8	1.09	1.2	9.2	78112	118620	34.1
	2hr	24 mm	S9	0.32	0.6	46.1	26424	32040	21.3
	2hr	24 mm	S10	0.31	0.6	45.2	26384	28620	8.5
	2hr	24 mm	S11	0.08	0.1	20	6857	6840	-0.3
	2hr	24 mm	S12	1.36	2.3	40.2	87940	147960	40.6

The calibrated parameters that were attained for the rainfall event of the 29/12/2010 to achieve coherence between the observed and predicted surface stormwater runoff volume and peak flow are given in Table 4-7.

Table 4-7 The values of the calibrated parameters for the Jeddah-SWMM model for the 29/12/2010 event.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	**90**		**S7**	CN	**91**	
	Manning's n	0.02	0.25		Manning's n	0.02	0.15
	Depression storage (mm)	1.7	9.4		Depression storage (mm)	1.5	11.5
	%zero	**7**	NA		%zero	**5**	NA
S2	CN	**91**		**S8**	CN	**91**	
	Manning's n	0.02	0.2		Manning's n	0.02	0.15
	Depression storage (mm)	1.6	8.2		Depression storage (mm)	1.5	14.6
	%zero	**7**	NA		%zero	**5**	NA
S3	CN	**90**		**S9**	CN	**91**	
	Manning's n	0.018	0.2		Manning's n	0.018	0.2
	Depression storage (mm)	1.7	9.8		Depression storage (mm)	1.7	11.5
	%zero	**10**	NA		%zero	**10**	NA
S4	CN	**90**		**S10**	CN	**91**	
	Manning's n	0.018	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.8	10.4		Depression storage (mm)	1.6	11.5
	%zero	**10**	NA		%zero	**15**	NA
S5	CN	**90**		**S11**	CN	**89**	
	Manning's n	0.018	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.8	11		Depression storage (mm)	1.7	9.3
	%zero	**10**	NA		%zero	**15**	NA
S6	CN	**89**		**S12**	CN	**90**	
	Manning's n	0.02	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.7	11.6		Depression storage (mm)	2	9.2
	%zero	**5**	NA		%zero	**10**	1.1

The full results of calibration by applying other historical rainfall events can be found in Section B-1 Appendix B.

4.3.4 The Calibrated JEDDAH-SWMM Model

Once all the calibrations had been performed for each historical rainfall event, the final calibrated parameters for each rainfall event scenario were averaged across all four events. These averaged parameters that are considered the calibrated Jeddah-SWMM model parameters

and will, therefore, be used as the default parameters for the operation of the model under the current scenario and simulations. The full set of averaged calibrated parameters is shown in Table 4-8.

Table 4-8 The average values of the parameters after calibration with five historical rainfall events.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	**90**		**S7**	CN	**91**	
	Manning's n	0.018	0.20		Manning's n	0.018	0.15
	Depression storage (mm)	1.5	9.4		Depression storage (mm)	1.6	12.5
	%zero	11	NA		%zero	9	NA
S2	CN	**91**		**S8**	CN	**91**	
	Manning's n	0.019	0.17		Manning's n	0.018	0.15
	Depression storage (mm)	1.6	9.2		Depression storage (mm)	1.6	12.8
	%zero	11	NA		%zero	9	NA
S3	CN	**90**		**S9**	CN	**91**	
	Manning's n	0.018	0.18		Manning's n	0.017	0.18
	Depression storage (mm)	1.6	9.6		Depression storage (mm)	1.5	12.6
	%zero	12	NA		%zero	10	NA
S4	CN	**90**		**S10**	CN	**91**	
	Manning's n	0.018	0.17		Manning's n	0.018	0.18
	Depression storage (mm)	1.7	11.95		Depression storage (mm)	1.6	12.6
	%zero	11	NA		%zero	13	NA
S5	CN	**90**		**S11**	CN	**90**	
	Manning's n	0.018	0.18		Manning's n	0.016	0.19
	Depression storage (mm)	1.8	12.4		Depression storage (mm)	1.5	8.5
	%zero	10	NA		%zero	18	NA
S6	CN	**89**		**S12**	CN	**91**	
	Manning's n	0.018	0.18		Manning's n	0.018	0.19
	Depression storage (mm)	1.7	12.9		Depression storage (mm)	1.9	9.4
	%zero	8	NA		%zero	10	NA

4.4.5 Verification of the Jeddah-SWMM Model

Subsequent to the calibration of the Jeddah-SWMM model using the four historical events, two independent historical events were selected and used for model verification (listed in Table 4-

3). As was done when selecting the calibration events, the verification events were also selected on the basis of the need to consider a variety of rainfall durations, total depths and average intensities. Likewise, during the process of verification, the generated runoff hydrographs of the verification events were compared with the hydrographs for the observed events. The outcome of the verification process for the 15/01/2011 event, which has a longer duration and bigger rainfall depth, indicates that the calibrated Jeddah-SWMM model has a relative error (PF) of 3.5% for the average peak flow and an RV of 16.9% for the total runoff volume across the 12 subcatchments. For the 02/12/2009 event, the calibrated Jeddah-SWMM model has a relative error (PF) of 20% and an RV of 30.1%, which has less accuracy compared to first events. This is due to having shorter duration and much less rainfall depth (14mm); therefore, there is not relatively high predictive accuracy for the Jeddah-SWMM model as indicated by the values for RE and DV being within ± 15% (Zhang, 2009); however, compared to similar studies, (e.g. Zhang, 2009; Eckart et al., 2018), the calibrated Jeddah-SWMM model has a higher accuracy and the calibrated model can provide a useful tool for the evaluation of potential SUDS placement within the selected study area.

4.5 Conclusion

In conclusion, this chapter presented a parameterised SWMM model optimised for the selected study area, Jeddah City. It was found that the Jeddah-SWMM model provided an accurate and detailed representation of the patterns of water flow within area of study and, therefore, will be a useful tool in the development of solutions to future stormwater management needs. The calibration process was thorough and based on the calibration of the model with four historical events, then two independent recorded events were used for verification purposes. Across the calibration, six model parameters were assessed for each of four historical rainfall events. In each calibration event, the calibration parameters were first adjusted to values which were a close approximation between the observed and predicted both total runoff volume and peak flow at each subcatchment outlet. After all the four calibrations had been completed, the values of the calibration parameters were averaged to provide a singular calibrated parameter value for each parameter to be included in the model. These averaged calibrated values were then verified using the two historical rainfall events. As to the overall goal of developing a SUDS DSS, the calibrated Jeddah-SWMM model predictions are reasonably accurate; thus, it can serve as the basis for evaluating SUDS practices in Jeddah City.

Chapter Five: Research Survey by Questionnaire

5.1 Introduction

This chapter outlines the methodology utilised to conduct the survey by questionnaire, reffered to as survey for simplicity throught this chapter. It also presents and discusses the survey findings. The primary aim of conducting a survey was to gather data and opinions from a range of experts in the field on the suitability of different types of SUDS for utilisation in arid regions, and information regarding the financial costs of building and maintaining such infrastructures. This was done to facilitate the identification of SUDS types suitable for application in Jeddah City and the corresponding financial costs of their implementation and maintenance.

5.2 Methodology

The qualitative method selected for this research was a survey which was undertaken by the distribution of the survey among selected, relevant experts in the field, including practitioners, academics, engineers (private sector and governmental) and contractors working in stormwater management in the KSA.

5.2.1 Questionnaire Design

The questionnaire was designed to focus on Jeddah City rather than arid regions in general due to the differing physical and environmental conditions of the different locations which would result in SUDS options varying by location. Thus, in order to gain an accurate insight into the case study location of Jeddah City, it was necessary that the questionnaire focused on the case study location alone.

The questionnaire was designed to be comprised of two parts. The first was focused on four themes (the sustainability of different SUDS, the appropriate types of SUDS, the challenges of SUDS implementation and expert opinions/comments), which contributed towards the aim of investigating the potential of SUDS application in Jeddah City and both arid and semi-arid regions in general. The second part of the questionnaire was focused on obtaining information pertaining to the potential financial costs of SUDS implementation and maintenance in Jeddah City. The participants were invited to complete either part one, part two or both parts of the questionnaire depending upon their self-assessed level of expertise. Table

5-1 below gives an overview of the survey themes, including questions and aim for each theme. A full copy of the distributed questionnaire is available in Section C-3, Appendix C.

Table 5-1 Survey themes including questions and aim for each theme.

Part One: Questions
Theme One: Suitability of SUDS
Theme Aim and Research Question
The aim of this theme was to validate the potential suitability and feasibility for the implementation of SUDS in the Jeddah City area. The following are the research questions that the theme aims to answer: three questions have been set under this theme. • Q1. Is the current drainage system in Jeddah City fit for purpose (i.e. does it prevent flooding)? Why? • Q2. SUDS have been proposed as a method of controlling flooding whilst reducing environmental impacts, do you think that this would be the outcome if they were used in Jeddah City? Why/Why not? • Q3. The use of SUDS is not widespread in Jeddah City; can you think of any reasons why this is so?
Theme Two: Appropriate Type of SUDS
The aim of this theme is to determine whether some SUDS present a more viable solution than others in the context of Jeddah City. The following are the research questions that the theme aims to answer: • Q4. The popular types of SUDS available include green roof, bio-retention, swales, rain garden, permeablepavement, rainwater harvesting and infiltration trench. Can you list in order the SUDS that you think are more appropriate for Jeddah? • Q5. Review of the literature shows that green roofs, permeable pavement, green gardens and bio-retention areas have all been suggested as SUDS that would be appropriate for Jeddah City. Do you think any one of these SUDS has merits over the others? Why? • Q6. Do you think any of the SUDS listed in the previous questions would be inappropriate for implementation in Jeddah City? Why?
Theme Three: Challenges of SUDS Implementation

The aim of this theme is to identify specific challenges that may arise during the process of SUDS implementation and maintenance in the context of the Jeddah City study area. The following are the research questions that the theme aims to answer: • Q7. Where do you think green roofs should be installed? On private houses or commercial buildings or government buildings? (Why or why not?) • Q8. Do you think that SUDS could be retrofitted in Jeddah City? Why/Why not? Can you identify any particular challenges to this undertaking? • Q9. Aside from the previous questions, can you think of any challenges to the use of SUDS in Jeddah City? How do you think these challenges could be overcome?
Theme Four: Opinion and Comments
The aim of this theme is to extract any opinions from the experts regarding SUDS implementation in Jeddah City that may not have been elicited in the context of previous questions. The following are the research questions that the theme aims to answer: Q10. In your opinion, what information needs to be gathered to facilitate the implementation of SUDS in Jeddah City? Q11. Any other comments on the use of SUDS in Jeddah City?
Part Two: SUDS Cost Estimation
The aim of this theme is to develop an understanding of the potential financial costs that may be incurred in the course of implementing and maintaining SUDS in the Jeddah City scenario. Cost includes capital cost (materials+ construction cost (label ….)); and operational and maintenance cost

5.2.1.1 Ethical Considerations

The survey by questionnaire was conducted following the University's strict ethical policies. Ethical review forms were submitted, reviewed by the ethical team and ethical clearance was received. Ethical considerations were explained to participants in an email and the consent form sent to them, which included detailed information about confidentiality and withdrawing from the research at any stage.

Regarding confidentiality, all information collected was kept confidential and only used by the PhD researcher and the supervision team. The answers and notes were digitised, encrypted and

stored on the University of Birmingham's servers (BEAR Datashare). The answers provided were summarised and reported in this thesis and publications without mentioning any individual names or companies. In addition, the participants were given the choice to withdraw from the research even after completing the questionnaire. (Ethical approval are attached in Section, C-4, Appensix C)

5.2.1.2 Questionnaire Conduction

The contact information for potential participants was obtained through processes that first involved the identification of relevant stakeholders through an Internet search (Google.com) using search terms such as water engineer, stormwater manger and hydrologist. Additional stakeholders were identified through personal recommendations made to the researcher by known individuals working in the subject field. Once the relevant stakeholders had been identified, their contact information was sourced from either websites or was provided by personal contacts. This process identified the contact information of 39 relevant individuals. Table 5.2 shows the number of individuals identified in each category.

Table 5-2 The groups of relevant experts identified and the number of individuals contacted in each group.

Group	Number of Individuals Contacted
Academics	10
Government Employees	11
Private Sector	10
Contractors	8

The initial contact with each identified individual was undertaken electronically via email. The first email included a general overview summary of the research project along with the overall aim of the survey, asking if they would be willing to participate in the research. If the individual responded positively, indicating their willingness to engage, then, a follow-up email was sent which included the consent form (attached in Appendix C-2) for them to sign electronically. Upon receiving a signed consent form, the questionnaire was sent to the individual in a subsequent email. If a response in the form of a completed questionnaire, or a withdrawal of consent, was not received within one week of the questionnaire delivery, then, a follow-up email was sent, including an additional copy of the questionnaire and a polite

reminder. This was also accompanied by the statement that, if they had any inquires or had found something unclear, then they could clarify this by email, phone or Skype communication with the researcher.

The success of a research study that relies on voluntary individual response to a questionnaire is directly related to the number of individuals that choose to participate. The likelihood of survey responses has been the subject of multiple research studies and the response rate has been found to be variable. For example, a meta-study examining questionnaire response rates conducted by Baruch and Holtom (2008) on 490 different studies that utilised surveys found that the response rate from individuals is, on average, 52.7% (with a standard deviation of 20.4). This was found to be similar to the response rate recorded by Bray et al. (2017) of 47% with regard to online questionnaires. Thus, it would be expected that, for the survey questionnaire distributed in the course of this study, the response rate would also be approximately 50%, which would be equal to 18 or 19 responses.

This supposition was found to hold true with 18 responses received in the form of completed questionnaires. Of those individuals who did not complete a questionnaire, some of the contacted individuals indicated that the subject matter was outside their expertise, and therefore, they felt unqualified to complete the survey. Of the 18 individuals who responded, 14 participants completed the questionnaire in English and four completed the questionnaire in Arabic. Six of the participants contacted the researcher with inquiries which were responded to by either telephone or Skype.

5.3 Data Analysis Methods

The data generated in the two parts of the questionnaire were analysed separately following different approaches on account of the nature of the data generated from each part of the questionnaire; part one elicited responses that were primarily qualitative and opinion based in nature, whereas part two, whilst also eliciting opinion based data, resulted in responses that were primarily numerical (therefore quantitative) in format.

The process by which part one of the survey responses were analysed is illustrated by the diagram in Figure 5-1. Thus, all part one responses were coded using the following format:

Participants were coded using a lettering and number format whereby:

A = Academics

B = Private Sector

C = Government Employee

D = Contractor

Individual responses within each category were identified by the addition of a numerical value; thus, respondent A1 represents academic respondent 1 and respondent D3 represents contractor respondent 3. Numerical identifiers were assigned in order of response received to eliminate the possibility of researcher bias arising from identifier assignment.

The responses to part one of the survey were thematically analysed. This involved the identification of emerging themes or patterns from the survey responses to each question. The overall goal of thematic analysis is the identification of themes or patterns that occur in more than one response within the qualitative data set (Maguire and Delahunt, 2017). The identification of patterns is the first step in the thematic analysis, while the second step aims to move beyond the patterns that permeate the data to interpret and understand the implications that these themes hold for the research subject. Thus, once the patterns within the data had been identified through the coding process, the data were examined at the latent level in an attempt to understand the ideas and assumptions which shaped the respondent's responses to the questions.

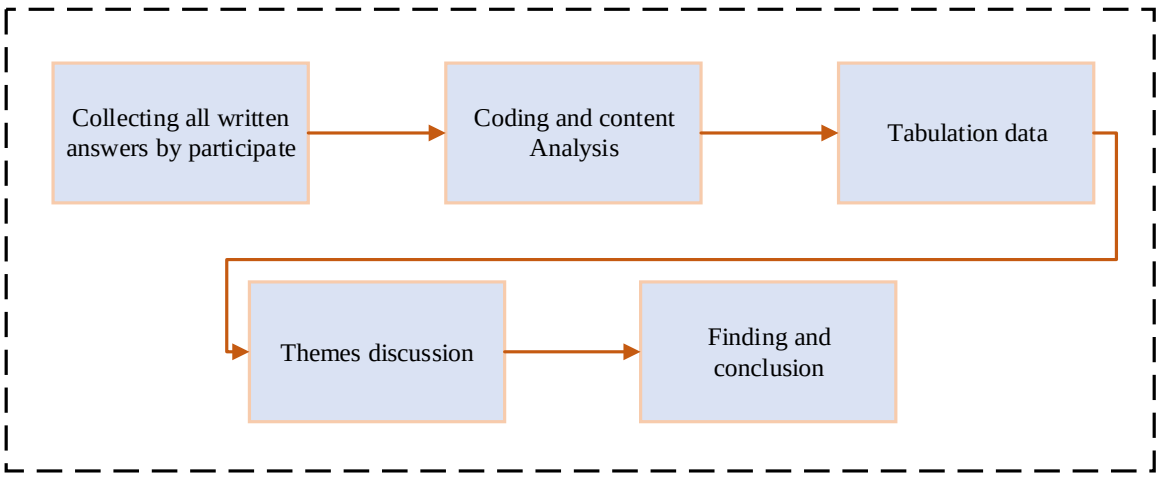


Figure 5-1 The analysis process for part one of the questionnaire survey responses.

Part two of the survey questionnaire was analysed by calculating the average cost estimation for each type of SUDS provided by the respondents. The number of respondents to part two of the questionnaire was limited; this was due to the level of expertise among the respondents, such that only four felt qualified to provide responses (as opposed to the 14 respondents who completed part one). The average cost estimation for each SUDS type was calculated by inputting the survey responses into equation 6-1 (Chapter Six). The calculations were done on Excel spreadsheet.

5.4 Results and Discussion

In total, 15 respondents completed the questionnaire survey (Table 5-3). There were 12 respondents who were based in Jeddah City and three respondents in Makkah. All of the respondents were employed in fields related to stormwater management, water and environmental engineering and management. Due to the limited application of SUDS in Jeddah there was very limited experience explicitly in this sector, however, the respondents were those individuals who were best placed due to relevant experience to provide a knowledgeable estimate about the potential implications and practicalities of implementing SUDS in Jeddah City.

Various different methods, such as tabulation, using automated software, journaling or using affinity diagramming techniques, are commonly used for the presentation of codes and themes identified through thematic analysis (Suter, 2012). Tabulation was the methodology selected for application to the collected questionnaire data, primarily for the ease of data interpretation for both the primary research and subsequent readers of the study. Additionally, the use of tabulation provides a robust framework for the development of the discussion points. Table 5-3 gives the identifiers assigned to each survey respondent. Each survey response was thematically analysed with the outputs collated captured in a tabulation table, as per the example given in Table 5-4 (full tabulation with answers is given in Section C-5, Appendix C). In the following sections, the findings of the questionnaire survey are presented, whereby, for each theme, the emergent patterns are summarised.

Table 5-3 The abbreviations that were used in the tabulation and analysis to identify the individual survey respondents.

Position	Symbol	Symbol Name Of	Coding of Each Participant	Response
Academic	AC	Participant A1	A1-AC	Email
Academic	AC	Participant A2	A2-AC	Email
Academic	AC	Participant A3	A3-AC	Email
Academic	AC	Participant A4	A4-AC	Email
Academic	AC	Participant A5	A5-AC	Email, Phone
Academic	AC	Participant A6	A6-AC	Email, Skype
Private Engineer	P. Eng.	Participant B1	B1- P.	Email, phone
Private Engineer	P. Eng.	Participant B2	B2- P.	Email
Private Engineer	P. Eng.	Participant B3	B3- P.	Email
Private Engineer	P. Eng.	Participant B4	B4- P.	Email
Governmental	Gov.	Participant C1	C1- Gov.	Email
Governmental	Gov.	Participant C2	C2- Gov.	Email, Phone
Governmental	Gov.	Participant C3	C3- Gov.	Email
Governmental	Gov.	Participant C4	C4- Gov.	Email
Governmental	Gov.	Participant C5	C5- Gov.	Email
Contractor	Cont.	Participant D1	D1- Cont.	Email
Contractor	Cont.	Participant D2	D2- Cont.	Email, Phone
Contractor	Cont.	Participant D3	D3- Cont.	Email

Table 5-4 The tabulation table method used to record the findings of the thematic analysis.

Theme Number: Theme Name	
	Questions related to the theme, such as Q1, Q2.
Participants' codes (names and positions) such as A1-AC	***Result (their answers)***

5.4.1 Theme One: The Suitability of SUDS for Jeddah City

In Table 5-5, a summary of the emergent patterns from the tabulated questionnaire responses on a per question basis is given (full tabulation is given in Section C-5, Appendix C). The key emergent pattern from the responses given to the questions under the theme of SUDS suitability for Jeddah City is that, overall, the majority of respondents believe that SUDS would present a robust and appropriate option for stormwater management in this region. The reasons given for this were varied; however, they all centred around the factor that the existing stormwater management system is either non-existent (depending on location within the city) or unsuitable for purpose where it does exist. It should be noted that two respondents were more supportive of the existing stormwater management system than the other respondents; however, even these two respondents indicated that there was a need for improvements to be made to the existing system to improve the functioning and reliability, which could potentially include the use of SUDS.

The reasons suggested for a lack of SUDS implementation thus far reflect the findings of the literature review, in that it is predominantly due to a lack of relevant published data that detail how SUDS could be applied and would function in arid and semi-arid environments, such as Jeddah City. This is seen in the patterns that emerged from the questionnaire whereby the respondents indicated that many of the barriers and challenges to SUDS implementation in Jeddah City stem from a lack of knowledge and a lack of prior implementation. An interesting point that was not identified during the literature review was the potential barrier presented by the cultural preference for traditional building design. This raises an aspect that should be included within the development and design phase of how SUDS could be integrated into the existing infrastructure and future developments whilst retaining the aesthetics of traditional design to overcome this potential barrier.

It is further apparent that there is currently a substantial knowledge barrier in regard to the potential implementation of SUDS as a future option for stormwater management in Jeddah City. This highlights the importance of the current research study in providing data which can address some of the concerns raised, and, thereby, increase the potential for SUDS to be selected as a sustainable stormwater management strategy for Jeddah City and other urban areas of similar climatic conditions.

Table 5-5 The emergent patterns from the three questions addressing the theme of SUDS suitability for Jeddah City in the distributed questionnaire.

Question	Emergent Patterns from Responses
Q1. Is the current drainage system in Jeddah City fit for purpose (i.e. does it prevent flooding)? Why?	• The current drainage system is not fit for purpose – flooding is not prevented. • There is a lack of a prior planning approach to stormwater management. • There is a lack of cohesive application and structure – stormwater management is unevenly applied across different city areas.
Q2. SUDS have been proposed as a method of controlling flooding whilst reducing environmental impacts, do you think that this would be the outcome if they were used in Jeddah City? Why/Why not?	• Yes – the SUDS would control flooding if applied. • There is a need to integrate SUDS into the existing infrastructure/stormwater management system. • The characteristics of Jeddah City built structure and the environmental conditions need to be considered.

Q3. The use of SUDS is not widespread in Jeddah City; can you think of any reasons why this so?	• There is a lack of stormwater management planning.
	• There is a lack of awareness of SUDS as an option
	  ○ Not covered in existing policies and regulations.
	  ○ There is a lack of decision-maker(s) support.
	• There is a lack of data pertaining to how SUDS could/would function in this environment.
	• Cultural barriers – there is a preference for traditional design.
	• Concerns regarding maintenance and upkeep.

5.4.2 Theme Two: SUDS Types Appropriate for Jeddah City

The suitability of SUDS in the survey was first examined by providing the respondents with a range of SUDS options and asking them to rank their perceived order of suitability for Jeddah City. From the rankings shown in Figure 5-2, it is apparent that permeable pavements (PPs) received the greatest support from the respondents, closely followed by bio-retention units (BRs).

In Table 5-6, a summary of the emergent patterns from the tabulated questionnaire responses for questions five (Q5) and six (Q6) is given, supporting the findings of question four (Q4). An examination of the justifications provided for this selection indicates that the majority of respondents selected this option because they believed that it is the most applicable under the current environmental and physical conditions in Jeddah City. Therefore, it would be relatively easy and straightforward to implement PPs as a stormwater management solution. This

suggestion is further supported by the observation of respondent A2-AC who suggested 'permeable pavement in the current time, bio-retention and green gardens in the future.' Some respondents did suggest other SUDS options as being most suitable, namely, green roofs (GRs) and rain gardens (RGs), mentioning the additional environmental benefits as the driving factor for these options, whereas, for BRs, the fit into existing infrastructure (both physical and political) was suggested as the driving factor.

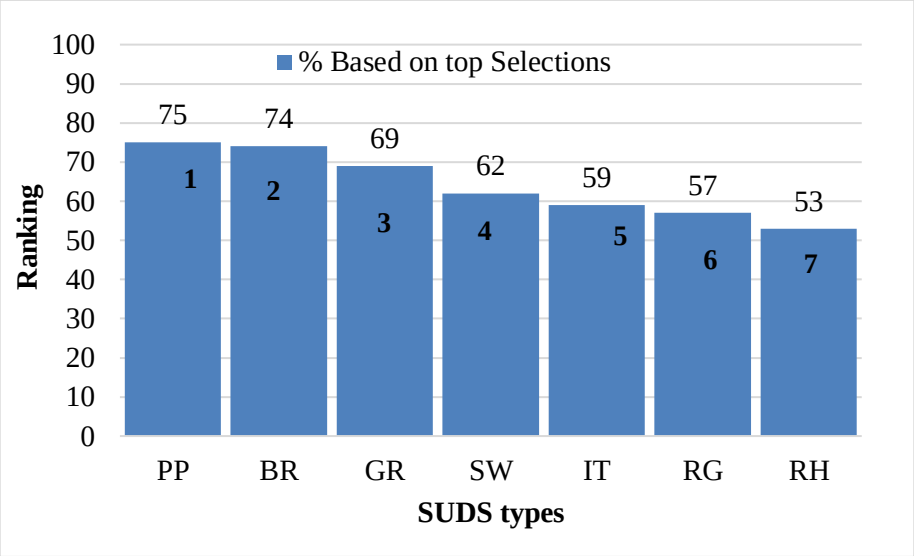


Figure 5-2 The respondents' ranking of SUDS options for Jeddah City where PP = permeable pavement, RH = rainwater harvesting, BR = bio-retention, RG = rain garden, IT = infiltration trench, SW = swales and GR = green roofs. The ranking of each SUDS option is given on the bar and the percentage of respondents is also shown.

When considering question six (Q6), the majority of respondents indicated that none of the SUDS option were inappropriate. However, where SUDS options were suggested by respondents as inappropriate, the reasoning was primarily given as being unsuitable due to either the environmental conditions of Jeddah City, the physical geography of Jeddah City or the perceived costs involved, this particularly applied to the RH option (see Table 5-6). Additionally, it is suggested that the respondents appeared to be focused on how SUDS options could be rapidly implemented at the current time without requiring substantial alterations to the design of the urban environment of Jeddah City.

Table 5-6 Emergent patterns from answers to questions (Q5) and (Q6) in theme two of the questionnaire: Appropriate SUDS for Jeddah City.

Question	Emergent Patterns from Responses
Q5. Review of the literature shows that green roofs, permeable pavement, green gardens and bio-retention areas have all been suggested as SUDS that would be appropriate for Jeddah City. Do you think any one of these SUDS has merits over the others? Why?	• Permeable pavement was the most frequently cited as the most appropriate for Jeddah City. Reasonings included: o Ease of applicability – can be utilised with the current urban infrastructure. o Already in use. o Ease of maintenance. The suitability for the prevailing environmental conditions. • Green roofs and rain gardens were suggested by some respondents, citing the additional environmental benefits that would be gained. • Bio-retention was supported by some respondents due to: o Relative ease of construction. o The fit with the existing infrastructure. o The fit with existing planning/legislation regulation.
Q6. Do you think any of the SUDS listed in the previous questions would be inappropriate for implementation in Jeddah City? Why?	• The majority indicated that none are inappropriate. • Bio-retention was suggested as inappropriate due to: o Costs o Construction o Potential for stagnation • Permeable pavements were suggested as inappropriate due to: o High water tables o High cost • Green roofs were suggested as inappropriate due to: o No framework for application o Rainfall variability (watering required in dry season)

The responses to questions (Q5) and (Q6) are summarised in the graphical representation given in Figure 5-3, clearly indicating the favourability of respondents for applying the SUDS option of PPs in Jeddah City. The response to BRs was the only SUDS option where the number of individuals suggesting that this solution was inappropriate was greater than the number of individuals suggesting that it would be appropriate.

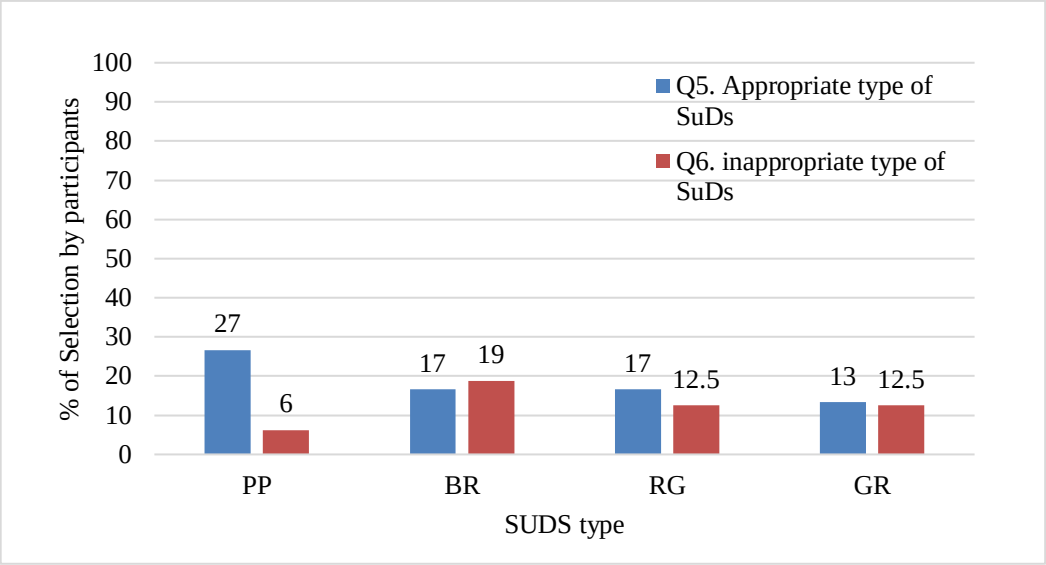


Figure 5-3 The percentage of respondents that indicated as to whether each of the four most popular SUDS options was either appropriate or inappropriate in the context of Jeddah City. Where PP = permeable pavement, BR = bio-retention, RG = rain garden and GR = green roofs.

5.4.3 Theme Three: Challenges of SUDS Implementation in Jeddah City

In the case of retrofitting GRs in Jeddah City, many of the respondents indicated that they should be retrofitted wherever possible. Other respondents demonstrated a clear preference for the retrofitting of GRs to government buildings, citing the availability of space and the ability to upkeep the GRs as the primary factors for this selection (see Table 5-7). Other respondents were primarily in favour of retrofitting GRs to private dwellings, suggesting that the specialised care needed for these SUDS would be more readily available. However, the potentially high cost and the acceptability of this option for private residents was raised as a concern.

When considering the challenge of retrofitting SUDS in Jeddah City, the opinions of the respondents were nearly evenly divided between those who believed it to be possible and those who did not, the latter citing d barriers, such as the cost, to the process of retrofitting that would reduce the likelihood of success, as outlined in full in Table 5-7. Interestingly, those who suggested that retrofitting would be possible included codicils to their assertions regarding some of the conditions that would need to be met to make retrofitting possible. This suggests that those respondents who are against retrofitting for reasons of existing barriers cannot envision those barriers changing, whereas those who suggested it is possible under certain conditions can envision systematic changes being made to enable retrofitting to occur.

Table 5-7 Emergent patterns from the three questions in theme three of the questionnaire: challenges of SUDS implementation in Jeddah City.

Question	Emergent Patterns from Responses
7. Where do you think green roofs should be installed? On private houses or commercial buildings or government buildings? (Why or why not?)	*Private (18 % of Participants):* For • Cheaper (for government) • Private residents can supply the special care needed • Citizens' responsibility to environment • Abundance of rooftops Against • High cost • Acceptability *Commercial (39% of Participants):* For • Large spaces – effective harvesting • Decreases costs of building operation Against • Availability of specialised care *Government (44 % of Participants):* For • Suitable space • Effective enforcement of regulations • Annual maintenance contracts will ensure upkeep • Large available water supplies Against Availability of care
8. Do you think that SUDS could be retrofitted in Jeddah City? Why/Why not? Can you identify any particular challenges to this undertaking?	Split opinions of respondents (38 %) No Lack of endorsement by authorities

	• High cost • Lack of available expertise • Not a priority • Environmental conditions are unsuitable (47%) Yes • If the appropriate contractors can be found • In areas which are not of traditional design • Under the appropriate regulations and design guidance • If government led

9. Asides from the previous questions, can you think of any challenges to the use of SUDS in Jeddah City? How do you think these challenges could be overcome?	• A lack of urban planning/modern planning
	• A lack of data pertaining to:
	  ○ Environmental conditions
	  ○ Hydrological conditions
	  ○ SUDS implementation in arid environments
	  ○ The maintenance/operational requirements
	  ○ Cost
	• A lack of available expertise
	• Overcoming climatic and environmental conditions
	• The level of awareness of SUDS options

The majority of the additional challenges that were cited by the respondents were related to the lack of available data pertaining to both the general application of SUDS in arid and semi-arid climates and that pertaining directly to the conditions within Jeddah City. The additional challenges that were cited by the respondents were, therefore, mainly related to factors that are within the remit of potential for change, by the process of accumulating more data and information. Interestingly, none of the respondents suggested any additional challenges that could not be overcome through the collection of additional data. This suggests that the use of SUDS in Jeddah City is a very real possibility and provides further justification for the need for this research study to be conducted. It is suggested that many of the challenges highlighted by the respondents have arisen from the position of uncertainty. There is simply insufficient data and information available to accurately assess the SUDS potential for application in the Jeddah City area.

5.4.4 Theme Four: Opinions and Comments

As the final part of the questionnaire survey, respondents were invited to provide their opinions on what information was needed for SUDS to be implemented in Jeddah City and to provide any further comments or suggestions that had not been addressed by other questions. The emergent patterns from these questions are summarised in Table 5-8.

It is apparent from the responses to question ten (Q10) that respondents perceived that there is a need for significant information to be gathered in order to enable SUDS to be implemented in Jeddah City. Only a few respondents suggested the need for feasibility studies to be conducted, whereas other respondents chose to highlight specific datasets that would be needed. All of the datasets that were individually highlighted by the respondents would form the datasets needed for inclusion in a feasibility study. Thus, it is suggested that it is possible to summarise that the majority of the responses as regard the information needed for feasibility studies to be conducted comprises the dataset that would be needed to be gathered.

There were only a limited number of additional comments given by the respondents and these were primarily focused upon the perception that the initiative to implement SUDS for stormwater management in Jeddah City should be a process led by the government. It is likely that this was a frequent suggestion due to the inherent need for legislation and regulation to be developed that would govern the development of SUDS solutions in Jeddah City and the KSA. Additionally, this response can be attributed to the fact that the government is responsible for providing and maintaining public services, including stormwater management and drainage in urban areas.

Table 5-8 Emergent patterns from the responses to questions (Q10) and (Q11) in theme four of the questionnaire: opinions and comments on SUDS data requirements.

Question	Emergent Patterns from Responses
Q10. In your opinion, what information needs to be gathered to facilitate the implementation of SUDS in Jeddah City?	• Geological data • Hydrological data • Groundwater maps • DEM analysis • Soil types maps • Hazards and vulnerabilities maps • Land use maps • Climate data • Surface and subsurface drainage networks maps • Jeddah City topography • Feasibility studies • Financial budget • Standardisation of practices and materials • Expert collaboration • Maintenance requirements • Planning strategies
Q11. Any other comments on the use of SUDS in Jeddah City?	• The process should be government led – the government should start to develop the necessary legislative requirements. • The needed expertise should begin to be developed.

5.4.5 Theme Five: Government Regulations and SUDS in Jeddah City

Government regulations on SUDS implementation were not included as a separate theme in the distributed questionnaire; however, the responses to different questions have highlighted how important government regulation is likely to be in the implementation process. Throughout the responses to the questionnaire, respondents repeatedly cited the need for the government to develop appropriate policies, regulations, legislation and guidelines to facilitate the SUDS implementation process. These responses ranged from the need to set an example by installing GRs on government buildings, to the development of legislation that ensures implemented SUDS options are fit for purpose and have standard codes to attain.

As the government is the principle stakeholder in the implementation of stormwater management within Jeddah City, it is highly likely that it will be the most influential stakeholder in the decision regarding whether to utilise SUDS or not. Thus, the support of SUDS solutions by the government will have a positive impact on the uptake rate of these solutions. If the government decides to support SUDS in Jeddah, then this will aid in increasing the awareness of this sustainable solution to urban drainage among companies, contractors, design firms and users, thereby increasing the likelihood of SUDS implementation. Indeed, a lack of awareness was often cited as one of the driving factors for a lack of SUDS implementation thus far.

The government is also in the position where there is a lack of awareness and available data for decision-makers; therefore, at the current time, it is likely that there is a lack of desire (on the part of the government) to move forward with widespread implementation of SUDS. Thus, the findings of this study will contribute substantially towards informing government decision-makers regarding the potential for SUDS to be implemented in Jeddah City. As this study will demonstrate to decision-makers how different SUDS can impact stormwater management differently and will provide insight into the potential for managing financial costs, reducing the potential for stormwater flooding and contributing positively to the environment.

5.4.6 Theme Six: Cost Estimates

Three contractors and one engineer completed the part of the survey that was related to the provision of cost estimates for SUDS. The contractors requested additional information to provide more accurate cost estimates and noted that, whilst they were more familiar with the concepts of PPs and RGs, their initial examination of GRs and BRs led them to suggest that these SUDS would be relatively easy to implement in Jeddah City.

The cost estimates provided in the survey were processed and an average was calculated from the provided estimates. This included estimates for both the implementation of new SUDS and the retrofitting of SUDS. During the process of average calculation, it was noted that the set of estimates provided (by respondent B2-P.Eng) was substantially greater than those provided by the three other respondents in terms of operational cost, in some instances by more than 25 times. It was, therefore, decided to omit the operational cost estimates from B2-P. Eng from the average calculations due to the effect of skewing the average that would have

otherwise resulted from its inclusion. The calculated averages for each SUDS type are shown in Figure 5-4. All of the cost estimates have been provided in the format of cost per m^2.

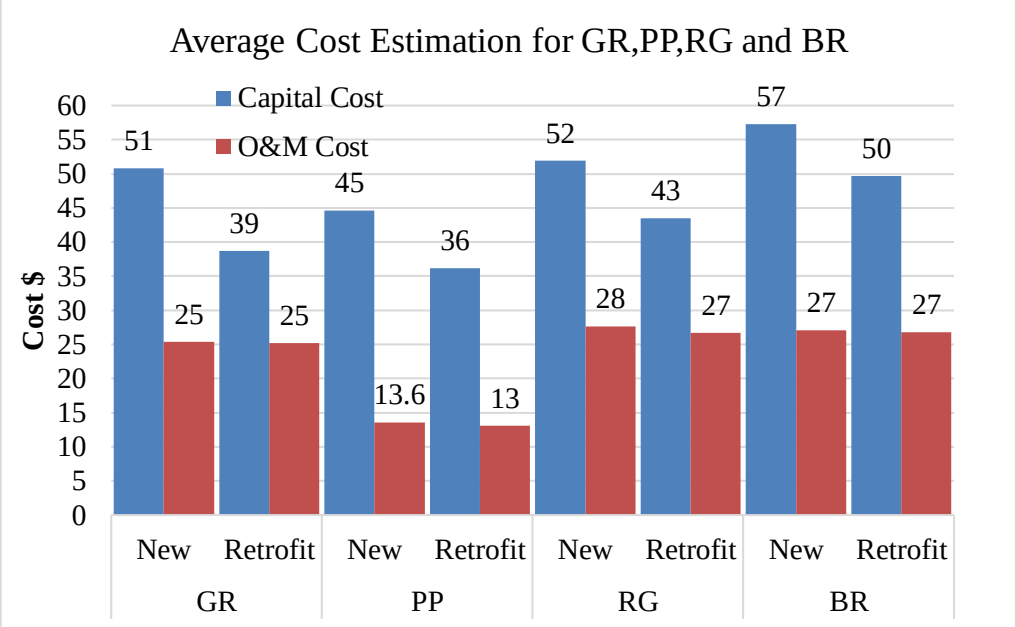


Figure 5-4 The average cost estimates for both new (installation on new buildings) and retrofitted (installation on existing buildings) SUDS in Jeddah City. Where GR = green roofs, PP = permeable pavement, RG = rain garden and BR = bio-retention. The cost estimates are given on the cost per m2.

It is evident that all the respondents indicated that the cost of retrofitting SUDS was lower per m^2 than the cost of installing new SUDS. This is due to the extent of the process required when comparing new with retrofitting. When retrofitting SUDS, there will be substantial existing infrastructure which can be adapted for SUDS, thereby reducing the potential costs incurred. In comparison, when constructing new SUDS, the whole process is begun from nothing. However, the difference between the costs of installing new SUDS in comparison to retrofitting SUDS was not significant. This is counter to the findings of some studies whereby it is suggested that the cost of retrofitting buildings is more expensive than new construction (Wilkinson et al., 2015). However, it is also noted in some studies that a lack of experience with extensive retrofitting of SUDS systems means that there is insufficient knowledge at the current time to accurately assess the true cost of retrofitting SUDS (Oluwayemi et al., 2019). This apparent disagreement is likely to stem from the inexperience of the survey respondents with SUDS implementation and a bias towards the idea that new construction is more expensive than improvements to existing structures. However, given the lack of even newly constructed SUDS

in Jeddah City it is not possible at the current time to definitively state whether new or retrofitted SUDS systems will be more expensive.

GRs and PPs were suggested to be substantially lower in cost than the construction of RGs and BRs. Similarly, the estimated costs of operation and maintenance were greater for RGs and BRs than for GRs and PPs (see Figure 5.4). In comparison to other studies, the cost estimates provided for PPs ($45/m2 for new) were within the range of other studies, ranging between 37.2-518.9 $/m2, and, for PPs ($36/m2 for retrofit), were slightly lower than those of other studies (Chow et al., 2014; DEFRA, 2015). However, the operational and maintenance cost estimates were substantially larger than estimates found in the literature, with $13.6/m^2 estimated in this study, compared to 0.74-1.74 $/m^2 suggested by Chow et al. (2014). In addition, Inflation was not into account in Chow work. However Even with accounting of inflation, the respective Chow estimates are still going to be substantially lower than those of this study.

The calculated cost estimates for GRs in this study ($51/m^2 for new) were found to be substantially lower than cost estimates in the published literature of 71.3-149.2$/m^2 (Chow et al., 2014; DEFRA, 2015). However, the operational and maintenance cost estimates of 25$/m^2 were significantly greater than the 0.25-0.87$/m^2 suggested in the published literature (Chow et al., 2014). This is because the grass would require water irrigation and the city is located in a semi-arid regions, consequently resulting in higher prices than those found in other regions. These differences are likely to arise from the fact that the costs calculated in the published literature are based on actual scenarios (i.e. where the SUDS have been implemented and the maintenance undertaken); therefore, it is possible to know the cost as the money has been spent. In comparison, the cost estimates produced by the respondents to the survey are estimates based on professional opinion and without actual real-world experience to base them upon. It may, therefore, be that, in reality, these costs will be higher and the respondents were significantly underestimating the cost due to a lack of such real-world experience.

No cost estimates were found in the literature directly pertaining to RGs or BRs. However, retention ponds and wetlands are similar SUDS concepts with cost estimates found in the literature of 38.94-64.85$/m^2 and 38.94-51.83$/m^2, respectively. These are similar to the cost estimates calculated for RGs and BRs in this study (see Figure 5.4) suggesting that these figures are in line with what would be expected.

The cost estimates for GRs were examined on a more detailed basis, looking at the individual estimates provided by each respondent. In Figure 5-5, the cost estimates provided by each respondent are shown. The cost estimates for new GRs ranged relatively widely from 10\$/m^2 to 58\$/m^2. However, it was noted that the cost estimates provided by B2-P. Eng did not appear to correspond with the variation in the cost estimates provided by the three other respondents, which suggests that there may have been either an error in the calculation of cost estimates by this respondent or a misunderstanding of the SUDS requirement. The range of cost estimates is suggested to be reflective of the novelty of this type of SUDS in Jeddah City and it is likely that the true cost will fall somewhere in this range.

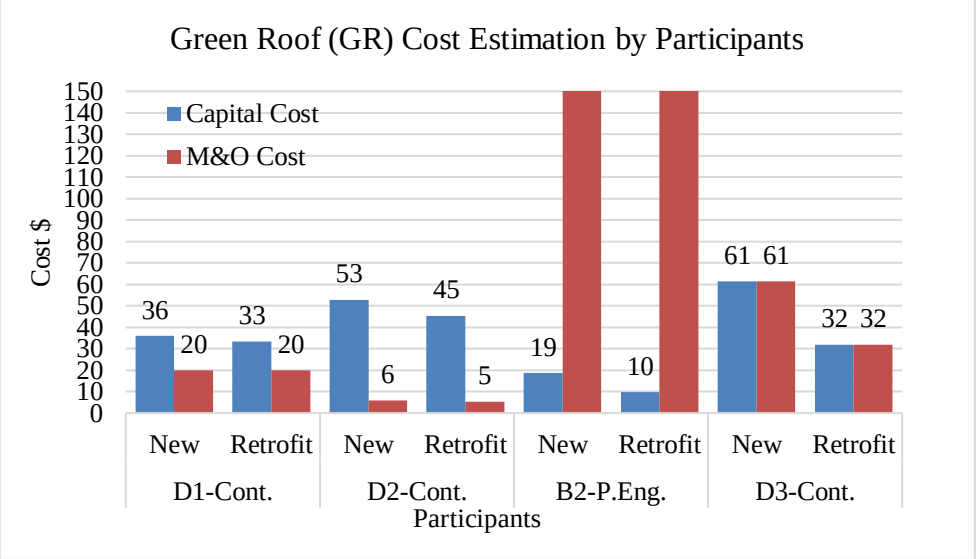


Figure 5-5 The cost estimates in \$/m2 provided by each respondent for both new and retrofitted green roofs.

5.5 Conclusions

In conclusion, the findings of the questionnaire survey indicate that there is a general widespread support for the potential implementation of SUDS as a solution to the issue of stormwater management to prevent flooding in ASARs such as Jeddah city. That being said, a number of concerns were repeatedly raised which may directly impact upon the potential for SUDS implementation in this area. Firstly, there is a lack of available data and conducted feasibility studies in regions that possess similar climatic conditions, meaning that decision-makers, particularly those in government positions, cannot make informed decisions and, therefore, have not demonstrated support for the use of SUDS options in Jeddah City thus far. From this, it can be surmised that, if SUDS are to be successfully implemented in Jeddah, then the decision-makers will need to be provided with substantiated evidence supporting the

successful implementation and operation of SUDS so that they can be viewed as a viable option. This provides validation for the current research study being conducted as it will afford evidence regarding the feasibility of SUDS in Jeddah City, including the most suitable SUDS options. The second concern was that there is a lack of current legislation and regulation related to SUDS that would facilitate their implementation in Jeddah City. This deficiency is again likely due to insufficient available data regarding all aspects of SUDS in this environment, ranging from the most appropriate types of SUDS through to operational and maintenance guidelines.

When the respondents were asked to consider what SUDS would be appropriate for implementation in Jeddah City, it was apparent that their suggestions were primarily based around how they could be integrated into the current urban infrastructure, alongside considerations of the potential disruption and cost estimates. This was apparent from the justifications provided by the respondents, indicating that some of the more desirable SUDS types would be suitable for implementation at the current time, whereas others were noted as desirable inclusions in future development. The use of traditional building designs in particular was noted as a limitation regarding what SUDS would be most suitable for retrofitting.

When respondents were asked to rank SUDS in order of desirability for implementation in Jeddah City, the preferences were as follows: PPs, BRs, GRs, swales, infiltration trench, RGs and rainwater harvesting, respectivly. This is interesting given that some of the respondents had indicated that large-scale SUDS, such as infiltration trenches or swales, which require a relatively extensive available linear space, would not be suitable for inclusion due to the constraints implied by the city's current urban infrastructure. However, it could be that these SUDS types were indicated as desirable due to the potential for inclusion in new development. Thus, from an examination of the survey findings, PPs, BRs, GRs and RGs, were found and selected as a more suitable option for purposes of this study. RGs were not indicated as the most appropriate by the survey respondents, comparing to swale and infiltration trench however, there were suitable areas identified within the study area that would be suitable for the inclusion of RGs. It was also found that GRs and PPs have lower construction, and maintenance and operation costs than RGs and BRs.

Chapter Six: Design of SUDS Parameters in SWMM and Development of Cost Functions

6.1 Overview

The inclusion of SUDS within the Jeddah-SWMM model was achieved by the use of the Low Impact Development (LID) toolset available in SWMM version 5.1. The four SUDS options that were deemed suitable for use in Jeddah City (based on the findings of the literature review, Section 2.2.6, and confirmed through the survey findings in Chapter Five) were green roofs (GRs), rain gardens (RGs), bio-retention units (BRs) and permeable pavements (PPs). Within SWMM version 5.1, it is possible for the user to select the type of LID that is required and enter the characteristics and parameters of the LID unit into the LID Control Editor, from which the model will perform the necessary calculations. However, the parameters and characteristics of each LID unit still have to be designed by the user. In the following sections the design of the four different types of SUDS used in the Jeddah-SWMM model are outlined (Section 6.1), followed by the calculation of total lifecycle financial cost for each designed SUDS (Section 6.2). The selected design parameters were based on a combination of the environmental conditions in Jeddah City and the desired outcome of the implementation of SUDS options, i.e., to avoid the flooding events that have occurred historically due to extreme precipitation events.

6.2. SUDS Design Strategy

6.2.1 The Design of Green Roofs

Jeddah City has a high potential for the application of GRs as a SUDS solution. However, there are some constraints, primarily derived from whether rooftops are publicly or privately owned. In the case of private dwellings, normally, the onus will be on the homeowner to finance both the installation and maintenance of the green roof system; this is likely to lead to variances in the rate of uptake and the type of GRs that would be installed unless the government offers subsidies. Therefore, for the purposes of this project, the potential for green roof installation is focused on commercial and government -owned buildings due to the relative ease of ensuring consistency and maintenance in such structures. However, due to the inclusion of some areas of extensive residential development in the selected study area, it was decided that an option should be included to consider the application of GRs on residential dwellings as this has the potential to add substantially to the areas in which SUDS solutions could be applied.

Thus, it was determined to allow the consideration of green roof potential on up to 20% of private homes to generate insight into the potential for this type of SUDS application to contribute to the stormwater management in Jeddah City.

It was decided that the area of green roof per building should be restricted to a maximum of 75% coverage of the rooftop. This is for the dual reasons of ensuring that the SUDS is easily installable and for ease of access for routine maintenance. Additionally, restricting the extent of the green roof reduces concerns regarding the potential for the load bearing capabilities of existing rooftops to be exceeded (Napolano et al., 2015). Typical structure of roofs in Saudia Arabia have a weight of between 260-360 kgm^{-2}(Saudi Biulding Code (SBC 303), 2019). However, it should be noted that buildings would need to be assessed on an individual basis to determine whether the existing structure is suitable for a green roof or if alterations to the building structure would be needed to ensure that the green roof weight can be borne. Due to this concern, it was decided that the type that would be modelled for this study would be based upon the design for an extensive green roof, which are deemed more suitable for use in retrofitting projects (Carter and Keeler, 2008) as they typically have a weight of between 60-150 kgm^{-2} in comparison to the weight of intensive GRs which typically have a weight of between 200-500kgm^{-2} (Razzaghmanesh and Beecham, 2014). This is a compromise between the potential water storage capacity and peak flow reduction - intensive GRs typically have a greater water storage capacity and, therefore, a greater peak flow reduction during periods of intensive rainfall (Razzaghmanesh and Beecham, 2014) - and the need to ensure the structural integrity of buildings that were not originally designed for GRs.

There are three-layer components to the modelling of a green roof within the LID toolkit of SWMM: surface, substrate/soil and storage/drainage layers (Rossman, 2015). The parameters that were utilised for the surface layer are given in Table 6-1. The storage depth on a green roof is set to zero as it is undesirable to have water ponding on the surface as this can considerable increase the stress on the building due to the greater weight which the structure has to bear (Zhang and Guo, 2012). Thus, the vegetative volume fraction is also zero as the vegetation does not occupy any portion of the storage area.

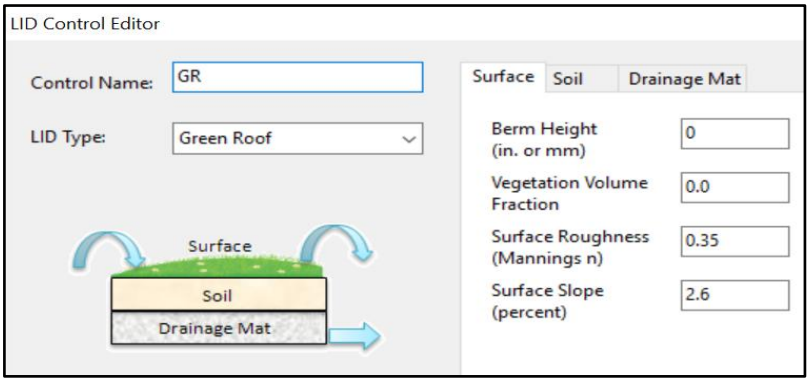


Figure 6-1 The structure of a green roof as modelled within SWMM.

The surface roughness can vary depending on the type of vegetation that is planted. For the purposes of this study, it was the equivalent to that used by Andres-Domenech et al.(2018) who investigated a green roof in a semi-arid Mediterranean coastal climate of Spain; therefore, it is likely that a similar type of vegetation would flourish on a green roof top in the Jeddah City climate. The surface slope of the green roof is set to 2.6% due to the need to have only a slight slope so as to encourage water infiltration into the green roof storage area, rather than aid surface runoff.

Table 6-2 gives the parameters used for the soil layer of the green roof and are based upon the extensive green roof that was modelled in SWMM by Peng and Stovin (2017); their model was based upon a standard green roof design widely applied in the United Kingdom, which comprised of an 80mm mixed crushed brick and fine substrate soil layer (Peng and Stovin, 2017). The conductivity slope is the value which quantifies the water movement through the soil horizon under gravity in the direction of the roof slope.

Table 6-1 Green roof surface layer parameters.

Parameter	Value Selected	Reference
Storage Depth (mm)	0	Andres-Domenech et al. (2018)
Vegetation Volume (fraction)	0	Rossman (2015)
Surface Roughness (Manning's coefficient)	0.35	Rossman (2015); Andres-Domenech et al. (2018)
Surface Slope (%)	2.6	Peng and Stovin (2017)

Note: Vegetation Volume (fraction): Normally, it can be ignored, but may be as high as 0.1 to 0.2 for very dense vegetative growth (Rossman, 2015), However In arid and semi-arid region assuming that not have dense vegetative

Table 6-2 Green roof soil layer parameters.

Parameter	Value Selected	Reference
Thickness (mm)	80	Peng and Stovin (2017)
Porosity	0.45	Rosa et al. (2015)
Conductivity of Soils (mm/hr)	25	Rosa et al. (2015)
Field Capacity	0.3	Rosa et al. (2015)
Wilting Point	0.05	Rosa et al. (2015)
Conductivity Slope	15	Palla and Gnecco (2015)
Suction Head (mm)	110	Rosa et al. (2015)

The drainage layer in a green roof is typically comprised of either a drainage mat or plate underneath the soil layer resting on top of the roof (Vesuviano and Stovin, 2013), thereby providing an impermeable barrier between the building and the green roof that directs the flow of infiltrated water. The parameters used for the drainage mat layer of the GRs considered in the Jeddah-SWMM model are given in Table 6-3.

Table 6-3 Green roof drainage layer.

Parameter	Value Selected	Reference
Thickness (mm)	25	Peng and Stevin (2017)
Void Fraction	0.5	Rossman (2015)
Surface Roughness (Manning's coefficient)	0.25	Rossman (2015)

6.2.2 The Design of Rain Gardens

Rain gardens are a relatively simple type of SUDS that are typically incorporated into areas where the aesthetic value of the SUDS option is an important characteristic. A rain garden within the LID toolkit of the SWMM model is comprised of three layers: surface, soil and storage layers (Rossman, 2015). Unlike other SUDS options, a rain garden will not typically

have a drainage layer as the intent behind the design is that the rainwater will be completely infiltrated into the soil.

Tables 6-4 and 6-5 respectively detail the parameters for the surface layer and soil layer of the rain garden. A rain garden will typically have a relatively substantial storage depth in comparison to the surrounding environment as its purpose is to channel rainwater into this area; therefore, it is necessary that provision is made for the rainwater to pond on the surface of this drainage option. The slope within a rain garden is typically 0%, as the purpose is for rainwater to collect in this area, not contribute to surface runoff. However, it should be noted that, in scenarios where the ponding area will be exceeded (i.e. the depth of water is greater than the surface storage depth), the use of a value in the slope parameter is necessary as it will contribute to the surface water flow and therefore needs to be accounted for when calculating the volume of water outflow.

Table 6- 4 Rain garden surface layer parameters.

Parameter	Value Selected	Reference
Storage Depth (mm)	150	Eckart et al. (2018)
Vegetation Volume (fraction)	0.1	Rossman (2015)
Surface Roughness (Manning's coefficient)	0.03	Rossman (2015)
Surface Slope (%)	0	Eckart et al. (2018)

Table 6-5 Rain garden soil layer parameters.

Parameter	Value Selected	Reference
Thickness (mm)	250	Rossman (2015)
Porosity	0.4	Rossman (2015)
Conductivity of Soils (mm/hr)	40	Rossman (2015)
Field Capacity	0.25	Rossman (2015)
Wilting Point	0.15	Rossman (2015)
Conductivity Slope	6	Rossman (2015)
Suction Head (mm)	75	Rossman (2015)

The storage layer in the rain garden SUDS option for Jeddah City is formed of the underlying soil and, thus, will have some variation by area if the soil type is different. In the geological survey of the Jeddah City area, it was indicated that Area D had underlying soil types, including both clay soils and sand soil (see Section 3.3.2). Therefore, parameters for clay soils and for sand soils have been included in the parameters for the storage layer (Table 6-6). The height of the storage layer is set to zero as it is not a limiting factor in the study. This is the same reason why the clogging factor has been set to zero as it is also not a factor to be considered given that the storage layer is set as the entire underlying soil horizon.

Table 6-6 Rain garden storage layer parameters.

Parameter	Value Selected	Reference
Height (mm)	0	Rossman (2015)
Void Ratio (volume of voids/volume of solids)	0.4	Eckart et al. (2018)
Conductivity of Underlying Soils (mm/hr)	2.21 (Clay) 15.0 (Sand)	Rahman (2007)
Clogging Factor	0	Scenario dependent

6.2.3 The Design of Bio-retention Units

BRs are designed similar to RGs with a few key differences, such as that they often contain an additional underdrain layer, which does not occur in RGs. Although it is not always the case that underdrains are included, one was included in the parameters modelled in the Jeddah-SWMM model as it was deemed necessary for this study since the SUDS is designed to cope with the extreme rainfall events which lead to the flooding event in Jeddah City; therefore, the BRs were designed under the premise that the quantity of rainfall and surface runoff entering the BR may be in excess of the soil infiltration rates, an under-drain layer would prevent ponding and surface overflow from occurring if this infiltration rates are exceeded.

Table 6-7 gives the parameters used for the surface layer of the BR. The storage depth was set at 300mm, which is on the high side for a BR, but this was purposefully designed with the goal of coping with extreme precipitation events that lead to significant flooding in Jeddah City. Thus, whilst high for typical daily and annual rainfall quantities, it is in line with the storage

depth necessary to cope with the extreme rainfall events leading to flooding (Gulbaz and Kazeyilmaz-Alhan, 2017).

Table 6-7 Bio-retention, surface layer parameters.

Parameter	Value Selected	Reference
Storage Depth (mm)	300	Scenario dependent
Vegetation Volume (fraction)	0.1	Rossman (2015)
Surface Roughness (Manning's coefficient)	0.03	Rossman (2015)
Surface Slope (%)	0	Eckart et al. (2018)

The soil layer properties of the BR are set the same as the parameters used for RGs (see Table 6-8). This is because these parameters are optimised for the Jeddah City environment and highlight the similarities between the two SUDS options. However, the storage layer parameters of BRs are different to those of RGs (see Table 6-9) due to the incorporation of underdrainage in the BR; therefore, there is a limit to the storage capacity of the BR before water outflow occurs via the underdrainage. This is contrary to the RG, wherein there is no limit to the storage layer due to it being comprised of the entirety of the underlying soil horizon.

Table 6-8 Bio-retention soil layer parameters.

Parameter	Value Selected	Reference
Thickness (mm)	250	Rossman (2015)
Porosity	0.4	Rossman (2015)
Conductivity of Soils (mm/hr)	40	Rossman (2015)
Field Capacity	0.25	Rossman (2015)
Wilting Point	0.15	Rossman (2015)
Conductivity Slope	6	Rossman (2015)
Suction Head (mm)	75	Rossman (2015)

Table 6-9 Bio-retention, storage layer parameters.

Parameter	Value Selected	Reference
Height (mm)	500	Rossman (2015)
Void Ratio (volume of voids/volume of solids)	0.4	Eckart et al. (2018)
Conductivity of Underlying Soils (mm/hr)	1.44 (Clay and Sand)	Rahman (2007)
Clogging Factor	0	Scenario dependent

6.2.4 The Design of Permeable Pavements

It is suggested that PPs should be implemented in Jeddah City, wherein there are relatively large areas of impermeable surfaces, excluding road surfaces due, to the difficulties in maintaining road surfaces as permeable surface under the high volume of use (Fassman-Beck and Blackbourn, 2008). Thus, all areas of sidewalks, pathways (such as within parks), car parks and driveways are considered for replacement with PPs in the study area, Area D. This means that there is likely to be a relatively high variability of the percentage of surface area which is to be replaced with PP in each subcatchment on account of the differing land uses/land cover in such subcatchments. For example, those subcatchments which have a high proliferation of residential villas will have a higher area of private driveways; in comparison, commercial areas are more likely to have a higher proliferation of car parks.

Within the LID toolkit of the SWMM model, the PP option has additional parameters, in the form of an extra modelled layer, in comparison to the other potential LID options. Figure 6-2 gives a diagrammatic representation of a PP and the pathway of water flows through the system. The layers that comprise a PP system are: surface layer, pavement layer, storage layer and the soil layer (Zhang and Guo, 2014).

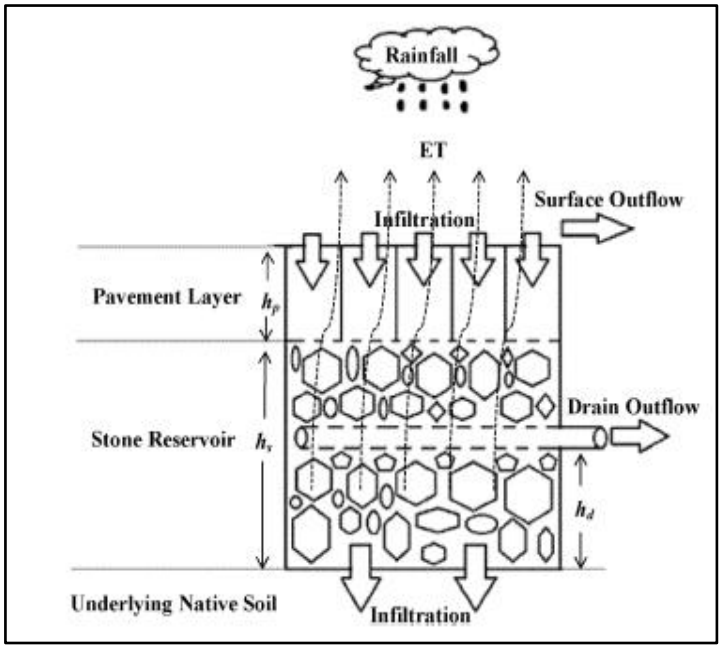


Figure 6-2 A diagram of a permeable pavement system and water flows through the system (Zhang and Guo, 2014 p.2).

The surface layer requires four parameters to be defined within the Jeddah-SWMM model: storage depth, vegetation volume, surface roughness (defined by the selected Manning's coefficient) and the surface slope. For all subcatchments, the storage depth, vegetation volume and surface roughness will be the same values (Table 6-10) since the PPs will be comprised of the same materials and construction. However, the surface slope value will be different across the subcatchments due to variations between catchments, thus, the surface slope value will fall between 1.05 and 2.33% (Table 6-10) depending upon the subcatchment in question (see Table 4-2 for more detail on the slope of each subcatchment).

The vegetation volume was selected as zero; this will hold true if the PP surface layer is regularly maintained and any vegetation growth removed. However, it may not reflect the fact that the surface layer may have vegetation growth occurring between maintenance periods, a factor which should be considered when assessing the accuracy of the modelled scenarios.

Table 6-10 The permeable pavement surface layer parameters.

Parameter	Value Selected	Reference
Storage Depth (mm)	1.5	Zhang and Guo (2014)
Vegetation Volume (fraction)	0	Design Choice
Surface Roughness (Manning's coefficient)	0.014	Rossman (2015)
Surface Slope (%)	1.05 – 2.33	See Section 4.1.2

The pavement layer is the additional layer required for this type of LID within SWMM (Rossman, 2015). The parameters included within this aspect of the permeable pavement will be variable depending upon the type of permeable pavement selected. It was determined that a permeable pavement design based on the use of pervious concrete would be utilised for this study; this is due to the common use of this approach in SUDS, meaning that there are sufficient data available to accurately represent this type of permeable paving within the Jeddah-SWMM model. As permeable pavements have not been widely used in the Kingdom of Saudi Arabia (KSA), it is not possible to know what type of permeable pavement would be best. Therefore, pervious concrete was selected due to the common use of this SUDS option in other locations, such as the United States (Alam *et al.*, 2012; Chandrappa and Billigiri, 2016).

An issue of particular note that influenced the selection of the pavement layer parameters for this model was described in detail by Zhang and Guo (2014), namely, that if the pavement layer is 120mm or less and the time intervals for the model are greater than 30 minutes duration, then the infiltration rate through the permeable pavement layers is calculated incorrectly which is an identified flaw in the SWMM programme. Therefore, to avoid this occurrence, the pavement layer thickness was selected as 130mm (Table 6-11).

Table 6-11 The permeable pavement layer parameters.

Parameter	Value Selected	Reference
Thickness (mm)	130	Zhang and Guo (2014); Rossman (2015)
Void Ratio (Volume of voids/volume of solids)	0.16	Zhang and Guo (2014); Rossman (2015)
Impervious Surface Fraction	0	Rossman (2015)
Permeability (mm/hr)	2840	Hou et al. (2008)
Clogging Factor	58	Yong et al. (2008); Eyre and Bhalchandra (2014); Rossman (2015)

The clogging factor for the PP is an important component of this type of SUDS in the Jeddah-SWMM model due to the higher potential for airborne particulates, especially fine sand, in arid and semi-arid areas (Eyre and Bhalchandra, 2014). Due to the lack of implementation of permeable paving systems in arid and semi-arid areas, it means there is a lack of data available; therefore, some assumptions were made to determine the clogging factor. It was assumed that it would take a 20 year time period for the system to become completely clogged, based on the findings of several studies investigating the clogging of PP and the known issue of airborne particulates in the United Arab Emirates (Yong et al., 2008; Deo et al., 2010; Eyre and Bhalchandra, 2014). This was used in combination with the other assigned parameter values, using the equation available in Rossman (2015) for calculating the clogging factor.

The storage layer parameters were calculated on the basis of using a crushed stone/gravel layer aggregate layer as this is the most frequently utilised material for the storage layers of PP (Yong et al., 2008). The conductivity of the underlying soils has the potential to be variable due to the differences in their types (discussed in detail in Section 2.2.4). Therefore, values for the conductivity of underlying soils are provided for both clay soils and sand soils (Table 6-12).

Table 6-12 The permeable pavement, storage layer parameters.

Parameter	Value Selected	Reference
Aggregate Depth (mm)	300	Rossman (2015)
Void Ratio (volume of voids/volume of solids)	0..6	Rossman (2015)
Conductivity of Underlying Soils (mm/hr)	2.21 (Clay) 15.0 (Sand)	Rahman (2007)
Clogging Factor	0	Rossman (2015)

6.3 Calculating SUDS Lifecycle Costs

6.3.1 Introduction

Having designed the selected SUDS for this study and finding the cost estimation for each SUDS (through the survey findings, in Chapter Five), this section will deliver the method and parameters used for calculating the lifecycle cost

6.3.2 Methodology for Calculating SUDS Lifecycle Costs

The complexity of calculating the lifecycle financial cost of SUDS can vary depending on the parameters that are to be included in the cost calculation (Houdeshel et al., 2010). In the most simplistic format, a cost calculation could be considered as the absolute financial outlay for the required materials and construction of the SUDS, such as that presented by Duffy et al. (2008). However, if the financial cost of a SUDS is considered from a lifestyle perspective, there are additional parameters that must be incorporated into the calculation to ensure that an accurate estimate of the SUDS financial cost is produced, such as ongoing maintenance and operation costs (Wolf et al., 2015). Thus, an estimate of the financial outlay that would be required over the lifecycle of a SUDS should include the following parameters:

- Material costs
- Construction cost
- Maintenance and operational cost on an annual basis
- Land purchasing costs

The fourth factor, land purchasing costs, will not be a consideration for all forms of SUDS systems. This is due to the fact that, in some instances, SUDS will be replacing existing drainage systems, or the land is already owned by those implementing the SUDS. Similarly, there may be no land purchase costs when the SUDS is retrofitted into an existing structure, such as the construction of a green roof on an existing building (Lamond et al., 2015). However, in some instances, depending on the type of SUDS to be retrofitted, there may be land purchasing costs, such as in the case of swales, in comparison to traditional drainage systems (Lamond et al., 2015). Whilst these examples will not incur land purchasing costs, the construction costs are likely to vary when a SUDS is incorporated into the initial building/area construction, as opposed to retrofitting.

Therefore, for estimating the overall financial cost of each SUDS type, the following equation is suggested:

$$FC = Capital\ cost + \sum_{t=1}^{N}((maintenance\ \&\ operational\ cost)_{*}A)$$

$$FC = LP + (M * A) + (C * A) + \sum_{t=1}^{N}(U_t * A) \quad (6\text{-}1)$$

where: *FC* is Financial Cost
LP is Land Purchase Price
M is Materials cost per m^2
A is Area of SUDS in m^2
C is Construction cost per m^2
N is Number of years
U is Upkeep and operation (or maintenance & operational) cost per m^2 per year

The initial capital costs, in general, include the land purchase cost, material cost and construction cost (labour, permits site preparation, etc.). Also, maintenance cost includes replacement of any damages and operational cost in such arid region includes irrigation and cutting of grass. The number of years (N) is included within the financial cost calculation as it is not possible to calculate the maintenance costs for an infinite time period. The inclusion of the number of years will allow the maintenance costs over the estimated lifetime of the SUDS to be calculated.

Whilst equation 6-1 considers all the direct financial costs incurred by a SUDS over the course of the lifecycle, some studies have suggested that estimates based purely on the incurred financial costs do not accurately portray the overall cost of a SUDS (Fisher-Jeffes and Armitage, 2011). This arises because the use of SUDS can also have benefits in terms of reductions in social and environmental costs that would be otherwise incurred with the use of a traditional drainage system, such as a decrease in the occurrence of flooding with SUDS thereby resulting in a decreased flood clean-up cost. Fisher-Jeffes and Armitage (2011) refer to these financial benefits of SUDS as 'Damage Avoidance Costs'. It is not, however, just an avoidance of environmental and social degradation that can affect the overall cost estimate of SUDS; Chow et al. (2014) highlight that some SUDS can result in financial cost savings from other aspects, for example, the use of a green roofing system can improve a building's insulation and, therefore, result in reduced heating and cooling expenditure.

The inclusion of financial benefits within a lifecycle cost analysis of a SUDS can arguably present a more accurate portrayal of their true cost; this is typically referred to as a cost benefit analysis (Jarvie, Arthur and Beevers, 2017). Although the inclusion of reductions in indirect financial costs will not impact the overall capital outlay for the SUDS implementation, it will offset the overall financial costs. However, the inclusion of areas of financial benefits can potentially be difficult within a lifecycle cost analysis. This is due to the differences in the potential benefits of each type of SUDS and the complexity of quantifying these benefits in monetary terms in addition to who is benefiting (Melville-Shreeve et al., 2018). For example, if a city council installs a SUDS in a housing area that is prone to flooding, resulting in a significant reduction in the occurrence of flooding events, then it is likely that the houses will increase in value (Chow et al., 2014). However, when the city council is attempting to quantify the lifecycle costs of the SUDS options, the financial benefit of housing value increases is not of benefit to the council, but rather to the homeowners and, therefore, should not be included within the financial cost analysis. It can thereby be identified that the inclusion of SUDS benefits within lifecycle financial cost calculations will be highly variable and dependent on the situation under consideration. Additionally, it can be argued that, as these financial benefits are hypothetical and not guaranteed to be realised over the lifespan of the SUDS, the inclusion of these factors within the calculation of SUDS lifecycle cost would provide a skewed estimation of the financial cost of a SUDS (O'Donnell et al., 2017).

In addition, since the cost estimation of SUDS changes according to the market price and differs from country to country and varies from time to time, an inflation rate is included in Equation 6-1. This will, then, give a more accurate estimation cost for this study. Therefore, Equation 6-1 is updated to be as the following:

$$\boldsymbol{LCFC} = LP + (M * A) + (C * A) + \sum_{t=1}^{N}(U_t * A) * (1 + \frac{IR}{100})^t \quad (6\text{-}1)$$

Where: IR= Inflation rate

The average inflation rate for the KSA, for the last 40 years, was found to be 1.5% per year, which is selected and applied for this study (Worlddata, 2019). The lifespan of a SUDS, for this study, is assumed to be 25 years, which is in line with different SUDS design guidelines, such as CIRIA (2019), Gardenista (2020) and Geosmart (2020).Table 6-13 shows the calculation of lifecycle cost for the different SUDS options.

Table 6-13 The total lifecycle cost calculations for each SUDS option, including inflation rate. All calculations were based on 1m^2 of SUDS surface area (A=1) & 25-year lifespan).

Clause		**LC per1m2 (Inflated)**
Green Roof (GR)	*New*	*$1,056*A*
	Retrofitted	*$1,034*A*
	% Difference	2.2
Permeable Pavement (PP)	*New*	*$583*A*
	Retrofitted	*$553*A*
	% Difference	5.1
Rain Garden (RG)	*New*	*$1,108*A*
	Retrofitted	*$1,098*A*
	% Difference	0.9
Bio-Retention (BR)	*New*	*$1,130*A*
	Retrofitted	*$1,122*A*
	% Difference	0.7

6.3.3 The SUDS Layout and Total Lifecycle Cost Calculation

The process by which the potential area and maximum unit number for each SUDS type and subcatchment were determined for inclusion in this study is outlined in the following section and includes the determination of the potential percentages of each type of SUDS which would be permitted as a maximum. The layout for implementing selected SUDS types into the subcatchments of the selected case study watershed was based on the various assumptions /considerations that were explored in depth in Section 6.2 and are summarised as follows:

- PPs: were assumed to be applied into all public sidewalks and pathways in public gardens, based upon the findings of the literature review and section 6.2.4 whereby the majority of published studies supported the inclusion of these SUDS type in these common urban areas.
- RGs: were assumed to be applied on 70% of all residential and public garden/park spaces. This relatively high maximum was determined due to a lack of appropriate open space in urban areas where rain gardens could be applied. By maximising the application of RGs in what space is available it maximises the potential contribution of the SUDS type.
- BRs: were established over 15% of all public park spaces and the landscape; and residential subdivision lots or commercial lots which are preferable locations for bioretention (Bioretention Design Specifications and Criteria, 2018)
- GRs: two different options for implementation were considered and examined both options are detailed in depth in section 6.2.1) Where GRs are permitted it was determined that a maximum of 75% of a rooftop could be utilised for the SUDS application, the remaining 30% of the rooftop would be kept clear to allow for access for maintenance.
- Because 86% of the selected study area is developed, the total cost is calculated based on the assumption that all SUDS are retrofitted into the existing infrastructure. An additional aspect which was included when calculating the costs of SUDS implementation and maintenance over time was to include inflation as a factor which increased the costs over time.

The calculated total potential area and maximum unit number for each SUDs type and subcatchment are given in Tables 6-14 & 6-15 for GR options 1 & 2, respectively. The possible

ranges for the SUDS numbers were calculated by dividing the maximum possible area of each SUDS type by the considered unit area for each type: 25m^2 (10m LX 2.5 m W) for BRunits, 100 m^2 (10m LX 10 m W) for both GRs and RGs and 80m^2 (20m LX 4 m W) for PPs. The areas which were selected for the maximum possible areas were determined from the consultation of a detailed aerial map of the study area. This allowed for an examination of the typical plot areas which would be available in the existing urban environment and, therefore, what would be the available space constraints, thereby placing the maximum area constraints when retrofitting SUDS solutions. In addition, based on the findings of Tables 6-14 & 6-15, the total Lifecycle Cost can be calculated through multiplying the SUDS surface area for each SUDS option with the values in Table 6-13. Further details about SUDS implementation scenarios and cost function within the SUDS-optimisation-framework are given in Chapter Seven. Also, the results of SWMM model for SUDS types and comparison of these results with the baseline data (without SUDS) are conducted and presented in Chapter Seven.

Table 6-14 Maximum number of each type of SUDS in each subcatchment for option one (Green roofs only on commercial and governmental roofs)

Sub-catchment	Area (m2)	GR			RG			BR			PP			Total area of possible Applying SUDs (% of Area)
		Area (m2)	% of Area	No. range	Area (m2)	% of Area	No. range	Area (m2)	% of Area	No. range	Area (m2)	% of Area	No. range	
S1	284100.0	17722	7.0	0-177	X	X	X	6542.3	3	0-262	21744.6	8.6	0-272	18.1
S2	433855.2	43572	10.0	0-436	X	X	X	14549.3	3	0-485	61772.4	14.2	0-772	27.6
S3	360664.3	18104	5.0	0-181	X	X	X	12836.2	4	0-513	43445.8	12.0	0-543	20.6
S4	248041.3	10418	4.2	0-104	X	X	X	8196.8	3	0-328	29324.4	11.8	0-367	19.3
S5	542196.9	12425	2.3	0-124	X	X	X	19837.4	4	0-793	62078.2	11.4	0-776	17.4
S6	795727.0	77845	9.8	0-778	X	X	X	21182.5	3	0-847	93069.0	11.7	0-1063	24.1
S7	416922.5	13627	3.3	0-136	X	X	X	8937.6	2	0-358	53389.8	12.8	0-667	18.2
S8	572752.5	11496	2.0	0-115	X	X	X	9755.4	2	0-390	61213.6	10.7	0-765	14.4
S9	131957.0	248	0.2	0-2	X	X	X	4557.5	3	0-182	14914.0	11.3	0-186	14.9
S10	138430.0	472	0.3	0-5	X	X	X	4386.5	3	0-175	15756.3	11.4	0-197	14.9
S11	41200.5	X	X	X	12503	30	125	616.4	1	0-25	4259.7	10.3	0-53	42.2
S12	888494.0	109243.3	12.3	0-1092	38612.3	4.3	386	31820.4	4	0-1273	84816.2	9.5	0-1060	29.8
Total	4854341	315173	6.5	0-3152	51115	1.1	511	143218	3	0-5632	545784.0	11.3	0-6822	21.9

Table 6-15 Maximum number of each type of SUDS in each subcatchment for option two (GR on commercial and governmental roofs + 20% of private homes)

Sub-catchment	Area (m2)	GR			RG			BR			PP			Total area of possible Applying SUDs (% of Area)
		Area (m2)	% of Area	No. range	Area (m2)	% of Area	No. range	Area (m2)	%of Area	No. range	Area (m2)	%of Area	No. range	
S1	284100.0	28493	11	0-285	X	X	X	6542.3	3	0-262	21744.6	8.6	0-272	22.4
S2	433855.2	66958	15	0-670	X	X	X	14549.3	3	0-485	61772.4	14.2	0-772	33.0
S3	360664.3	38264	11	0-383	X	X	X	12836.2	4	0-513	43445.8	12.0	0-543	26.2
S4	248041.3	27755	11	0-278	X	X	X	8196.8	3	0-328	29324.4	11.8	0-367	26.3
S5	542196.9	53169	10	0-532	X	X	X	19837.4	4	0-793	62078.2	11.4	0-776	24.9
S6	795727.0	108292	14	0-1083	X	X	X	21182.5	3	0-847	93069.0	11.7	0-1063	28.0
S7	416922.5	47913	11	0-479	X	X	X	8937.6	2	0-358	53389.8	12.8	0-667	26.4
S8	572752.5	55123	10	0-551	X	X	X	9755.4	2	0-390	61213.6	10.7	0-765	22.0
S9	131957.0	11330	9	0-113	X	X	X	4557.5	3	0-182	14914.0	11.3	0-186	23.3
S10	138430.0	10032	7	0-100	X	X	X	4386.5	3	0-175	15756.3	11.4	0-197	21.8
S11	41200.5	X	X	X	12503	30	0-125	616.4	1	0-25	4259.7	10.3	0-53	42.2
S12	888494.0	109243.3	12.3	0-1092	38612.3	4.3	0-386	31820.4	4	0-1273	84816.2	9.5	0-1060	29.8
Total	4854341	556574	11.5	5566	51115	1.1	511	143218	3	0-5632	545784.0	11.3	0-6822	26.9

Chapter Seven: Selection and Placement Optimization of SUDS in the Jeddah Study Watershed

7.1 Overview

The purpose of the multi-objective optimisation process is the identification of the pareto-optimal front which represents trade-offs between the objectives of the simulation, namely, surface water runoff peak and flow volume and total cost as a result of implementing a set of SUDS solutions in the watershed. The goal is to identify optimal solutions that reduce the surface runoff peak flow/volume whilst minimising the financial outlay. The trade-off of these objectives is represented in the format of cost-benefit curves which could then form the basis of planning decisions by facilitating sustainable decision making and strategies for stormwater management in arid and Semi-Arid urban regions. The decision variables, which are number of each SUDS option in each subcatchment identified in Section 7.2.3, are incorporated in the SWMM input file. The identified solutions are evaluated through fitness functions using the SWMM model with the incorporation of the cost functions (the Borg MEOA). Thus, when the SWMM model is linked to Borg, a feedback process is created whereby at each iteration, Borg alters some of SWMM's input parameters, which are number of each SUDS option in each subcatchment, and in turn receives outputs from the SWMM model which it uses for evaluating the objectives, thereby converging towards optimised solutions through the evaluation of the objectives. In the following sections, the optimisation methodology is presented followed by an overview of the investigated SUDS scenarios. Finally, the results of applying the SUDS-optimisation-framework to the study watershed are presented and discussed. In this chapter, analyses were performed to identify the optimal SUDS solutions under different scenarios with varying type of SUDS options permitted.

7.2 Optimisation Methodology

7.2.1 Layout of Optimisation Simulation Framework

The SUDS-optimisation-framework is comprised of two components; the Jeddah-SWMM model (chapter Four) and the Borg optimisation algorithm (Section 2.9). A link between the two components was made to establish a feedback process whereby Borg was able to alter the parameters within the SWMM model in an iterative process to attain optimum outcomes. The link between SWMM and Borg is a complete loop whereby the Borg evaluates the solutions identified by SWMM and feeds the results of the evaluation back to the SWMM model so solutions can be optimised. The SUDS-optimization-framework was developed in MATLAB,

linking the SWMM input file, which includes watershed characteristics and SUDS options, i.e number of each selected SUDS type in each subcatchment, and Borg that includes many components including objective functions such as the SUDS cost function. Once developed, the optimisation framework was applied to optimise the selection and placement of SUDS for the Jeddah study atershed. This optimisation is done through constantly changing the SWMM input files. The fitness functions evaluate the "goodness" of each identified solutions through taking the decision variables as inputs and calculating objective values. The fitness functions are evaluated from the outputs of the SWMM model and the use of cost functions defined in section 7.2.2 (Eq.7-3), (The codes for SUDS-optimisation-framework are attached in appendix D).

A diagrammatic representation of the developed SUDS-optimisation-framework is given in Figure 7- where the process of essential data flows between Borg MOEA and SWMM is detailed. Figure 7-2 is an expanded diagram that depicts more details of the procedures and calculations within the SUDS-optimisation-framework. The updates to the SWMM input file were achieved through the use of read-write functions that parse the input file and subsequently affect changes to the portions of the input file which were targeted. The parsing functions account for the Borg decision variables, arrays of subcatchment properties and arrays of unaltered subcatchment parameters which are used to calculate the correct values which should be written into each string which is targeted in the SWMM input file (attached in Section B-2, Appendix B).

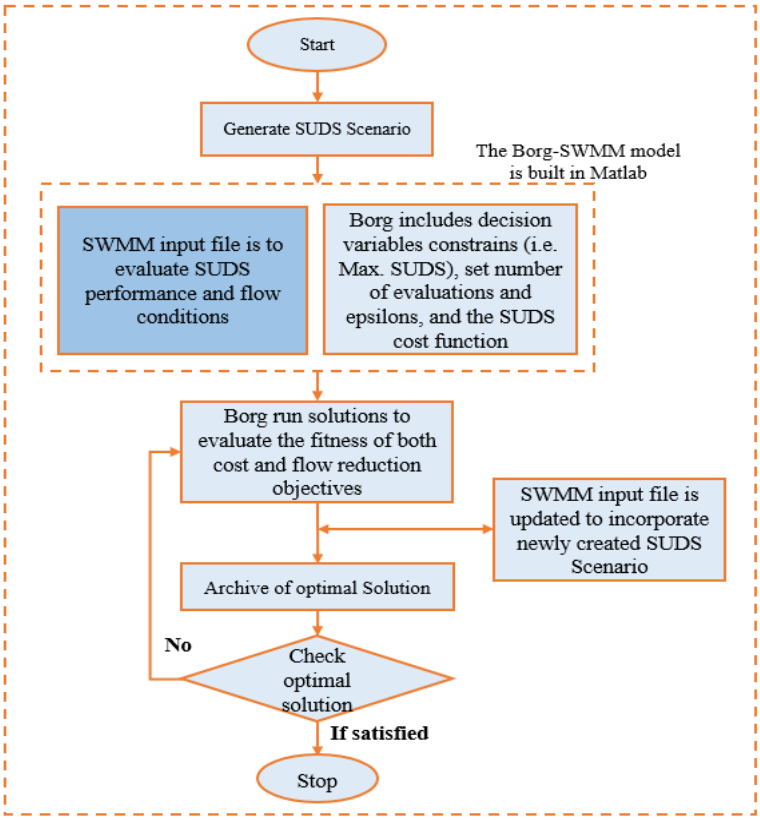


Figure 7-1 Borg-SWMM model framework showing the pathways of data flow between the two combined components.

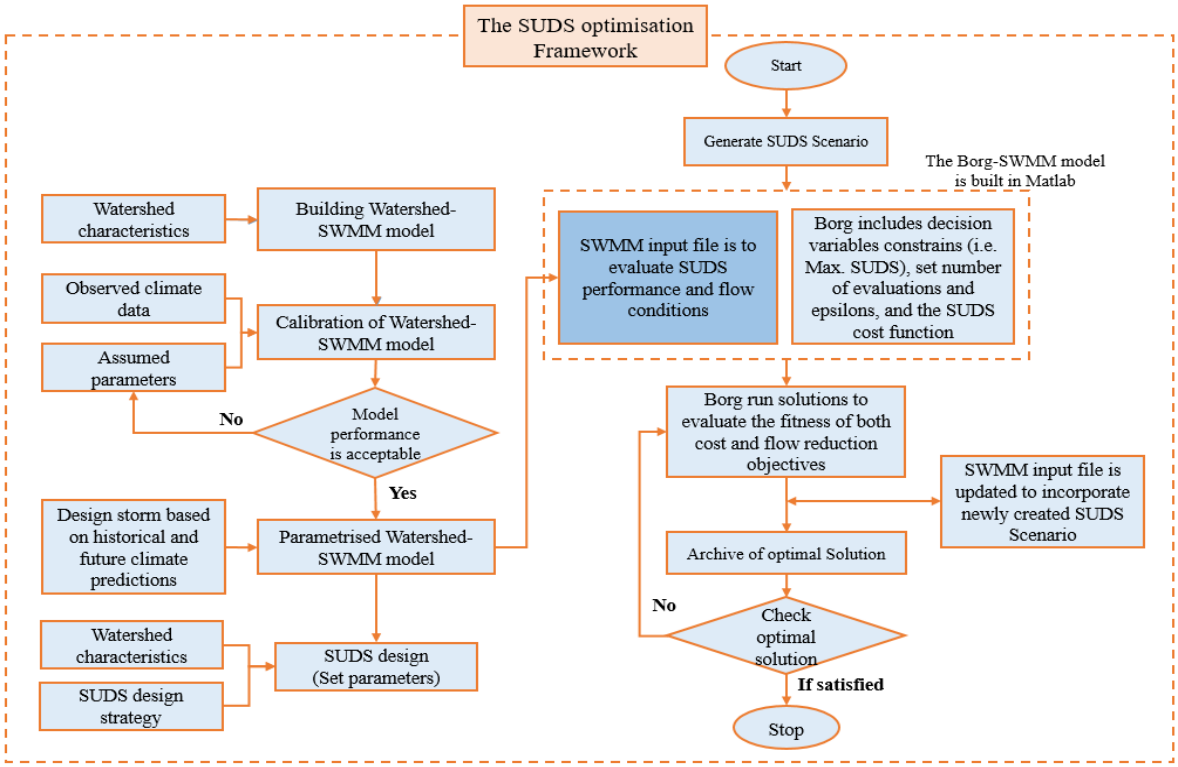


Figure 7-2 The SUDS-optimisation-framework

7.2.2 Objective Functions

The objective functions within Borg represent the overall goals of the optimisation process. The objective functions considered initially were:

1. Minimisation of stormwater peak flow at the outlet of each subcatchment,
2. Minimisation of flow volume at the outlet of each subcatchment, and
3. Minimisation of the total financial cost.

The objectives were carefully selected to ensure that the optimisation outcomes, i.e. selected SUDS solutions, were beneficial across the entire study catchment. This was to ensure that solutions which reduced the potential for flooding in a specific subcatchment did not have the undesirable impact of increasing the potential for flooding occurrence in an adjacent subcatchment. Thus, the objective functions selected were the reduction of the peak flow and the flow volume across the whole catchment. Essentially, the selection of these objectives ensures the most favourable outcome for the whole catchment not solely for targeted subcatchments that had been identified as vulnerable to flooding.

The flow volume and peak flow are mostly linked, as a higher flow volume will typically result in a higher peak flow due to the increased volume of water flowing through the catchment; nevertheless, they were initially kept as separate objectives. This was to facilitate the interpretation of the results and avoid confusion which could potentially arise if the two were interlinked. Combining runoff volume and peak flow objectives would require their normalisation and weighting which makes the objective values in the output more complex.

The factors which influence flow volume and peak flow are summarised as:

$$min \sum_{t=0}^{e} \sum_{s=1}^{n} \mathrm{Rn}_s^t \tag{7-1}$$

Where Rn_s^t = total runoff volume from the subcatchment s at time point **t** (***e*** which is the end of the simulation) and n is total number of subcatchment.

$$min \sum_{t=0}^{e} \sum_{s=1}^{n} \mathrm{Q_P}_s^t \tag{7-2}$$

Where Q_p= the maximum flow rate (peak flow).

The cost of SUDS is a function of the type of SUDS in the selected solution and their unit size and number within each subcatchment. To determine the total cost, the following equation was used:

$$min \sum_{s=1}^{n} \sum_{i=1}^{m} C_s^i (Z, N) \quad (7\text{-}3)$$

Where C_s^i is the cost of SUDS type **i** in subcatchment **s**, *Z* is the SUDS unit size (m^2), *N* is the number of SUDS units in a given subcatchment and m is total number of SUDS types. The cost of each SUDS type was determined based on the the Equation (6-1) as detailed in Section 6.2.

7.2.3 Decision Variables

The selection of decision variables was a key aspect of the SUDS-optimisation-framework. Decision variables is the term applied to factors which can potentially influence the outcome of the simulation and represent a moment where a decision has to be made, for example, the diameter of the stormwater drainage pipe (Park *et al*., 2012). Thus, the greater the number of decision variables included in the model, then the greater the level of detail and control over the simulation scenario. There is an advantage of including a relative high number of decision variables within a model. However, the disadvantage is that this would require more complex coding for linking Borg MOEA to the SWMM model. Furthermore, this would introduce increased difficultly in convergence to a Pareto-optimal front, as it would increase the parameter space size and consequently the computational time. This would subsequently result in an increased possibility of having evenly spaced good solutions with different sets of variables, thus, a lack of uniqueness in the identified solution. Therefore, to balance the positives and negatives of having a high number of decision variables it was decided to only include decision variables associated with the type of SUDS solutions and their numbers within each subcatchment. It was felt that this selection of decision variables provided sufficient information to explore potential solutions whilst also increasing the likelihood for Borg to adequatly explore the solution space and converge to the Pareto-optimal front within a reasonable timeframe.

For the study watershed, which contained 12 subcatchments, 37 decision variables were considered. Only one subcatchment, S12, was deemed suitable to accommodate all 4 type of SUDS considered within this study, i.e. GRs, RGs, PP and BR. Due to limitations imposed by existing infrastructure and land avaialbility, determined from land use map analysis, subcatchments S1 to S10 were considered to only have three SUDS types: GRs, PP and BR. Finally, S11 which is a less developed subcatchment was considered to have RGs instead of GRs. The values determined for the maximum possible number of SUDS that could be selected for each subcatchment, i.e. lower and upper bounds of the search space, were stored in arrays (see Tables 6-14 & 6-15) and used in the Matlab code.

7.2.4 Parameter Settings for the Optimisation Process

Borg has multiple internal parameters that can potentially be altered to make it more efficient in finding optimum solutions (see section 2.9). Therefore, the first step in using the algorithm was to set the internal parameters of Borg. This was achieved through testing different combinations of internal parameters in an iterative process to identify the optimum values that should be used. Based on the findings of similar studies (e.g. Zhang, 2009; Eckart *et al*., 2018), it was determined that not all parameters needed to be changed from the default values for this study.

The final aim of multi-objective search algorithms such as Borg is to identify a range of highly diverse solutions on the pareto-optimal front. The two factors that were deemed highly influential on the convergence to a diverse Pareto-optimal front, were the epsilon factor and number of evaluations conducted (Zhang, 2009; Eckart *et al*., 2018). To determine the optimum value for these parameters, a range of epsilon values and number of evaluations were selected from similar studies in the literature (Table 7-1). Test simulations were then conducted to determine the optimum values to be used in this study. The test simulations were conducted under the different scenario conditions given in Table 7-1. In each subsequent tested simulation scenario, the evaluations number was changed (evaluations numbers used were 100, 500, 1000, 5000, 10000 and 20000) which were tested for each epsilon (0.2, 0.1, 0.01. 0.001 and 0.0001).

Table 7-1 Range of Borg internal parameters tested for this study

Parameters	Tested	Default	Note
Epsilon values	0.2, 0.1, 0.01, 0.001. .0001	.01	After testing each epsilon value with changing all selected number of evaluations (100 to 20000), 0.01 was selected due to the resendable accuracy and a good number of generations, therefore selected and default for this study
Number of evaluations	100, 500, 1000, 5000, 10000, 15000 and 20000	10000	By comparing the Pareto front curves between the different number of evaluations and epsilons, 10000 evaluations were found to give near optimal solutions (identified by convergence on the Pareto-optimal front) and there is no big change between 10000 and 20000, therefore selected 10000 for this study for all scenarios.

In Figure 7-3, the outcome of test simulations with same epsilon values and varying number of evaluations is given. It is evident that as the number of evaluations increases, so does the conversion of a more dominant pareto-optimal front. It can be seen that there is a large improvement in the quality of the obtained Pareto fronts, in terms of number and density of converged solutions, when 5,000 or more functional evaluations are considered. However, convergence to a dominant pareto optimum front appears to occur when the number of functional evaluations falls between 10,000 and 12,500; this is similar to the findings of Zhang (2009) and Eckart *et al.*, (2018). Increasing the number of evaluations beyond 12,500 does not improve the findings as beyond this point, as there are no longer solutions being identified that can be classified as more optimal. Thus, it was determined that using 10000 functional evaluations would be sufficient to ensure that the pareto-optimal solutions were identified.

The values of the epsilon parameter impact the resolution of the Pareto optimum front. Thus, higher epsilon values mean a coarser resolution which will decrease the distance separating the identified solutions (in this instance distance is an objective term measuring between two plotted solutions). In Figure 7-4, the results of simulations using 10,000 functional evaluations with variable epsilon values are shown. There was little variation identified in the convergence shown by use of the different epsilon values, therefore, it was determined that an epsilon value of 0.01 would provide sufficient resolution for the purposes of this study. An epsilon value of 0.01 was also supported by other studies (Zhang, 2009; Eckart *et al.*, 2018). Thus, it was concluded that the use of 10,000 functional evaluations and an epsilon value of

0.01 should enable the pareto-optimal front to be identified with a suitable diversity of potential solutions. These default settings selected are summarised in Table 7-2.

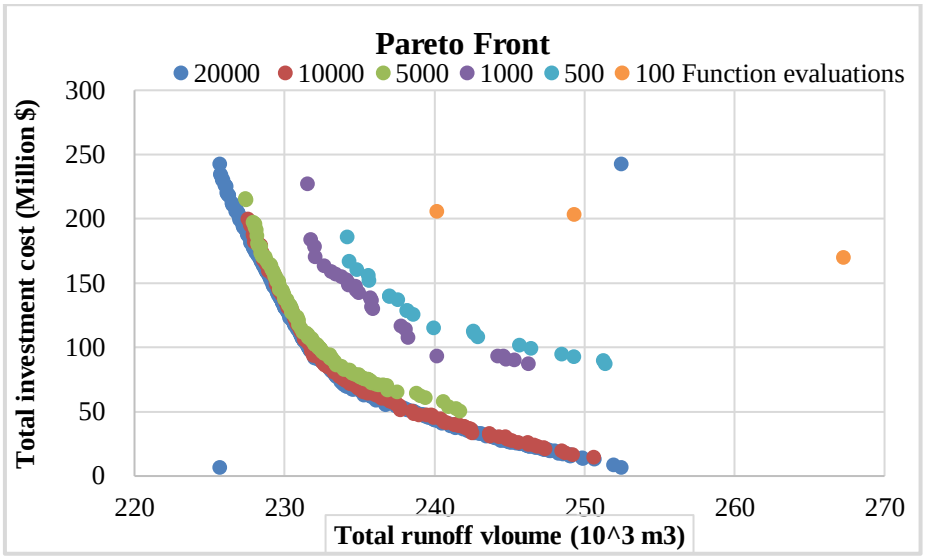


Figure 7-3 Comparing between different numbers of function evaluations and using an epsilon value of 0.01.

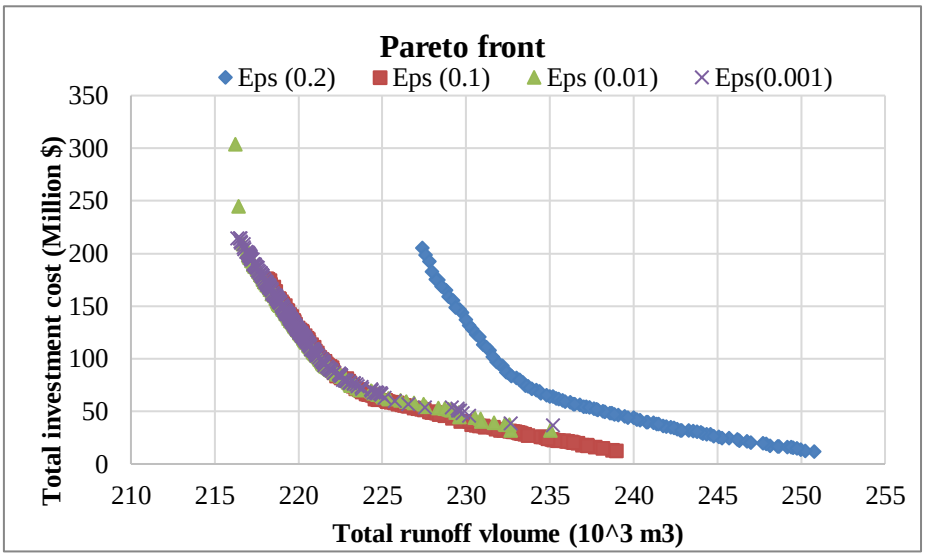


Figure 7-4 The comparison between the outputs for epsilon values of 0.2, 0.1, 0.01 and 0.001 with 10,000 function evaluations.

Table 7-2 Parameter settings (defaults for this study) for the SUDS optimization framework

Parameters	Value
Epsilon	0.01
number of function evaluations	10,000
Average maximum generations per run	400
Average minimum generations per run	30

7.2.5 Verification of Optimisation Framework

To ensure that the optimisation system was functioning in an appropriate manner, two methods were used to verify the functioning of the framework. The first verification process was conducted when the SWMM input files were linked to Borg. Trial runs were conducted, and the outputs were manually checked to ensure that the linkage had been conducted properly and thus the SWMM input files were being correctly updated from the outcome of the Borg results. The second verification process involved running a scenario in SWMM using the values provided by Borg. At the end of a test run, some of the optimal solutions which created archived outputs were selected for cross-checking. The decision variables which were contained within these outputs were subsequently applied for use in a single test run of the SWMM model to ensure that the surface runoff and peak flow values which were output by the model were correct.

Table (7-3) gives the outcomes of conducting a simulated scenario (a made up scenario) in SWMM and its comparison with the outcomes of a known scenario (a scenario which has occurred in reality), in this instance, using a *6-hour 2-year rainfall as input rainfall and considering SUDS option 1* (scenarios defined in section 7.3.2). It was found that the difference between the simulated outcomes and the actual outcomes were very similar, differing by 0.85% for rainfall volume and 0.9% for peak flow rate. This suggests that the modelled outcomes are good agreement with what would occur in reality and indicate that the margin of error will be low.

Table 7-3 The outcomes of the known 6-hour 2-year rainfall and SUDS option scenario in comparison to the simulated outcome from the same scenario run in SWMM.

	Result of optimal SUDS Solution	Running a scenario in SWMM	Difference in %
Runoff volume (m3)	64780	65330	0.85%
Peak flow (m3/s)	10.3	10.74	0.9%

7.3 Development SUDS optimisation scenarios for the Jeddah study watershed

Different SUDS scenarios were tested by the SUDS-optimisation-framework to assess the effect of varying conditions, i.e. climate conditions and implementation constraints, on the optimum SUDS solutions. The comparison of the outcomes of different scenarios aids in providing a more thorough understanding of how SUDS influence performance under different conditions. four different design storms, based on historical climate data, with a duration of 6 hours, and return periods of 2 years, 10 years, 25 years, 100 years were considered. Two other design storm with a 100-year return period, modified based on projections of future climate change (CC) were also considered.

7.3.1 Design Storm and Climate Change

7.3.1.1 Development of Design Storms

The design storms were generated using intensity-duration-frequency (IDF) curves based on historical recorded data. The IDF curves were sourced from AECOM's Jeddah stormwater programme (AECOM, 2014) (Figure A-3 in appendixes A). The IDF curves were obtained using rainfall data collected from stations located around Jeddah City (Section 3.4.2). The analysis of rainfall data showed an average storm duration of approximately 3.8 hours and a maximum duration of 11 hours. The most noticeable historic events were the 2011 flood event that lasted for 3.5 hours and the 2009 event that lasted for 3 hours (Yousef et al., 2016; AECOM, 2014). In addition, the majority (94%) of the limited sub-daily rainfall data available indicated that storm events are less than 6 hours (AECOM, 2014). Therefore, selecting storm durations longer than 11 hours would conflict with the observed local data and have the effect of lowering intensities and runoff, thereby potentially underestimating the flood risk.

Thus, a critical design storm of 6 hours duration was selected as it is longer than the average storm duration and the majority (94%) of available data, and accounts for the possibility that longer storms can occur. In addition, six hours suggested by AECOM (2014) as the worst time for flooding and period of high-water flow was after the commencement of the rainfall event. As this was determined to be the critical time period for flooding in Jeddah City it was determined that this would be an appropriate design storm duration for the simulations. Thereby allowing identified solutions to address the most critical time point (being the time point at which flooding is most likely to occur) for potential flooding events to occur.

In order to develop IDF curves it is necessary to know what the total rainfall depth would be for alternative durations for different return period events. The daily annual maximum series of rainfall depth for both J134 and 41024 stations were analysed and used to create IDF for different return periods by AECOM (2014). The use of the IDF curve allowed the calculation of six-hour rainfall events, design rainfall depths are consequently available for the one, two, three, four, five, and six hour storm events. Since the six-hour storm depth is based upon an analysis of daily data, the same depths would be adopted for the twenty four hour event (AECOM, 2014).

The alternating block method developed by Chow et al., (1988) was applied to the IDF curves supplied by AECOM to change the depth duration data into a designed rainfall. The Alternating block method constitutes an easy means of creating a design storm from an IDF curve. Design storms resulting from this system denote the depth of rainfall that occurs at "n" successive time intervals of duration (Δt) over a total duration ($Td = n * \Delta t$). Working from the design return period, the intensity of rainfall was infered from the IDF curve/relation for every duration (Butler and John, 2011). The hyetograph denotes rain with a definite return period and a length of rainfall that is the same as or lower than Td. Additionally, when the duration of rainfall is lower than Td, the section of the hyetograph that will be used is the central segment, with the rainfall length of Td (Behbahani, 2009). However, for the study watershed, an examination of a storm hyetography for a rainfall duration of 6 hours highlighted that the majority of the rainfall occurred within the first 1.5 hours of rainfall onset (AECOM, 2014). Therefore, the second hour of the 6-hour Design Storm was selected and used as a central segment, i.e. the segment which experiences the peak flow. In Figure 7-5, the generated rainfall hyetographs for selected design storms of different return periods used in this study are shown. 2, 10, 25 and 100 year return period design storms were selected for this study as they provide an overview of the performance of SUDS solutions over different timescales. This has important implications for cost effectiveness as it provides information on the short and long-term costs of SUDS solutions, thus these return periods are frequently used in similar studies evaluating SUDS solutions.(Zhang, 2009; Giacomoni and Joseph, 2017; Eckart *et al.*, 2018).

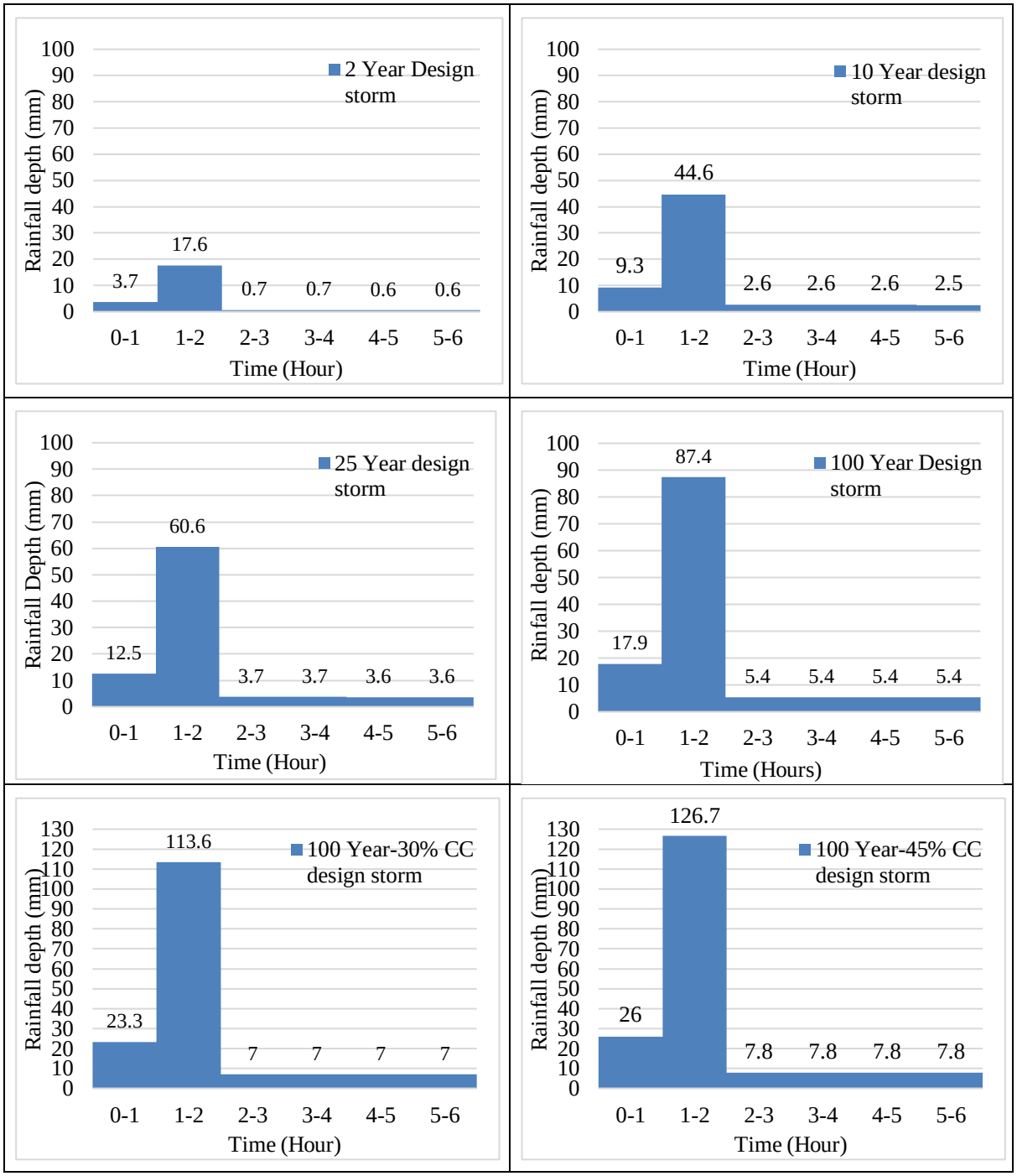


Figure 7-5 The rainfall distribution hyetographs for the 6-hour design rainfall event for the 2-year, 10-year, 25-year, 100-year, 100-year + 30% CC and 100-year + 45% CC scenarios, developed by applying the alternative block method

7.3.1.2 Climate change (CC)

The future rainfall under CC scenarios is a necessary component that should be included when developing sustainable stormwater management systems (Brown *et al*., 2009). This means that the design and scope of the implemented system should be sufficient to cope with the current level of rainfall and the predicted future rainfall (Arisz and Burrell, 2006). The predicted and observed impact of CC on rainfall patterns is not consistent globally, therefore, the influence of CC on rainfall patterns is likely to be highly variable with location (Trenberth, 2011). However, an extra complication is that there is a variability in the predictions for CC impacts on precipitation patterns (Hasanean and Almazroui, 2015). Jeddah City is no exception and there is substantial disagreement between studies regarding how rainfall patterns in Jeddah will be influenced by CC (Donat *et al*., 2014).

An example of the extent of this disagreement was highlighted in a report published by the KSA Meteorological Office (2011) highlighting the lack of detailed studies conducted in Saudi Arabia and the fact that where studies had been conducted, some suggested that the flood risk will increase, whilst other studies suggested that it will lessen (Meteorological Office, 2011). Similar studies have also indicated that changes in precipitation in the Jeddah City area are likely to see increased rainfall and increased rainfall intensity under future CC; for example, Subyani and Hajjar (2016) suggest that the rainfall in the rainy season is increasing in intensity. When examining the historical rainfall data for the Jeddah City area, Subyani and Hajjar (2016) found that there was a variation in the trends observed at different weather monitoring stations in the area, for instance, an urban monitoring station located in Jeddah City was found to have a trend of increasing rainfall at the rate of 1.09 mm per year (based on data from 1971-2012). However, a monitoring station in the mountains surrounding Jeddah City was found to have a decreasing rainfall trend over the same time period (Subyani and Hajjar, 2016). When examining rainfall pattern changes and rainfall intensities, Subyani and Hajjar (2016) observed that whilst there is no trend for an increasing length of rainfall, there is a general trend indicating that the intensity of rainfall is increasing.

One of the contributing factors to the debate on future rainfall in Saudi Arabia stems from the use of different climate models to generate predictions. For example, a study by Almazroui *et al*., (2017) compared the outputs of multiple (3) different models to the same set of historical precipitation data for the Arabian Peninsula. It was found that whilst the three

models produced similar predictions in terms of the spatial variation in future precipitation, there was a high degree of variation between the models with regards to the magnitude of the predicted precipitation changes (Almazroui *et al*., 2017). The degree of difference between the three models was significant, two of the models predicted precipitation variations of between -30 and +35% for the near and far future (2021-2050 and 2070-2099 respectively), whereas the third model predicted precipitation changes of -30 to +70% for the near future and -30 to +100% for the far future (Almazroui *et al*., 2017). When developing a stormwater management system that will be sustainable and functional under future CC scenarios, the variation in precipitation changes between different models can potentially be problematic as seen in Almazroui *et al*., (2017); this is because there will be a substantial difference in developing a stormwater management system that will be able to cope with a +35% increase in precipitation in comparison to the development of a system that can cope with a +100% increase in precipitation.

However, the cost of the stormwater management system should be considered as well, as the predictions of rainfall under future CC are uncertain, the validity of designing a system that could cope with, for example, a 100% increase in rainfall could be difficult to justify from a financial perspective. Therefore, it was determined that a predicted rainfall cumulative depth increase of 30% and 45% should be applied to the designed storm developed from the IDF curve (see Figure 7-5). These increases were determined to be reflective of the likely scenarios to occur in Jeddah City under future CC as these rainfall increases were found to be common to several research studies extrapolating potential future rainfall under CC. The rainfall increases of 30% and 45% were chosen to reflect that there is a degree of uncertainty in the predictions of future rainfall increases, therefore the inclusion of two scenarios with different predicted rainfall increases incorporates this degree of uncertainty into the research study.

7.3.2 SUDS Implementation Options

Three distinct SUDS implementation options, representing logistic constraints, were examined in this study. Throughout all the considered options, PP, BR and RG were permitted without restriction, thus, what was varied between the three scenarios was the permitted area of GR inclusion. Throughout all options SUDS placement is referred to by the nature of the buildings upon which they are permitted, this also includes the surfaces in immediate proximity to the building which is considered as part of the building property.

- SUDS option 1 – Applied GRs to all commercial and government buildings
- SUDS option 2 – As above + 20% on residential buildings
- SUDS option 3 Not applied GRs to any building

In addition to these SUDS options, the SWMM model was also run without any SUDS options (the benchmark scenario). The purpose of conducting this benchmark simulation was to provide a reference base level benchmark which the reduction in flow volume and peak flow for each scenario could be compared against (see Table 7-5).

The different SUDS implementation scenarios were calculated on the basis of the data shown in Tables 6-14 & 6-15. As was noted earlier, the majority of subcatchments were deemed only suitable for three of the four SUDS types. This is due to the fact that the urban area of Jeddah city examined for this study is extensively developed, thus there was limited scope within the majority of the identified subcatchment for the establishment of RGs.

An additional SUDS options was considered to be retrofitting to existing land use as most of the area is already developed, approximately 86% of the study watershed is developed. This means that the majority of SUDS solution options will need to be able to be retrofitted into the existing urban infrastructure.

In Table 7-4 the details of the scenarios that were studied are presented, including the design storm, the SUDS option and the objective functions used for each simulation. Given the number of simulation scenarios that were conducted (18 in total), it was not feasible to report all simulation outputs. Instead, a number of scenarios that had relatively higher significance were selected to be presented in this chapter . In particular, the peak flow vs cost was only considered for Scenarios 1 and 5. This was decided due to the prioritising of determining the cost of reducing surface runoff and the logical assumption that a reduction in the surface runoff would subsequently also reduce the peak flow volume, therefore it was determined to be redundant to calculate the reduction vs cost for all scenarios for both the surface flow and the peak volume. This reduced the time required to conduct the scenarios whilst sill providing a valid and reliable outcome which could be used to inform the study conclusions. The relative significance was determined on the basis of what the simulation findings would mean in the context of SUDS implementation in Jeddah City. The simulations which are not presented here are included in the overall critical analysis and comparison of simulation outcomes.

Table 7-4 An overview of the scenarios that were studied.

Scenario	Design Storm	SUDS option	Objective function
Scenario #1	6-hour, 2-year rainfall	SUDS option 1	run off volume & cost; peak flow vs cost
Scenario #2	6-hour, 2-year rainfall	SUDS option 2	runoff volume & cost
Scenario #3	6-hour, 2-year rainfall	SUDS option 3	runoff volume & cost
Scenario #4	6-hour, 10-year rainfall	SUDS option 1	runoff volume & cost
Scenario #5	6-hour, 10-year rainfall	SUDS option 2	run off volume & cost; peak flow vs cost
Scenario #6	6-hour, 10-year rainfall	SUDS option 3	runoff volume & cost
Scenario #7	6-hour, 25-year rainfall	SUDS option 1	runoff volume & cost
Scenario #8	6-hour, 25-year rainfall	SUDS option 2	runoff volume & cost
Scenario #9	6-hour, 25-year rainfall	SUDS option 3	runoff volume & cost
Scenario #10	6-hour, 100-year rainfall	SUDS option 1	runoff volume & cost
Scenario #11	6-hour, 100-year rainfall	SUDS option 2	runoff volume & cost
Scenario #12	6-hour, 100-year rainfall	SUDS option 3	runoff volume & cost
Scenario #13	6-hour, 100-year+ 30%CC*	SUDS option 1	runoff volume & cost
Scenario #14	6-hour, 100-year+ 30%CC*	SUDS option 2	runoff volume & cost
Scenario #15	6-hour, 100-year+ 30%CC*	SUDS option 3	runoff volume & cost
Scenario #16	6-hour, 100-year+ 45%CC*	SUDS option 1	runoff volume & cost
Scenario #17	6-hour, 100-year+ 45%CC*	SUDS option 2	runoff volume & cost
Scenario #18	6-hour, 100-year+ 45 %CC*	SUDS option 3	runoff volume & cost

It can be observed in Table 7-4 that the objective functions considered for scenarios 1 and 5 are different from other scenarios where both surface runoff volume & cost, and peak flow & cost were examined. The decision for using runoff volume & cost in the majority of the simulations was made subsequent to an examination of the normalised outcomes from simulations 1 and 5 where a correlation between the volume of surface runoff and the peak flow rate was found for the study watershed. It was observed that when the surface runoff increased, the peak flow rate did too with a similar rate. Thus, a higher surface runoff was found to correspond to a higher peak flow rate, therefore, it was concluded that meeting the objective of reducing surface runoff volume, would lead to same level of reduction in peak flow rate. Therefore, it was determined to be redundant to include both reduction in peak flow

and surface runoff volume in the optimisation. The subsequent simulations were thereby conducted using only surface runoff and cost as the objective functions.

Table 7-5 The outcomes of the simulations conducted using the benchmark scenario for all scenarios. Therefore providing the baseline outcomes.

Return period of 6-hr design rainfall	Rainfall depth (mm)	Runoff attributes	Sub-catchments											
			S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**Total**
2-Year	23.9	Runoff volume (10^3 m^3)	5.2	8.8	6.6	4.8	10.8	13.6	8.8	11.9	3.2	2.8	0.7	14.7	91.8
		Peak flow (m^3/s)	1.1	1.5	1.2	0.9	1.7	2.3	1.4	1.7	0.7	0.6	0.2	2.1	15.3
10-Year	64.2	Runoff volume (10^3 m^3)	16.8	26.8	21.1	14.8	32.7	43.8	25.8	35.0	9.5	8.1	2.4	48.8	285.5
		Peak flow (m^3/s)	3.2	4.9	3.9	2.8	5.7	7.4	4.6	5.9	1.9	1.6	0.5	7.6	50.1
25-Year	87.7	Runoff volume (10^3 m^3)	23.8	37.5	29.7	20.8	45.8	62.6	35.8	48.7	13.2	11.3	3.5	69.5	402.1
		Peak flow (m^3/s)	4.6	7.1	5.6	4.0	8.4	11.1	6.6	8.6	2.6	2.2	0.7	11.5	73.1
100-Year	126.9	Runoff volume (10^3 m^3)	35.5	55.2	44.1	30.8	67.6	94.1	52.3	71.3	19.3	16.5	5.2	104.0	596.0
		Peak flow (m^3/s)	7.0	10.6	8.5	6.0	12.7	17.1	9.9	13.1	3.8	3.3	1.1	17.9	110.8
***100-Year**	165	Runoff volume (10^3 m^3)	47.0	72.6	58.2	40.6	88.8	124.8	68.4	93.3	25.3	21.6	6.9	137.7	785.2
		Peak flow (m^3/s)	9.2	14.0	11.2	7.9	16.8	22.9	13.0	17.3	4.9	4.2	1.4	24.0	146.8
****100-Year**	184	Runoff volume (10^3 m^3)	52.7	81.2	65.3	45.5	99.4	140.2	76.5	104.3	28.2	24.2	7.8	154.6	879.8
		Peak flow (m^3/s)	10.3	15.7	12.6	8.9	18.9	25.9	14.5	19.5	5.5	4.7	1.6	27.2	165.3

* means 100-year design storm + 30% added due to CC projections

** means 100 year design storm + 45% CC added due to CC projections

7.4 Results and Discussion

7.4.1 Overview

First, the benchmark scenario was investigated to obtain stormwater runoff and peak flow in the study watershed that would occur in the absence of SUDS in any of the designated subcatchments this provided the baseline (Table 7-5). Then the optimisation process was conducted using 6-hour design rainfalls with 2, 10, 25, 100 year return periods, and with 100-year return period with added 30% and 45% due to CC impacts, and three SUDS implementation options, making 18 simulation scenarios in total (Table 7-4).

To ensure that convergence was achieved by the SUDS-optimisation-framework and to account for the impact of the random number generator used by Borg, the simulation of Scenario one was repeated 10 times and generated outcomes were examined. It was determined that since each run provided comparable outcomes and converged to the same Pareto front it was appropriate to assume that this would also be the case for others scenario. Therefore, it was deemed necessary to run subsequent scenarios only once. The optimisation process required three hours on i5 CPU @ 2.4 GHz to conduct all 10,000 functional evaluations for each scenario. The post processing involved the plotting of the identified trade-off curves for each subcatchment within the Jeddah City study watershed. This allowed the most optimal solutions to be identified, subsequently, the SUDS practices components of selected SUDS solutions were examined in detail.

In the following sub-section, the outcomes for selected simulation scenarios, i.e. Scenarios 1, 4, 7, 10 and 13 are presented in full detail. These scenarios were selected to present an overview of how the return period of the design rainfall event may influence the simulation outputs. (The results of of all other scenarios are attached in Section D-4, Appendix D).

7.4.2 Scenario 1: 6-hour 2-year rainfall and SUDS option 1

In Figure 7-6, the results of the optimisation framework in the form of Pareto front of optimal SUDS solutions are shown. It can be seen that as the cost of the SUDS solution decreases, the total stormwater runoff gradually increases towards the total stormwater runoff that occurs in the catchment without SUDS implementation, i.e. 91.8 $x10^3$ m^3 (Table 7-5).

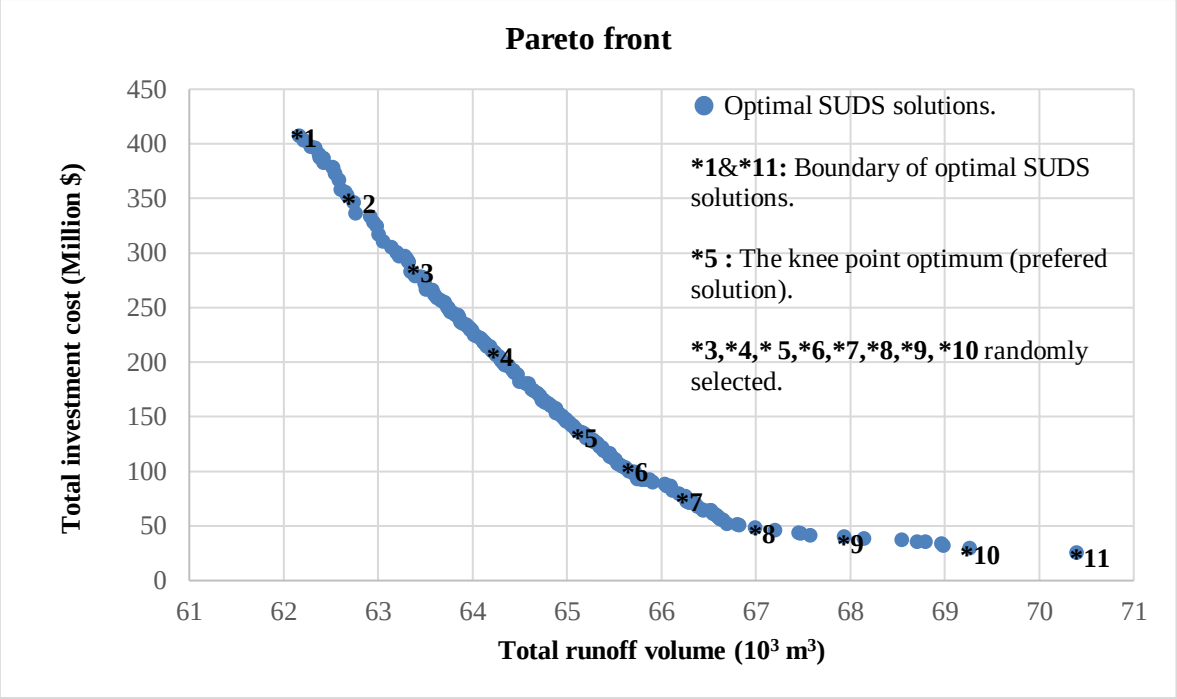


Figure 7-6 Pareto-optimal front of SUDS solutions for scenario 1: 6-year, 2-hour rainfall and SUDS option 1.

The directionality of the trade-off curve in Figure 7-6 was the expected outcome of optimisation. This is because it is consistent with how a SUDS system is expected to function. A SUDS solution over a larger surface area will increase the percentage of the surface runoff that is captured but will incur a greater cost.

Eleven of the optimal solutions shown in Figure 7-6 were selected for a more detailed analysis. These solutions are indicated in Figure 7-6 by a * followed by a number. Solutions *1 and *11 are the non-dominated boundary solutions; Solution *1 represents the solution that has the greatest cost and the greatest total runoff reduction, and Solution *11 represents the solution that has the lowest cost and the lowest reduction in total runoff. Solution *5 represents the knee of the Pareto front, defined as the Pareto front member with minimum normalized Euclidean distance to the origin. Past this point an improvement in meeting one of the trade-off objectives will result in moving further away from attaining the other objective. If there are no objective functions other than the two included in the optimisation, then the knee point typically represents the solution of greatest preference. The other solutions were selected randomly to represent an even spread of solutions on the pareto optimal front.

The trade-off between cost and total runoff reduction for the selected optimal solutions is given in Table 7-6. The lowest cost for SUDS solution is approximately $25M and the highest cost SUDS solution is approximately $407M. This is a significant cost increase for an additional

total stormwater runoff reduction of 8.9%. In comparison, the knee point solution (*5) has an approximate cost of $107M with a stormwater runoff reduction that is 5.3% greater than the cheapest solution and only 3.6% lower than in the costliest solution.

Table 7-6 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 1 (6-hour 2-year rainfall and SUDS option 1).

ID of SUDS solution	Total cost (Million $)	Total runoff Volume (m^3)	% of Reduction
*1	407	62200	32.4
*2	353	62700	31.8
*3	283	63300	31.2
*4	197	64300	30.1
*5	129	65200	29.0
*6	89.9	65900	28.4
*7	72.4	66300	27.9
*8	46.4	67200	27.0
*9	38.7	68100	26.0
*10	29.8	69300	24.7
*11	25.9	70400	23.5

In Figure 7-7, the percentage coverage of each SUDS type within each subcatchment for the selected optimal solutions are shown. As expected, the lowest cost SUDS solution (*11) presents a solution that has a substantially lower surface area coverage of SUDS. In the greatest cost solution (*1), the area coverage percentage is equal to or greater than the lowest cost solution for all subcatchments and all SUDS types. For half of the catchments, the lowest cost solution does not include the use of green roofs at all; in comparison, only one subcatchment of the most expensive option does not include GRs use. This is due to the relatively high costs of GR and lower impact on flood volume retention.

Permeable pavement represented the greatest surface area coverage in the majority of the optimal solutions for almost all of the subcatchments. The main reason behind this is that this SUDS option is a relatively cheaper option compared to the other SUDS solutions, which enables the coverage of a larger area for a lower cost and thereby decreasing the surface total runoff for a lower price. There is also the potential that the good performance of permeable

pavement is attributable to the efficiency of permeable pavements. Meaning that permeable pavements are very efficient at managing stormwater surface runoff and therefore present the most effective solutions at a low cost point.

All of the SUDS solutions which were identified as optimal did not include any use of GRs in subcatchment 11. This is due to subcatchment 11 not meeting any of the criteria which permits the use of GRs under SUDS implementation option 1, therefore the SUDS solutions generated for this scenario simulation only permit the use of RGs, BRs and PPs within this subcatchment.

Some of the SUDS solutions are very different in terms of combination of SUDS types. For instance, solutions 1 – 4 all require some use of BRs in subcatchment 12, whereas all the other solutions suggest very little use of BRs. A similar outcome was observed in subcatchment 3 whereby SUDS solutions 1-4 suggest the use of 1.3% - 2.8% of BRs, whereas the SUDS solutions 9 – 11 suggest no use of BRs and SUDS solutions 5 – 8 suggest 0.2% - 0.5% use of BR. This suggests that BRs does not present an effective solution for stormwater management in this catchment given the trade-off objectives and therefore this SUDS option is not present in large areas in the optimal solutions identified.

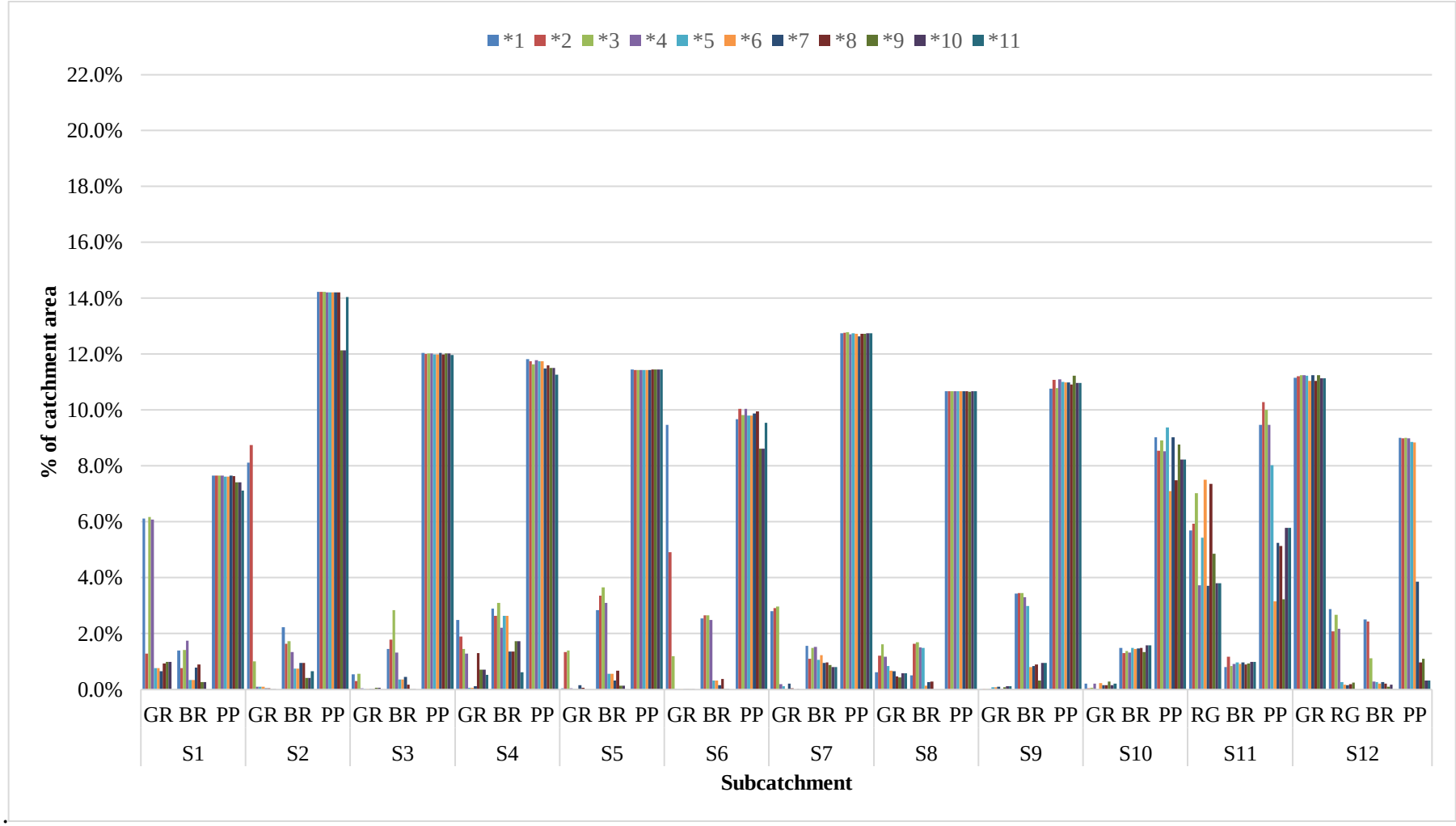


Figure 7-7 SUDS percentage coverage in each subcatchment for scenario 1's selected optimal solutions.

Scenario 1 was rerun with a different set of objective functions: reducing peak flow and cost. In Figure 7-8, the output of this simulation is given. Similar to the previous investigated simulation, i.e. using total surface stormwater runoff as the objective, there is a substantial difference in both the cost and peak flow rates for the optimal SUDS solutions, with the knee point approximately halfway between the two. At the outlet of each subcatchment there was little observed difference in the reduction of water flow of the solutions generated for the two objective functions (see Table 7-6).

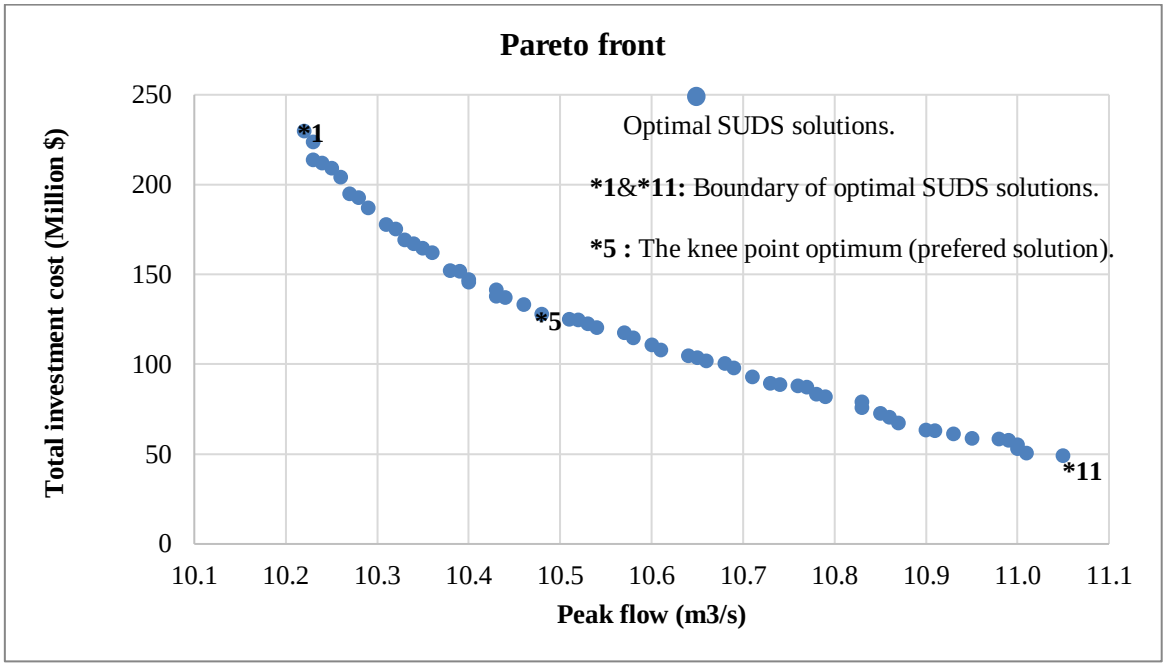


Figure 7-8 Pareto-optimal front of SUDS solutions for scenario 1 using peak flow and cost objective functions.

In conclusion, it was identified that the selection of optimal solutions for surface water total runoff will also have an impact on reducing the peak volume flow due to the SUDS solutions implemented. This relationship, whereby reducing surface water total runoff also reduces the peak flow volume, was observed in both simulations of scenario 1 and 5 (included in Section D-4, Appendix D). A reduction in total surface runoff will have an impact on reducing the peak flow volume due to the nature of the SUDS that are implemented. SUDS solutions are primarily based on the retention of rainfall and the gradual release of this rainfall either into the drainage system or into the soil horizon happens over a longer time period compared with traditional drainage systems. Thus, by reducing the surface runoff volume, the potential runoff that could constitute the peak flow is also reduced. The extent of this relationship is partially dependent upon the rainfall retention capacity of the SUDS solutions which are implemented; SUDS solutions with a greater retention capacity will likely have a higher potential to reduce the peak flow volume. In comparison, SUDS solutions with a lower rainfall retention capacity will have

a lower impact on peak flow reduction, particularly during events of high rainfall intensity as they will reach the maximum retention capacity more rapidly, and subsequently, will not influence the flow rate volume. From this perspective the relationship between SUDS surface runoff reduction and peak flow reduction is also likely to be influenced by rainfall intensity and duration; the greater the rainfall intensity and duration, then the more rapidly the SUDS maximum retention capacity is attained. Thus, it was determined that in attaining the objective of reducing surface runoff volume, then the peak flow volume would also be concurrently reduced meaning that it was not necessary to conduct a separate cost optimisation simulation for peak flow and cost.

7.4.3 Scenario 4: 6-hour, 10-year rainfall and SUDS option 1

The optimal solutions forming the pareto-optimal front for scenario 2 are plotted in Figure 7-9. As with the optimisation performed for Scenario 1, selected solutions were examined in detail. For this scenario, the total surface stormwater runoff without SUDS implementation was 285.5 x 10^3 m^3 (Table 7-5). It can be seen that all identified optimal solutions reduce this surface stormwater runoff.

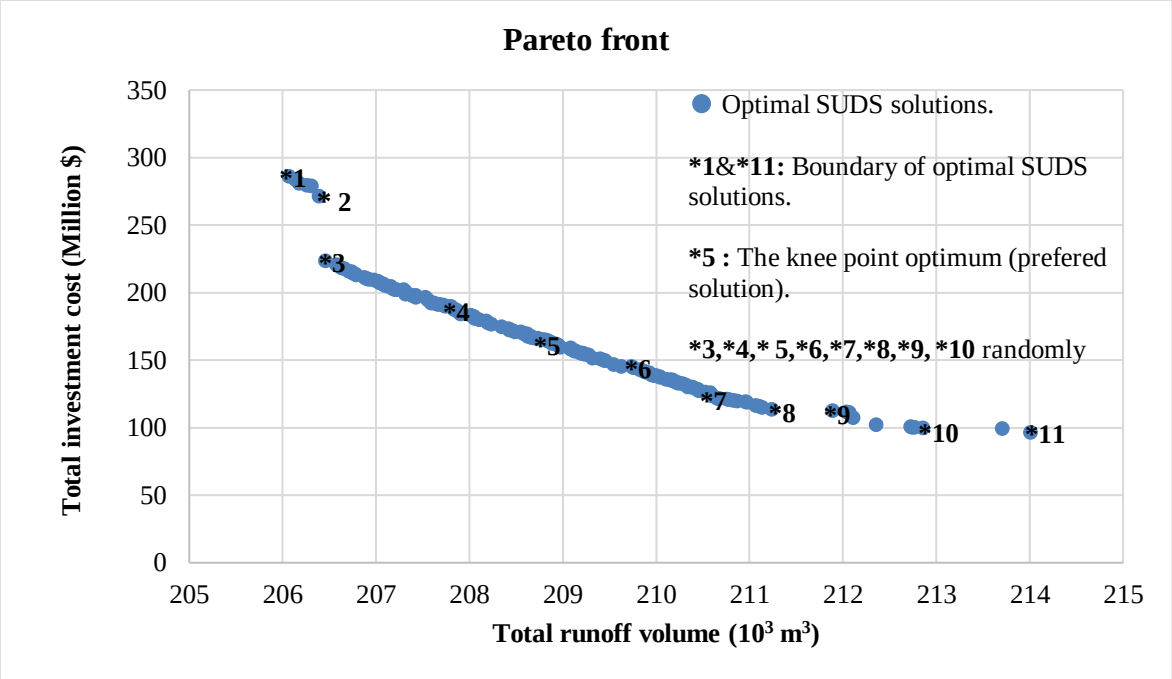


Figure 7-9 Pareto-optimal front of SUDS solutions for scenario 4: 6-hour, 10-year rainfall & SUDS option 1.

In Table 7-7 it can be seen that the greatest percentage reduction was 27.8% and the lowest reduction was 25%. However, the costs associated with achieving these reductions were

$286M and $96M respectively, a significant outlay cost for only a 2.8% increase in surface runoff reduction.

Table 7-7 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 4 (6-hour 10-year rainfall and SUDS option 1).

ID of SUDS solution	Total cost (Million $)	Total Volume (m^3)	% of Reduction
*1	286	206070	27.8
*2	272	206390	27.7
*3	224	206460	27.7
*4	191	207720	27.2
*5	167	208700	26.9
*6	146	209630	26.6
*7	121	210790	26.2
*8	115	211140	26.0
*9	113	211890	25.8
*10	100	212860	25.4
*11	96.9	214010	25.0

In the subcatchment, as was found with the 2-year, 6-hour design rainfall event, the optimal solutions had an extensive utilisation of the PPs option in comparison to the other SUDS options. This is further seen in the graph shown in Figure 7-10 comparing the SUDS solutions for each subcatchment. The RGs SUDS option was only included in the optimal solutions for subcatchments S11 and S12, which is primarily due to the necessity of sufficient open space for application of this SUDS option which is lacking in the other subcatchments. GRs were suggested for all subcatchments (excluding subcatchment S11), however, only the SUDS solutions identified for subcatchment S12 had a relatively high percentage of GRs in solutions with some solutions proposing GRs applications in excess of 8% of the subcatchment (see figure 7-10). However, none of the proposed solutions had GRs inclusion which approached the maximum permitted percentage under the different scenarios. BRs were suggested for all subcatchments solutions, solutions 1 – 4 suggest the use of 1.9% - 2.6% of BRs in subcatchments S2,S6,S9 and S12, whereas all the other solutions suggest 0.2% - 0.6% use of BRs. All solutions in other subcatchments suggest very little use of BRs.

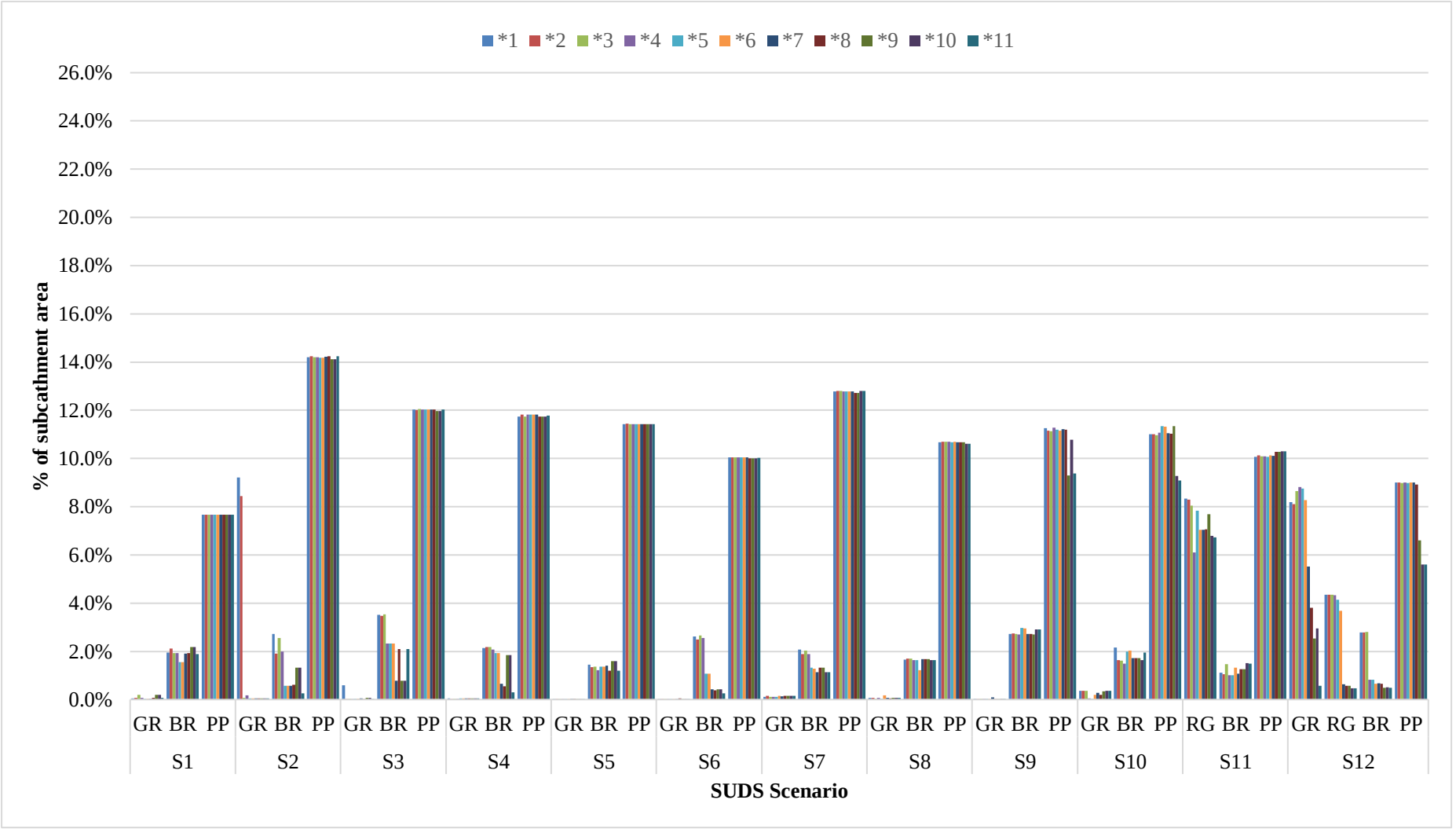


Figure 7-10 SUDS percentage coverage in each subcatchment for scenario 4's selected optimal solutions.

7.4.4 Scenario 7: 6-hour, 25-year rainfall event and SUDS option 1

For the 25-year, 6-hour design rainfall event considered for scenario 7, it was found that there were 178 optimal solutions forming the pareto-optimal front, these are plotted in Figure 7-11. As with the optimisation performed for other scenarios, selected solutions were examined in detail. The total surface stormwater runoff without SUDS implementation was 402.1 x10^3 m^3 (Table 7-5). It can be seen that all identified optimal solutions reduced this surface stormwater runoff.

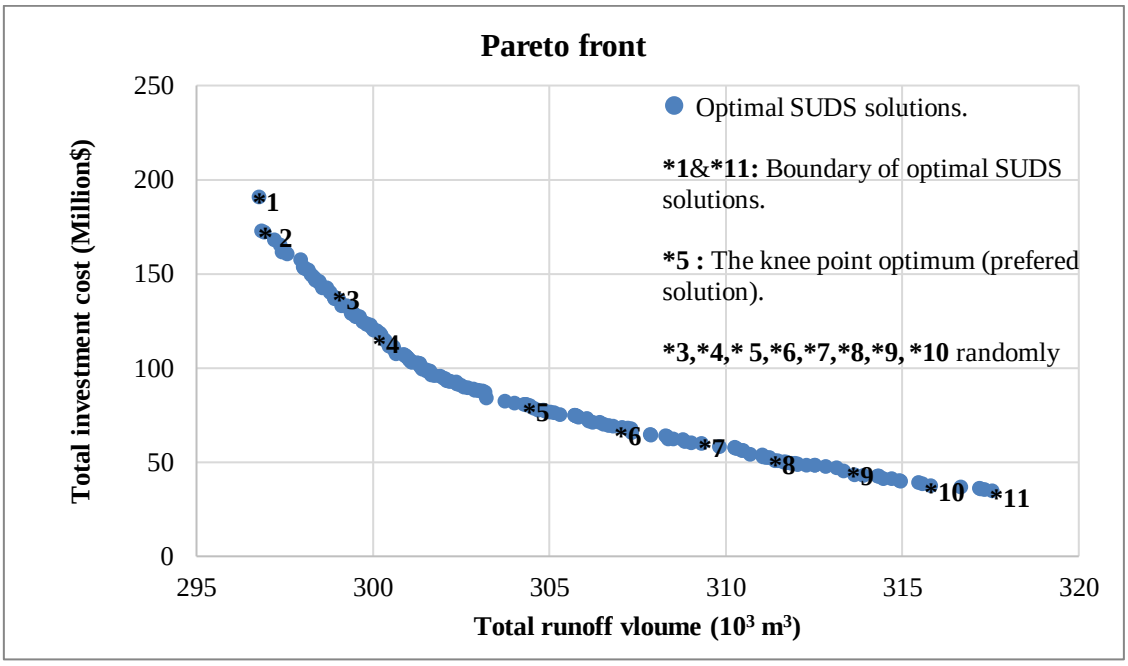


Figure 7-11 Pareto-optimal front of SUDS solutions for scenario 7: 6-hour, 25-year rainfall event & SUDS option 1.

The surface water runoff reduction percentage was lower than that observed when examining scenario 1, which is important because reducing surface water runoff is one of the primary objectives of the study; in Table 7-8 it can be seen that the greatest percentage reduction was 26.2% and the lowest reduction was 21%. The costs associated with achieving these reductions were $191M and $34M respectively (See Table 7-8).

Table 7-8 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 7 (6-hour 25-year rainfall and SUDS option 1).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m^3)	% of Reduction
*1	191	296760	26.2
*2	173	296840	26.2
*3	133	299110	25.6
*4	127	300000	25.4
*5	78.6	304550	24.3
*6	69.1	306800	23.7
*7	60.0	309310	23.1
*8	52.9	311040	22.6
*9	45.4	313340	22.1
*10	39.0	315450	21.5
*11	34.7	317540	21.0

The combinations of SUDS in each subcatchment that make up each optimal solution are given in Figure 7-12. In the vast majority of identified optimal solutions, the largest SUDS option coverage was PP, highlighting the effectiveness of this SUDS option in reducing stormwater surface flow whilst minimising financial outlay. Subcatchment S2 had the greatest use of PP, with all optimal solutions utilising more than 14% surface area coverage. Subcatchment S12 solutions had the greatest variability in the use of PP with some solutions using less than 1% PP coverage, whilst others used approximately 9% PP coverage. In six subcatchments there was no use of GR in any of the identified optimal solutions (figure 7-12).

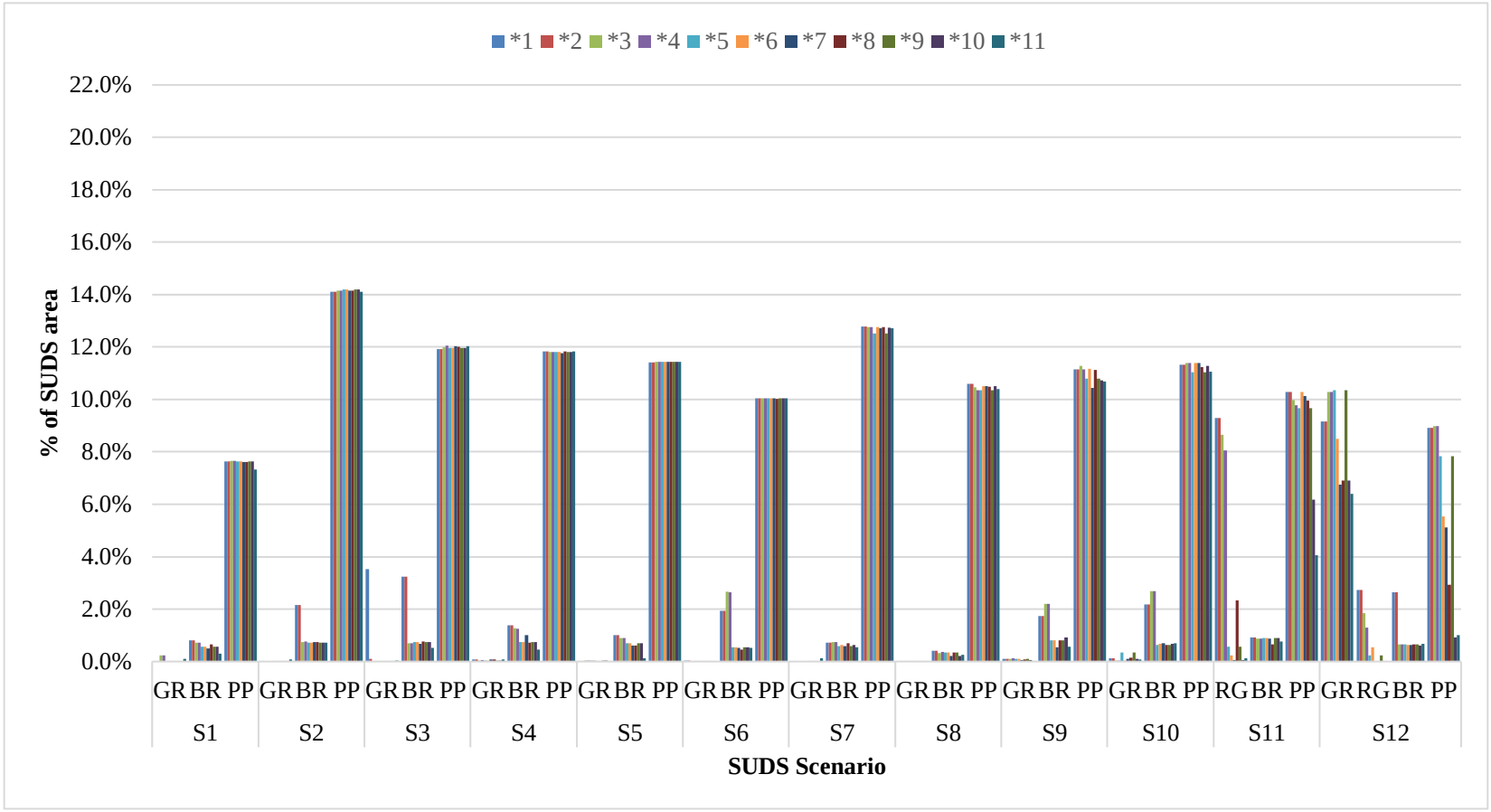


Figure 7-12 SUDS percentage coverage in each subcatchment for scenario 7's selected optimal solutions.

7.4.5 Scenario 10: 6-hour 100-year rainfall and SUDS option 1

The pareto-optimal front obtained for scenario 10 is plotted in Figure 7-13. As with the optimisation performed for scenario 1 and other scenarios, selected solutions were examined in detail. Under scenario 10, the total surface stormwater runoff without SUDS implementation was found to be 596 x 10^3 m^3 (Table 7-5). All of the identified optimal solutions reduced this surface stormwater runoff.

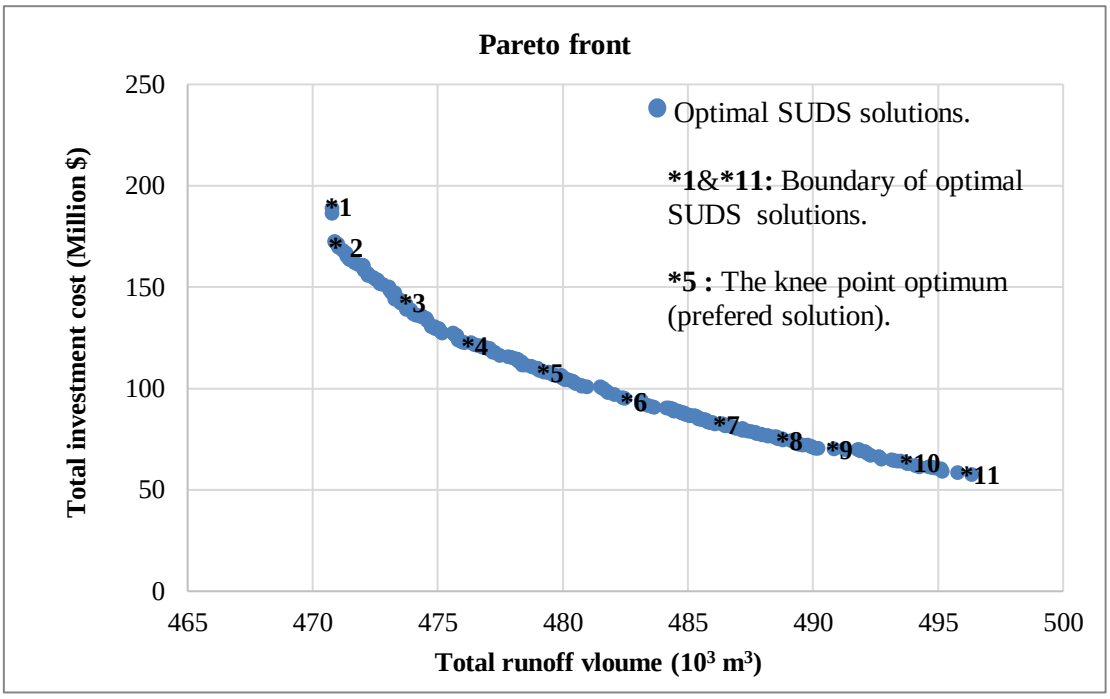


Figure 7-13 Pareto-optimal front of SUDS solutions for scenario 10: 6-hour 100-year rainfall & SUDS option 1.

The surface water runoff reduction percentage was lower than that observed when examining scenario 1, which suggests that the conditions of scenario 1 do not produce the most optimal SUDS solutions this comparison between scenarios allows the identification of the most optimal solutions; in Table 7-9 it can be seen that the greatest percentage reduction was 21% and the lowest reduction was 16.7%. The costs associated with achieving these reductions were $189M and $57M respectively.

Table 7-9 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 10 (6-hour 100-year rainfall and SUDS option 1).

ID of SUDS solution	Total cost (Million $)	Total Volume (m^3)	% of Reduction
*1	189	470780	21.0
*2	173	470900	21.0
*3	144	473300	20.6
*4	124	475800	20.2
*5	112	478400	19.7
*6	97.1	482100	19.1
*7	83.8	485800	18.5
*8	76.6	488200	18.1
*9	70.5	490200	17.7
*10	64.4	493400	17.2
*11	57.8	496350	16.7

The combinations of SUDS types that make up the solution for each optimal solution is given in Figure 7-14. As was found with scenario 1, the optimal solutions utilised the permeable pavement option most extensively. PPs use was found to be greatest in subcatchment S2 at approximately 14% coverage with PPs in all optimal SUDS solutions. All of the identified optimal SUDS solutions included a very small area of GRs (<0.05%) with the exception of subcatchment S11 which did not have any GRs and subcatchment S12 which had GR use of between 6 and 7% across all SUDS solutions. SUDS solution *3 contained the highest individual coverage of one SUDS option, which was approximately 17% for RG in subcatchment S11. All of the other RGs use in S11 were 14% or lower.

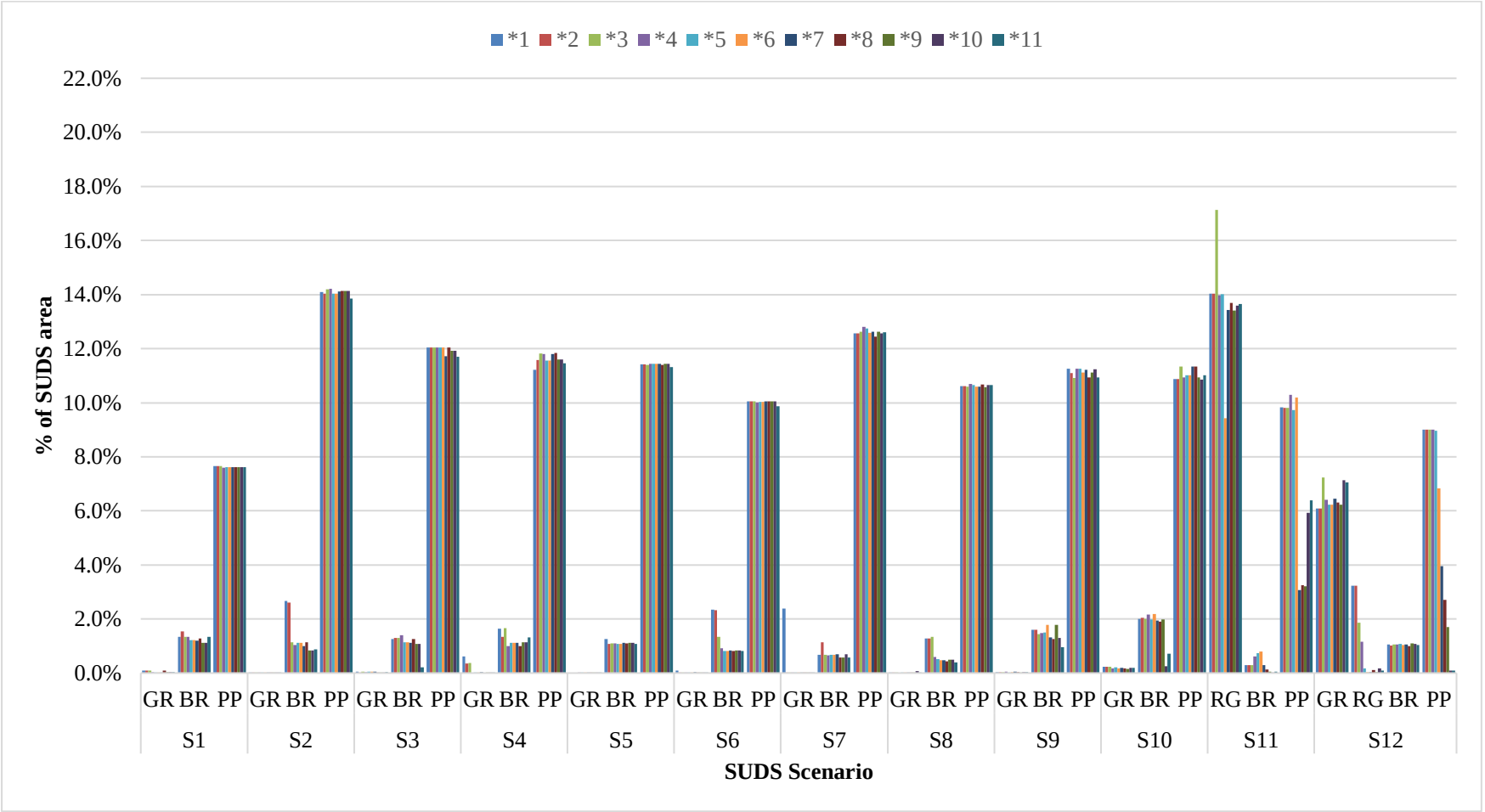


Figure 7- 14 SUDS percentage coverage in each subcatchment for scenario 10's selected optimal solutions.

7.4.6 Scenario 13: 6-hour 100-year rainfall under 30% CC and GR option 1

The pareto-optimal front for scenario 13 is plotted in Figure 7-15. CC impact was simulated by the assumption of a 30% increase in rainfall over the 100-year design storm. Under scenario 13, the total surface stormwater runoff without SUDS implementation was 785.5 x10^3 m^3 (Table 7-5). The optimal solution that were identified were found to reduce the surface stormwater runoff (Figure 7-15).

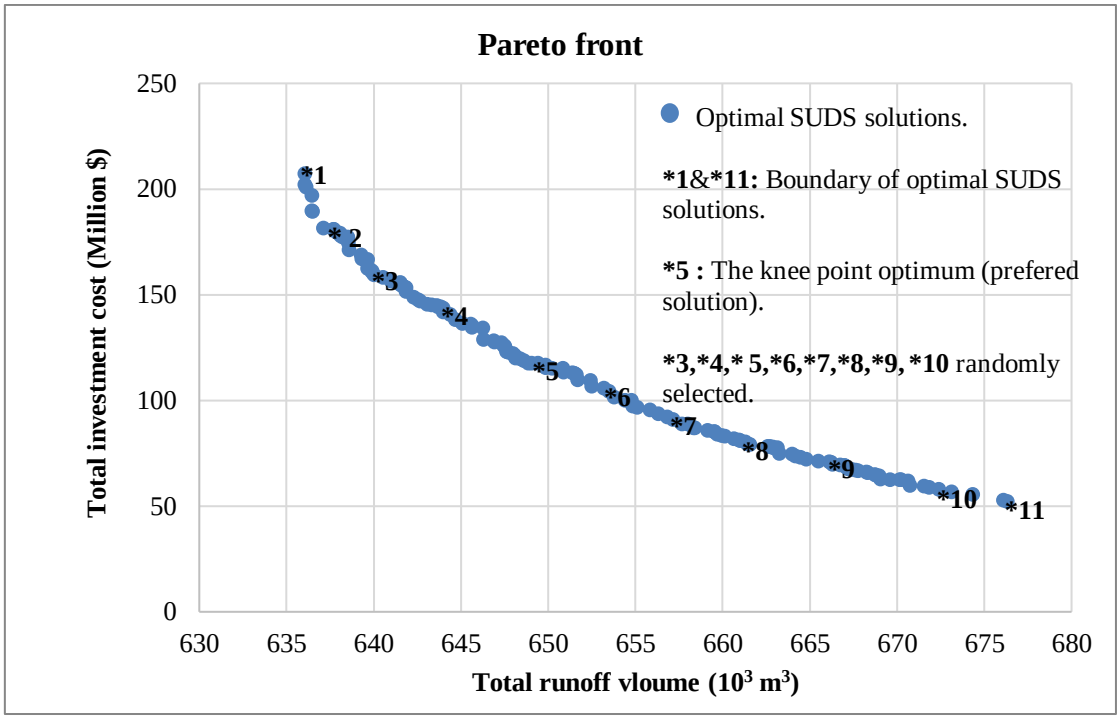


Figure 7-15 Pareto-optimal front of SUDS solutions for scenario 13: 6-hour 100-year rainfall +30%CC & SUDS option 1.

The surface water runoff reduction percentage was lower than that observed when examining scenario 1; in Table 7-10, it can be seen that the greatest percentage reduction was 18.8% and the lowest reduction was 13.6%. The costs associated with achieving these reductions were $207M and $52M respectively.

Table 7-10 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 13 (6-hour 100-year +30 CC rainfall and SUDS option 1).

ID of SUDS Solution	Total cost (Million $)	Total Volume (m^3)	% of Reduction
*1	207	636030	18.8
*2	182	637110	18.6
*3	161	639900	18.3
*4	144	643650	17.8
*5	118	648830	17.1
*6	107	652490	16.7
*7	92	656820	16.1
*8	81	660640	15.6
*9	71	665470	15.0
*10	59	671810	14.2
*11	52	676300	13.6

As was found with scenario 1, the optimal solutions utilised the permeable pavement option most extensively. This is further seen in the graph shown in Figure 7-16 comparing the SUDS solutions for all subcatchments. The use of RG was found to be greatest in subcatchment S11, with one optimal SUDS solution (*1) utilising 29% coverage with RG, the solution *2 had the second greatest SUDS RG coverage at just over 24% (see figure 7-16). For all other SUDS options, the coverage was found to be lower than approximately 14%. GR was included in the optimal solutions for 6 out of the 12 subcatchments. However, of these 6 subcatchment it was observed that GR was suggested for only 1 SUDS solution in the subcatchments S1, S5, S7 and S10. Thus, only subcatchments S4 and S12 had multiple SUDS solutions which utilised GR.

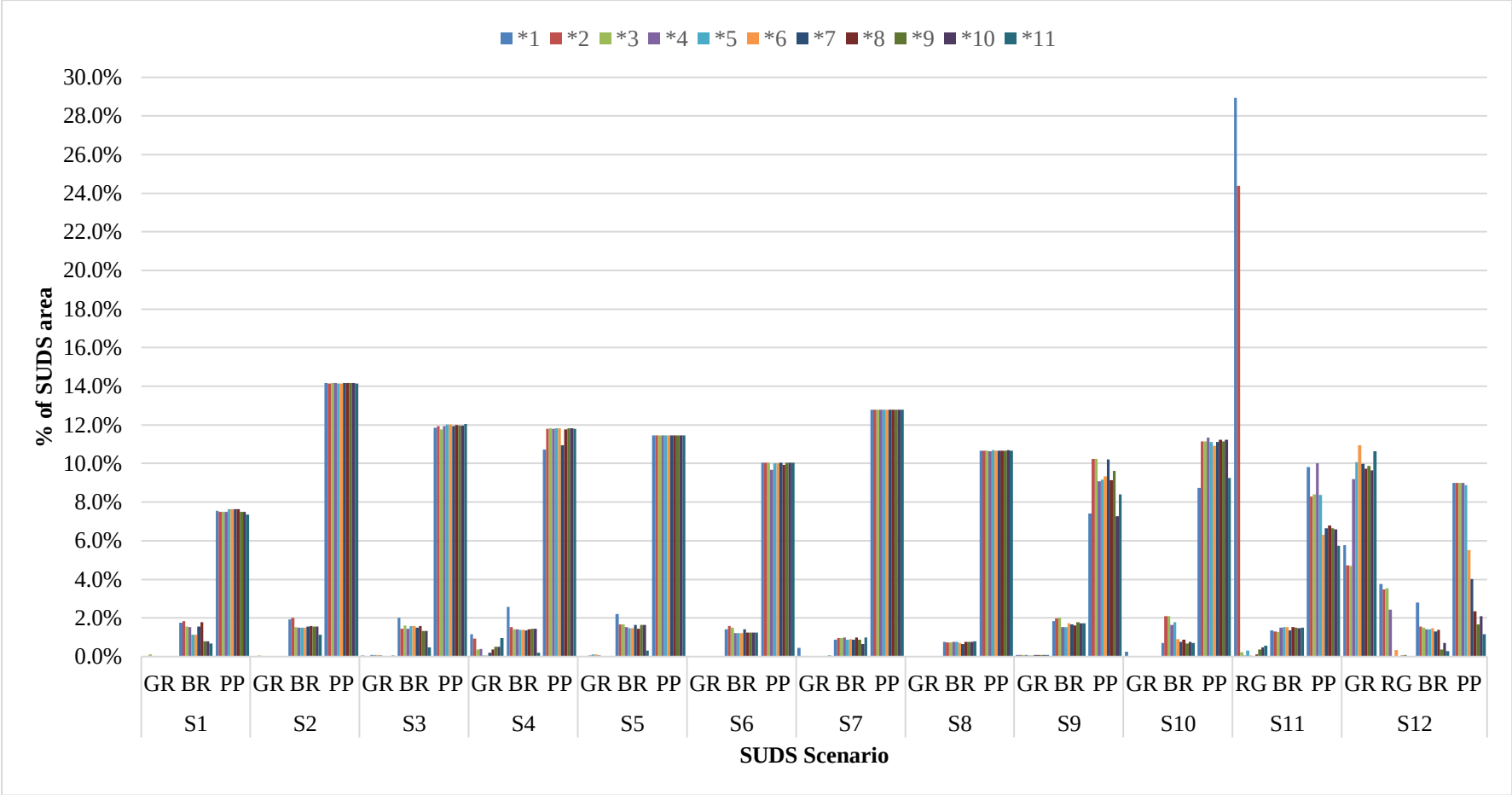


Figure 7-16 SUDS percentage coverage in each subcatchment for scenario 13's selected optimal solutions .

7.4.7 Comparison of Scenarios

In order to compare the surface runoff reduction and the cost of SUDS solutions between scenarios, the outputs of all simulations were further analysed. This involved the comparison of simulations results between scenarios with the same design storm return period. To conduct a meaningful comparison, the cost and the surface runoff reduction outputs were normalised and plotted on one graph. An additional analysis was performed to calculate the cost for 1% reduction in surface runoff volume for each scenario. By processing the output dataset in this manner, it was possible to compare between different simulations and to identify which SUDS implementation scenario provided the optimal return on investment in terms of surface runoff reduction. In the following sections, the findings of this analysis are discussed for each design storm return period, separately.

7.4.7.1 Scenarios with 2-year return period design storm

In Figure 7-17 the obtained normalised cost and surface runoff for all scenarios that had a 2-year return period design storm are given. The SUDS option 2 scenario was found to always have the greatest cost of SUDS solution in comparison to SUDS options 1 and 3, for the same surface runoff reduction. SUDS option 2 allows for potentially the most extensive use of GR in the SUDS solutions identified. SUDS option 1 which also allows for the use of GR in SUDS solutions. but in a more limited capacity than in option 2, was found to have a greater cost than SUDS option 1 (no GR permitted) up to an approximate surface runoff normalised reduction of 0.5. For surface runoff reduction volumes greater than 0.5, 2-year simulations with SUDS option 1 were observed to be the lowest cost option (Figure 7-18). The highest cost solution was found to occur under SUDS option 3 and was approximately $16M for a 1% reduction in surface runoff volume. The lowest cost solution was found to occur under SUDS option 1 and was approximately $1M for a 1% reduction in surface runoff volume (figure 7-18). The lowest cost solution *5 (knee solution) that was found was under SUDS option 3 and was approximately $2M for a 1% reduction in surface runoff volume. It was observed that for all SUDS options, the lowest and greatest surface runoff volume reduction converged to same normalised values, indicating that when surface runoff volume reductions at these magnitudes are considered, then there will be little to no difference in the cost and effectiveness of whatever SUDS solution is selected.

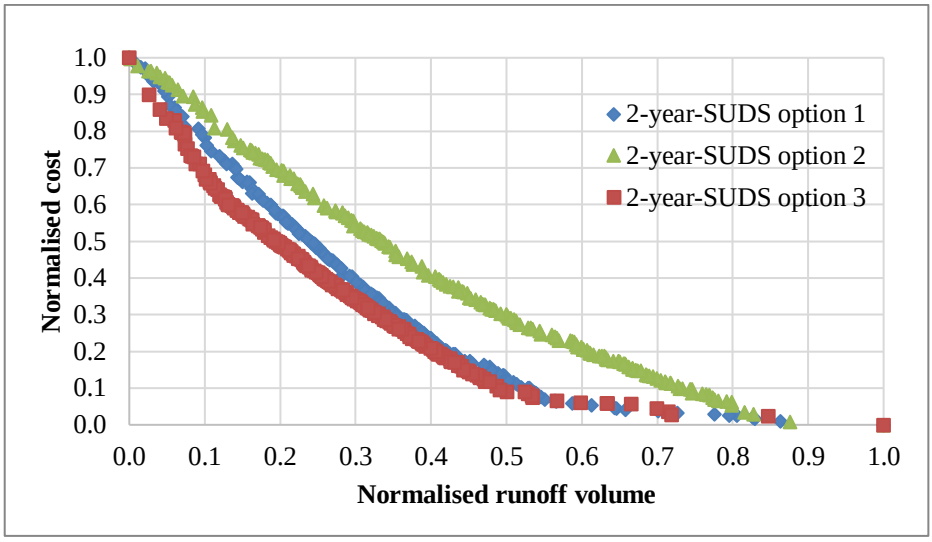


Figure 7-17 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 and using a 2-year return period design storm.

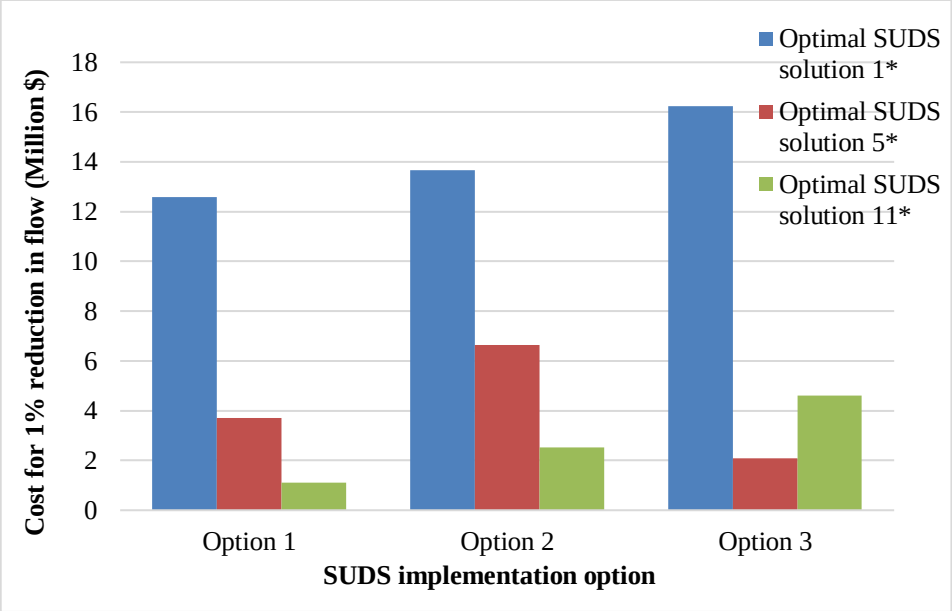


Figure 7-18 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 2-year return period design storm.

7.4.7.2 Scenarios with 10-year return period design storm

For scenarios with a the 10-year return period design storm, the obtained results (Figure 7-19) indicate that for normalised surface runoff reductions of between approximately 0.2 and 0.3 there is relatively little difference in the normalised cost of SUDS solutions. For these scenarios, the most notable differences occur at the low surface runoff reductions, with

relatively high costs and the high surface reductions with relatively lower normalised costs. When the normalised surface runoff reduction is less than approximately 0.18, the SUDS solutions under SUDS implementation option 3 have the greatest normalised cost and the SUDS solutions under option 2 the lowest normalised cost.

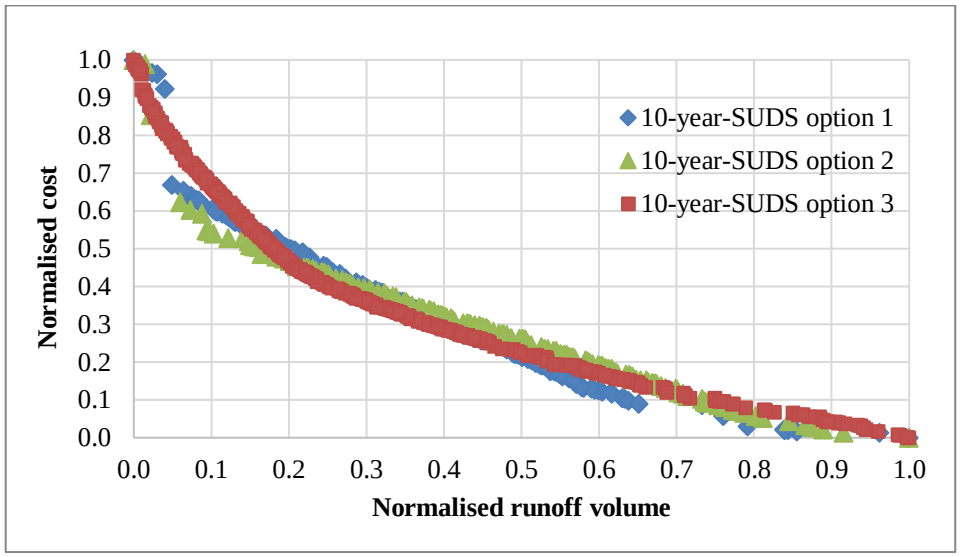


Figure 7-19 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 10-year return period design storm.

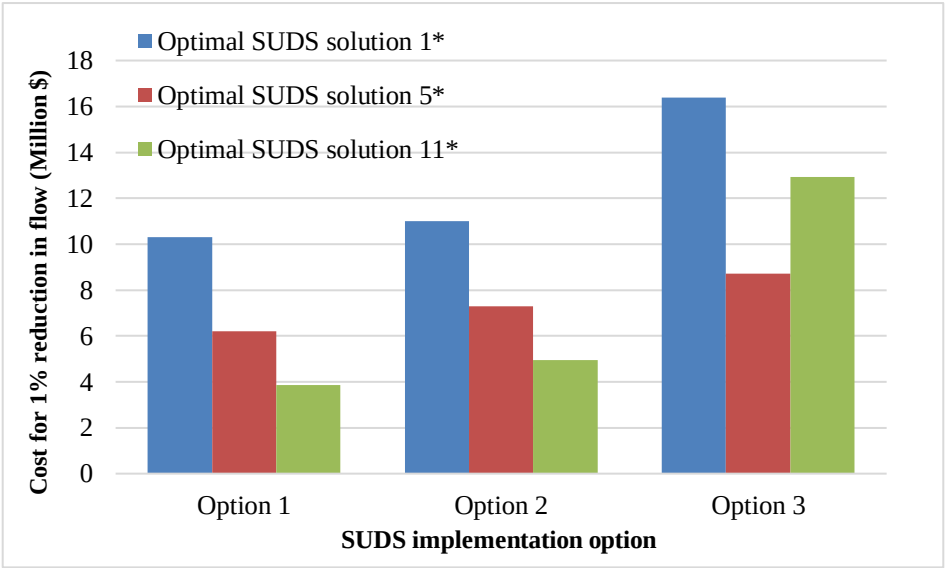


Figure 7-20 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 10-year return period design storm.

The optimal SUDS solution 1* (the highest cost solution), 5* (the knee point solution) and 11*(the lowest cost solution) for each SUDS implementation option were also compared across the scenarios. In all these optimal solutions (1*, 5* and 11*) it was found that the greatest cost for a 1% reduction in surface runoff volume was attributed to solutions which were generated from simulations using SUDS option 3. The highest cost solution was found to have a cost of approximately $16.2M for a 1% reduction in surface runoff for SUDS option 3, whereas the lowest cost solution was found to have a cost of approximately $3.9M for a 1% reduction in surface runoff volume (Figure 7-20). All of the lowest cost solutions were found to be generated when using SUDS option 1. The difference between the cost of 1% reduction for SUDS option 1 compared to SUDS option 2 across all the selected optimal SUDS solutions was found to be lower than the difference between the cost of a 1% reduction for SUDS option 2 compare to SUDS option 3. This suggests that when considering the surface runoff reduction cost optimisation care must be taken as it is possible to have optimal solutions identified that incur significantly greater costs than other potential solutions without an appreciable gain in surface runoff volume reduction.

SUDS implementation option 3 was found to consistently have the greatest cost per 1% reduction in surface runoff volume. Option 3 does not allow for the inclusion of GR, whilst or the scenario with 2-year design event, option 3 was consistently the lowest cost option for the greatest reduction in surface runoff volume (Figure 7-20). It is suggested that this difference is due to the cost being considered over a longer return period, such that the return on investment is greater.

7.4.7.3 Scenarios with 25-year return period design storm

The combined results for scenarios with a 25-year return period design storm exhibited a different surface runoff reduction and cost pattern for the normalised data that was seen in the two previous scenarios (2-year & 10-year design storms). For simulations with 25-years design storm it can clearly be seen that that SUDS implementation option 3 had greater normalised costs for the same normalised surface runoff reduction than either SUDS option 1 or option 2 (Figure 7-21). SUDS option 1 was generally found to have the lowest normalised costs, although there was some overlap observed with SUDS option 2.

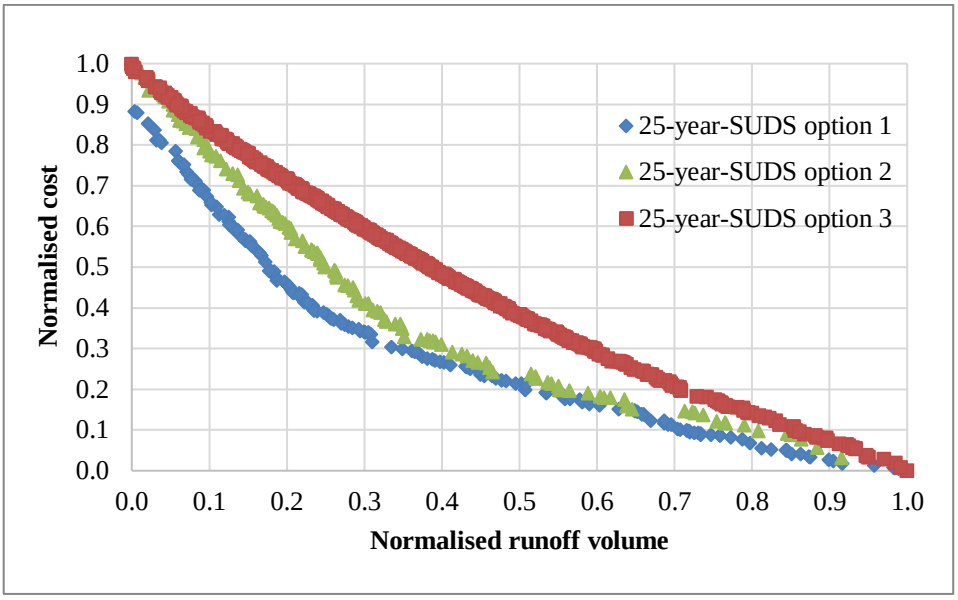


Figure 7-21 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 25-year return period design storm.

When the cost for a 1% reduction in surface runoff volume was examined, the substantially greater relative cost of SUDS option 3 was again evident (Figure 7-22). When considering optimal SUDS solution 5*, the cost for SUDS option 3 (approximately $11M) is more than double that of SUDS options 1 and 2 (approximately $3M and $4.2M respectively). Even under the lowest cost scenarios 1*, SUDS options 3 is approximately double that of SUDS option 1 (Figure 7-22). It is readily apparent that with a 25-year design storm, SUDS option 3 with no permitted GR is a substantially greater cost option that the other SUDS implementation options, with no increase in surface runoff volume that could justify the additional expenditure.

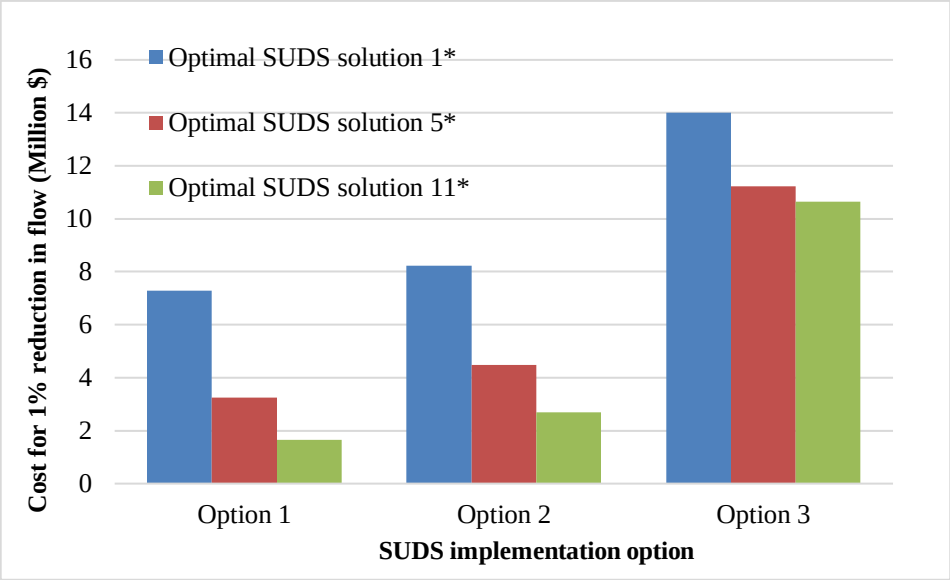


Figure 7-22 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted using a 25-year return period design storm.

7.4.7.4 Scenarios with 100-year return period design storm

An examination of the normalised runoff reduction values against the normalised cost of solutions for the 100-year return period design storm clearly identified the SUDS solutions under SUDS option 3 as incurring lower financial costs than those incurred under SUDS options 1 and 2 for the same reduction in surface water runoff volume (Figure 7-23).

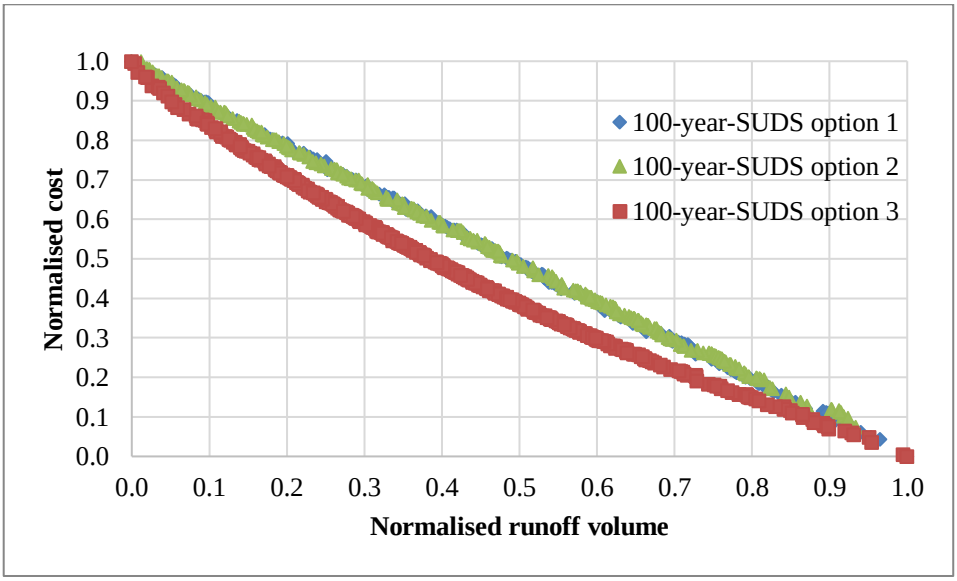


Figure 7-23 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm.

When the cost for a 1% reduction in surface runoff volume is compared for the three optimal SUDS solutions selected, it is clearly seen that there is only a marginal difference in the lowest cost (1*) optimal SUDS solutions for all SUDS implementation options (Figure 7-24). SUDS implementation options 1 and 2 have approximately the same lowest cost for 1% reduction (approximately $8.5M), whereas SUDS implementation option 3 is slightly greater (approximately $9.3M). However, when optimal SUDS solution 5*, the knee solution, is examined the opposite is true, SUDS implementation options 1 and 2 again have a similar cost for a 1% reduction in surface runoff volume, but SUDS option 3 has a lower cost by approximately $1.3M (Figure 7-24). The same was also observed to occur for the highest cost optimal solution (11*) where SUDS option 3 was substantially lower than that of SUDS options 1 and 2 for the same percentage reduction in surface runoff.

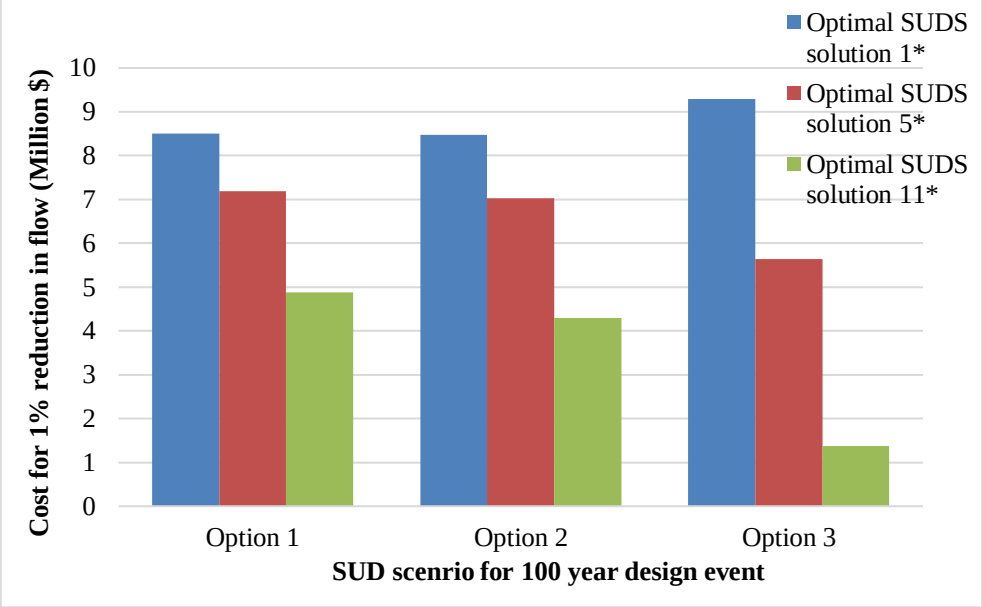


Figure 7-24 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event.

7.4.7.5 Scenarios with 100-year return period design storm + 30% CC

When a 30% CC influence is incorporated into the 100-year design storm, there is an apparent difference in the outcomes of the simulations for different SUDS implementation options (see Figure 7-25). SUDS implementation option 3 has a clearly greater normalised cost for surface runoff reduction in comparison to SUDS implementation options 1 and 2. When the normalised runoff reduction that is considered is less than 0.8. SUDS implementation option 2 has a consistently lower normalised cost than SUDS option 1 for the same normalised runoff

reduction value. However, at normalised surface runoff reductions of greater than 0.8, SUDS options 1 and 2 were observed to have similar normalised costs.

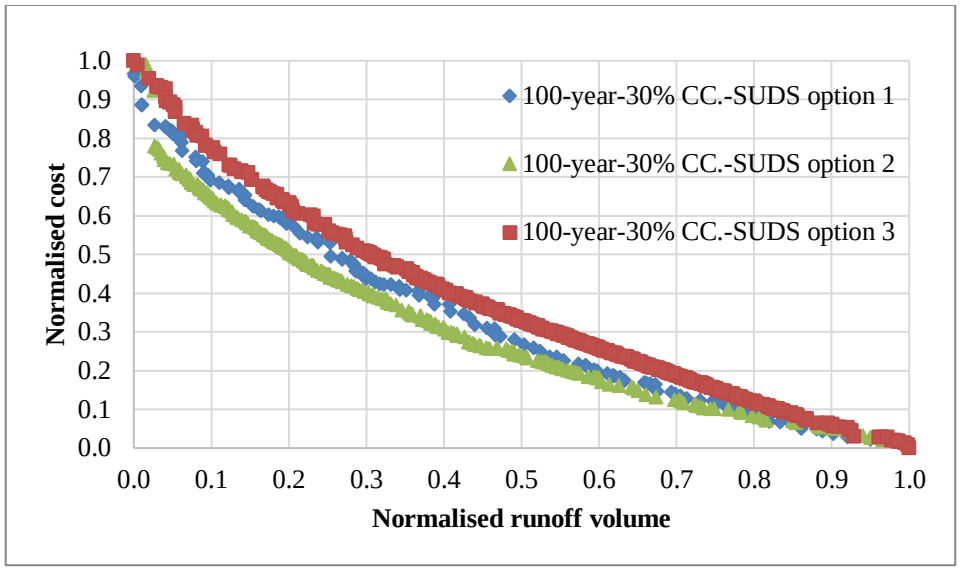


Figure 7-25 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm with 30% CC.

The higher cost of SUDS implementation option 3 was also evidenced when examining the cost for a 1% reduction in surface runoff (Figure 7-26). Under all the optimal SUDS solutions considered, SUDS implementation option 3 was substantially greater than the cost of either option 1 or option 2. There was no substantial difference found in the 1% reduction costs across all optimal SUDS solutions for SUDS implementation options 1 and 2, although for all optimal solutions, the cost of SUDS implementation option 2 was slightly greater than those of SUDS implementation option 1.

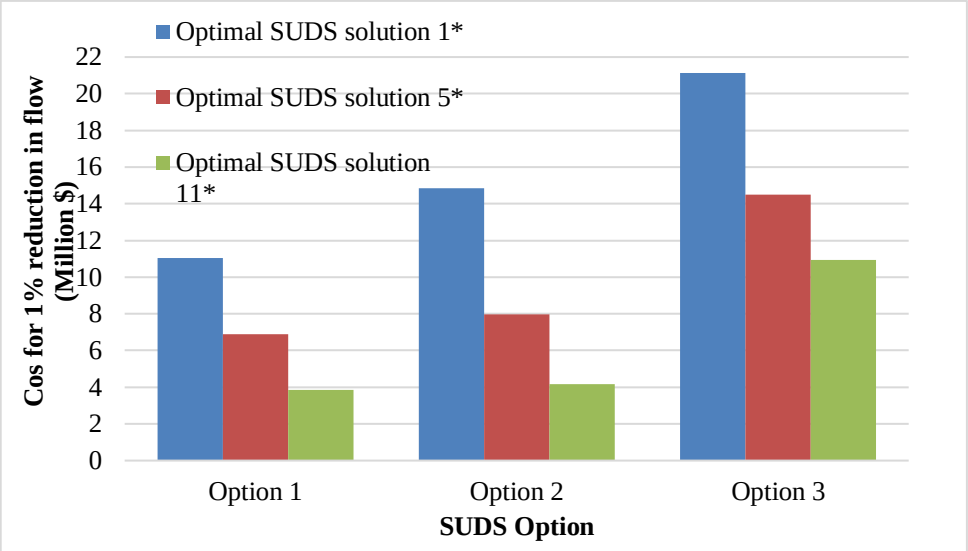


Figure 7-26 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event with 30% CC.

7.4.7.6 Scenarios with 100-year return period design storm + 45% CC

The normalised surface runoff reduction and normalised cost for all SUDS implementation options with a 100-year design event with added 45% for CC are shown in Figure 7-27. In comparison to the other return period design storm, the simulations outcomes under the different SUDS implementation options were observed to be the most similar under this design event. Whilst the normalised outcomes were highly similar, likely due to the extended time period which was considered, the simulated outcomes for SUDS implementation option 2 had slightly lower normalised cost and SUDS implementation option 3 has slightly higher nor.cost.

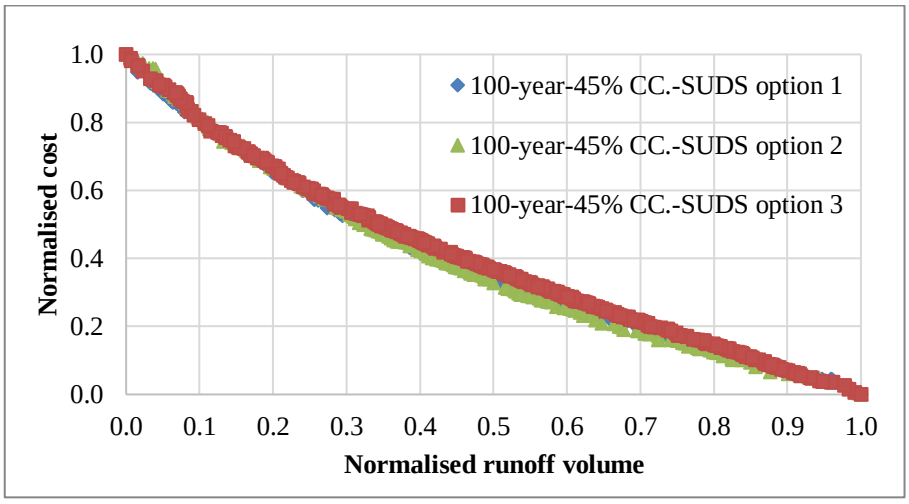


Figure 7-27 The normalised runoff volume reduction against the normalised cost of solutions for SUDS implementation options 1, 2 and 3 for simulations using a 100-year return period design storm with 45% CC.

Although the normalised data displayed similar simulation outcomes for all three SUDS implementation options, when examined on the basis of the cost for a 1% reduction in surface runoff volume, it was apparent that the lowest cost optimal SUDS solutions (1*) SUDS option 2 had a substantially greater cost than SUDS options 1 and 3 (Figure 7-28). The optimal SUDS solutions identified for the knee point (5*) indicated that under SUDS implementation option 3, the cost for a 1% surface runoff reduction is lowest and SUDS option 2 has the highest cost.

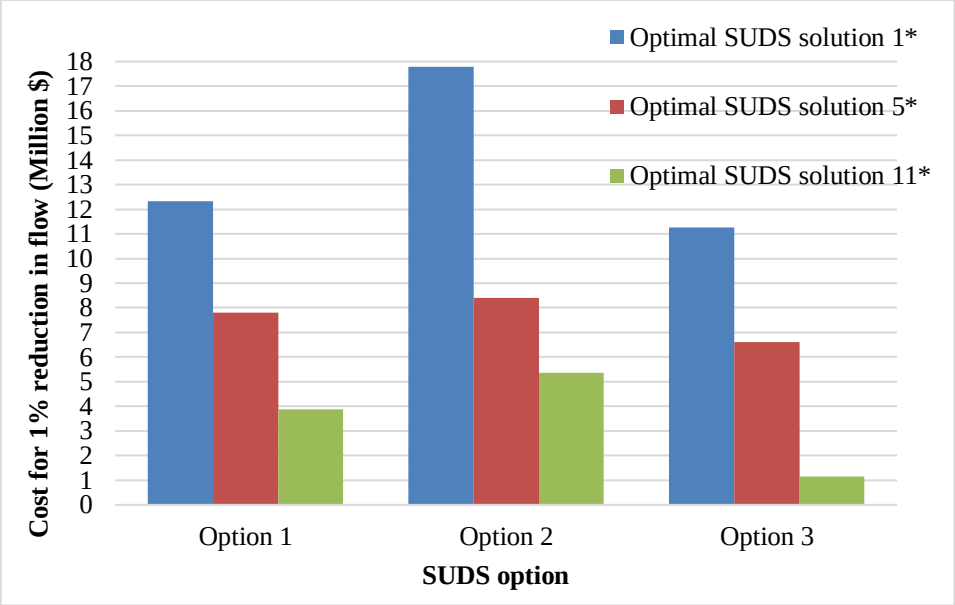


Figure 7-28 A comparison of the cost for a 1% reduction in surface runoff flow volume for SUDS implementation options 1, 2 and 3 identified in the optimal SUDS solution 1*, 5* and 11* for simulations conducted over a 100-year design event with 45% CC

The comparison of the normalised simulation outputs and the cost per 1% reduction in surface runoff volume highlights the importance of considering the influence of return on investment when selecting SUDS solutions. The design event return period was found to be a highly influential factor that produced different SUDS optimal solutions when minimising for cost. For 4 of the 6 design events, it was found that SUDS implementation option 1, i.e. permitting GR on commercial and government buildings only, resulted in the most cost effective SUDS optimal solution 5* with the lowest financial cost of achieving a 1% reduction in surface runoff volume. In comparison, SUDS implementation option 2, permitting GR additionally on private dwellings, did not result in the most cost-effective SUDS optimal solution 5* for any design event return period.

7.4.8 SUDS Optimisation with a Fixed Annual Budget

An attempt was made to show a more realistic application of the proposed SUDS-optimisation-framework as a decision-support-system that could be used to aid decision makers in making optimum SUDS solutions. For this purpose, the framework was applied to find optimum SUDS solutions in the Jeddah City study watershed with the goal of achieving maximum reduction in flooding, whilst adhering to a fixed annual financial budget.

A hypothetical situation was considered where an annual budget of $3M for both construction and maintenance of SUDS solutions was provided to the council for SUDS implementation in the study watershed. The 25-year design storm with SUDS implementation option 1 was used for the simulations. The aim of the exercise was to determine what portion of the fixed budget each year could be spent on new SUDS solution construction and how many years the construction of new SUDS would be possible while achieving maximum flood reduction throughout.

7.4.8.1 Method and Result

The simulation of this hypothetic situation required a small adjustment to be made to the SUDS-optimisation-framework. In its original form, the cost function would calculate the total combined cost of construction and maintenance costs over the entire 25-year period . To address the aim of this simulation exercise, it was required to consider the SUDS cost function on a yearly basis and to separate the financial costs associated with construction from the financial outlay necessary for maintenance. Hence, for the first year, only the construction cost of new SUDS was considered. In subsequent years the budget available for construction of new SUDS was calculated by subtracting the maintenance costs of SUDS built in previous years from the fixed annual budget.

The optimisation framework was run for the first year dedicating all the budget to construction costs. The obtained pareto-optimal front (Figure 7-29) was used to identify the most effective SUDS solution that could be constructed with the $3M budget. It was found that a budget of $3M would result in a SUDS optimal solution with a surface water runoff volume reduction of 92.2 $x10^3$ m^3 (22.9% of reduction). (Note surface reduction= the benchmark scenario from Table7-, 402.2 $x10^3$ m^3 for Scenarios with 25-year return period design storm-310 = 92.2 $x10^3$).

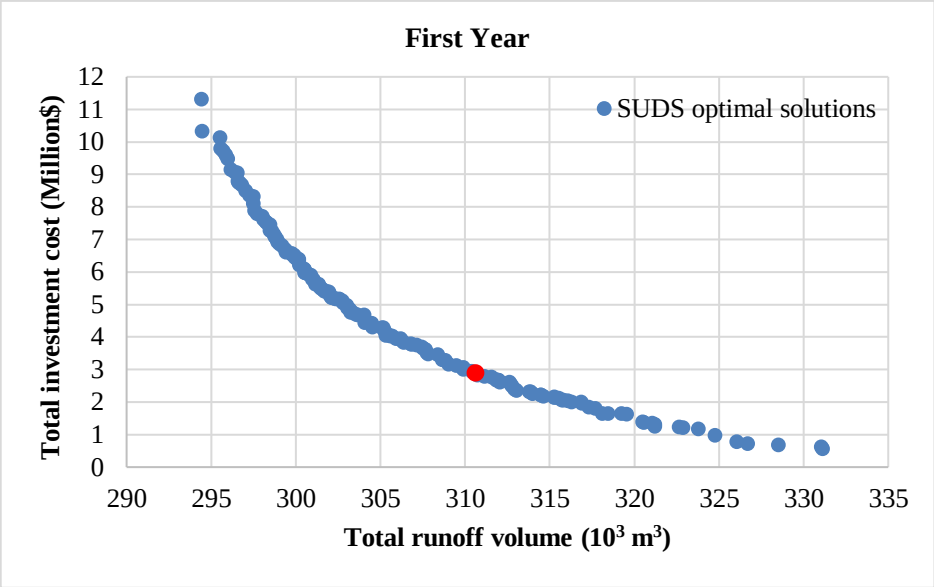


Figure 7-29 The pareto optimal front obtained for year 1 considering construction costs only. The most effective SUDS solutions that could be constructed with the $3M budget is found using the red circle.

The number of SUDS units in each subcatchment of the study watershed for the identified feasible optimal solution are shown in Figure 7-30. This information is used to calculate maintenance costs in following years, which for year 2 equates $1.5M. As the total annual budget is $3M, then $1.5M will be left in the budget of year 2 for construction of further SUDS practices. To identify the optimal SUDS solution with the additional budget, the budget available for construction for the first two years was summed, providing an overall budget of $4.5M. Thus, the percentage of SUDS coverage for each option increased on an annual basis, with the exact percentage increase dependent upon the financial resources which were available. The budget which was remaining after the maintenance costs had been deducted was the financial resources available for SUDS expansion.

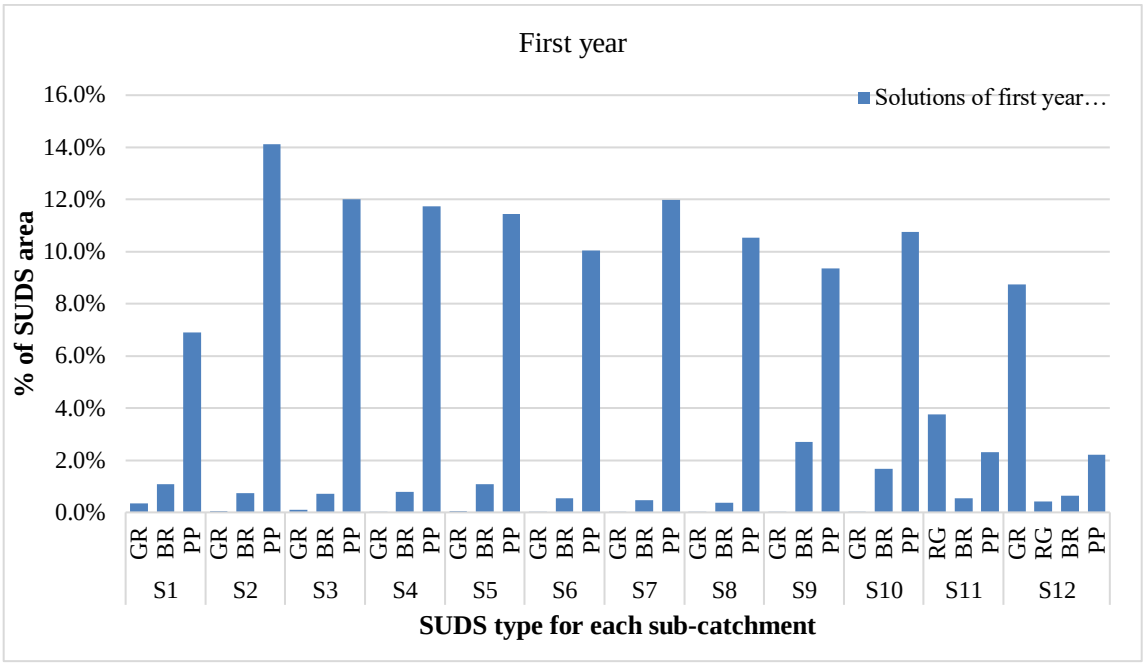


Figure 7-30 The SUDS optimal solution (SUDS percentage coverage) on a per subcatchment basis for year 1.

The optimisation framework was run again for year 2, but this time the parameters of the framework were changed so that the minimum SUDS solution for each subcatchment was set as the outcome of the first year (shown in Figure 7-30). The outcome of the second simulation is given in Figure 7-31. Note that in this output, the construction budget is $4.5M which influences the optimal SUDS solution selected. The outcome of this simulation indicated that the surface runoff volume reduction is 97.2 x10^3 m^3 (24.2% of reduction), a lower surface runoff volume than was produced in the first-year simulation indicating that the inclusion of additional SUDS solutions has reduced the surface runoff volume. The SUDS optimal solution on a per subcatchment basis and type of SUDS to be implemented is given in Figure 7-32.

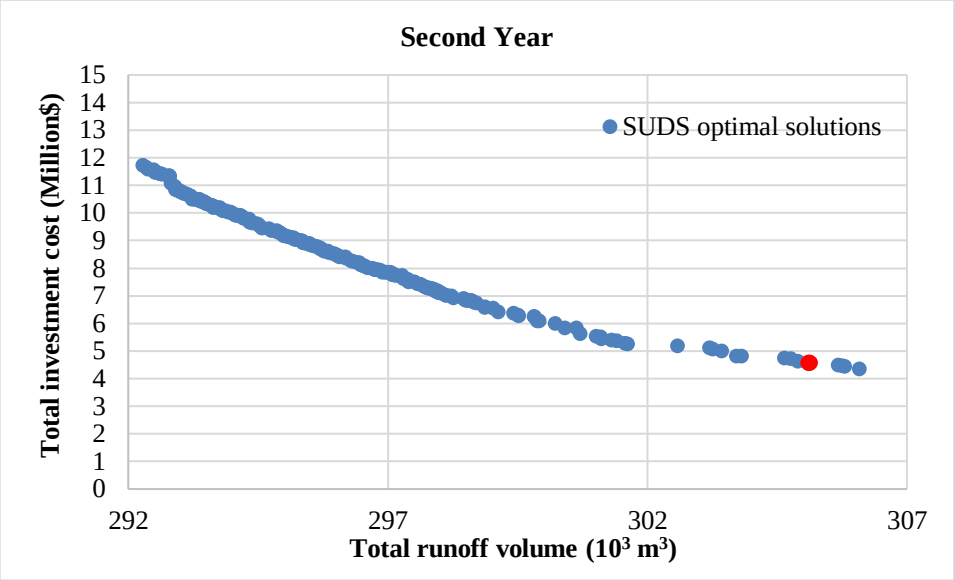


Figure 7-31 The pareto optimal front obtained for year 2 considering construction costs in year 1 ($3M) and year 2 ($1.5M)

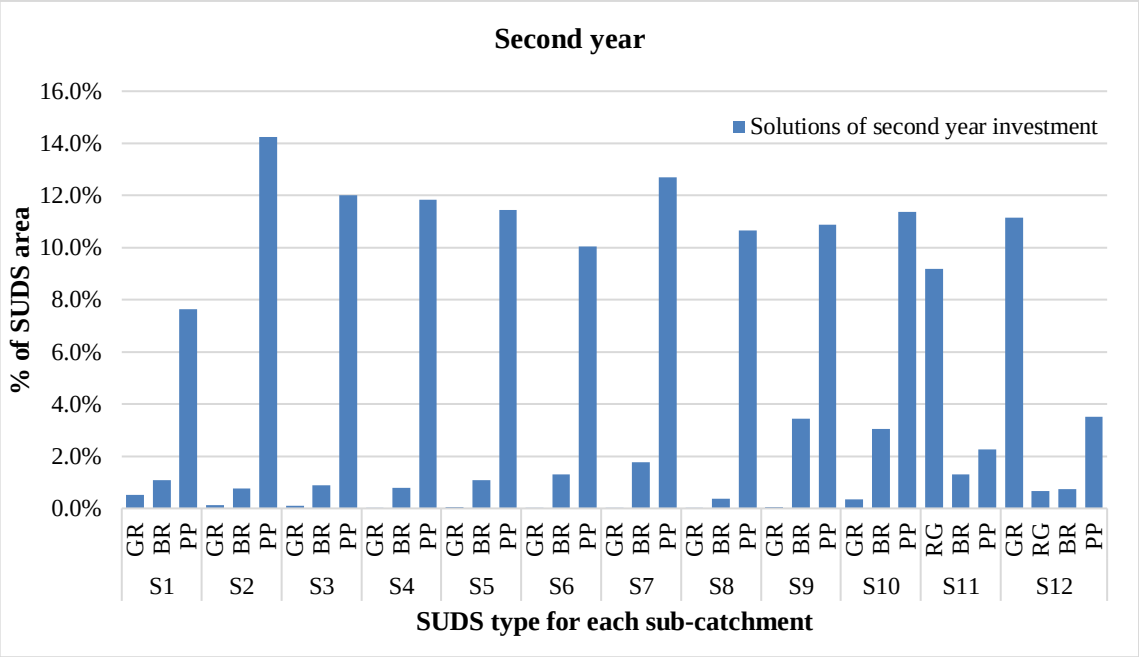


Figure 7-32 The SUDS optimal solution (SUDS percentage coverage) on a per subcatchment basis for year 2 ($4.5M investment).

The maintenance costs for the additional SUDS solutions constructed during the second year calculated at $0.81M. Therefore, the total maintenance cost of the SUDS solution in the third year will be the sum of yearly maintenance cost for the SUDS constructed in the first year

($1.5M) plus the maintenance costs of the SUDS constructed in the second year ($0.81 M) which equates to $2.31M.

The next stage is to repeat the calculations for year 3, where the portion of the annual budget for new construction is $3M minus the combined maintenance costs of $2.31M that gives $0.69M. Again, the procedure followed in the second year is repeated, and the total cumulative budget for new construction is $6.69M. The optimisation framework was then set with the minimum SUDS solutions as the cumulative SUDS constructed in the first and second year and the simulation was run, and the pareto optimal front found (Figure 7-33). The outcome of this simulation indicated that the surface runoff volume reduction is 100 x10^3 m^3 (25% of reduction) a reduction on both years 1 and 2.

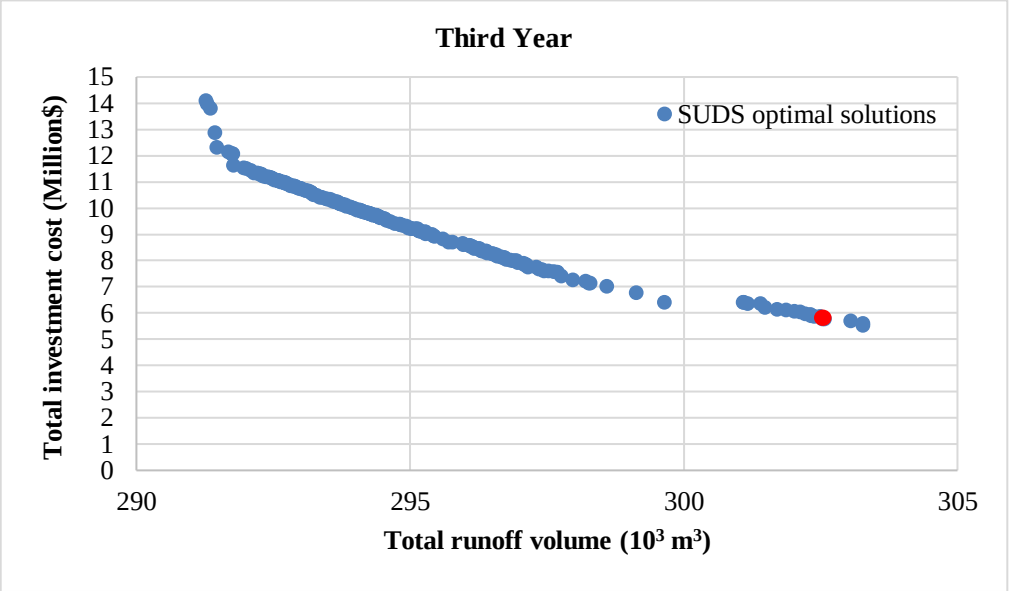


Figure 7-33 The pareto optimal front obtained for year 3 considering construction costs in year 1 ($3M), year 2 ($1.5M) and year 3 ($0.81M)

The SUDS solutions that would be implemented in this scenario are summarised in Figure 7-34.

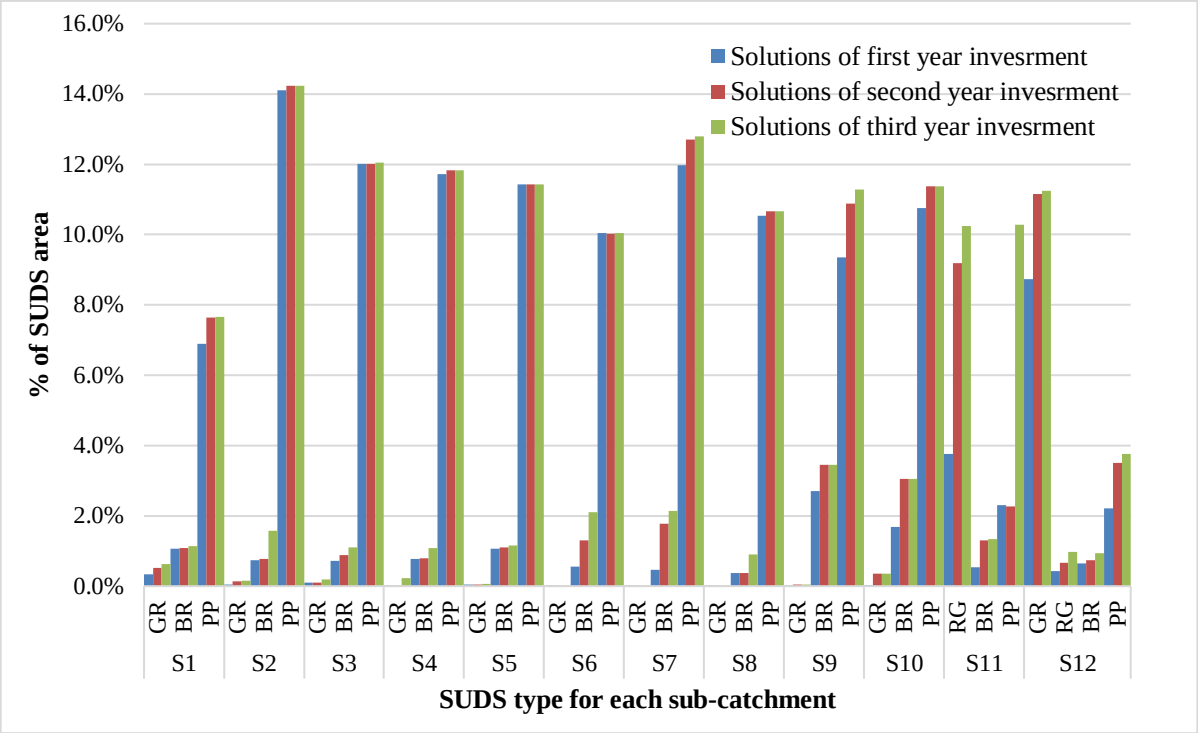


Figure 7-34 The optimal SUDS solutions for each subcatchment derived from the optimisation framework simulations conducted for years 1, 2 and 3.

The same procedure was then followed for the fourth year. The maintenance cost for the SUDS solutions constructed in the third year were calculated as $0.65M resulting in a remaining budget of $.04M (Almost 0) for new SUDS construction in the fourth year. Therefore, it was determined that the on-going maintenance cost for the SUD/S solution identified in this scenario would be $2.96M per year (almost reach a Fixed Annual Budget $3M). When accounting for the influence of inflation, calculated as a 1.5% increase annually, by year 25, the end of the design event, the maintenance cost would be $3.8M annually, $0.8M more than the annual budget. This mean all Fixed Annual Budget will be spending on SUDS maintenance starting form the fourth year.

This hypothetical scenario exemplifies how decision makers could potentially utilise the SUDS-optimisation-framework to make informed decisions on the implementation of a SUDS solution. The process of determining what SUDS solution to construct and when allows decision makers to engage in a dynamic process whereby the financial budget is not exceeded whilst still achieving substantial improvements in stormwater management. This process also highlights how the use of an optimisation framework can identify the extent of SUDS implementation that is possible within a set budget, what the actual surface runoff reduction

will be, the timeframe for SUDS implementation completion and at what point further SUDS implementation does not result in significant benefits in terms of runoff reduction. Thus, the decision that is made is one which is appropriately informed, practical and will result in substantial improvements.

7.5 Summary

In this Chapter, the SUDS implementation options 1 through 3 were utilised to conduct the SWMM analysis and optimisation-framework for the identification of optimal SUDS solutions considering the trade-off between surface volume runoff reduction and financial cost of solutions.

The main findings of the Jeddah City simulations were:

- The most cost-effective SUDS implementation option was most frequently found to be option 1, the use of GR only on commercial and government buildings.
- The existing infrastructure within each subcatchment has a substantial influence on the potential for the use of green roofs.
- All scenarios returned a stormwater runoff reduction of at least 12 % even in the lowest cost solutions.
- The timespan of the design event had a substantial impact on the trade-off between surface runoff reduction and cost. This resulted in a variation of which SUDS implementation option presented the optimal trade-off under different design events.
- It was observed that when GRs were permitted on residential rooftops (SUDS option 2), the subcatchments with a greater area of residential space had a correspondingly greater proliferation of GRs within the optimised SUDS solutions in comparison to areas with lower residential area. This resulted in a substantial increase in the cost of the SUDS solutions that were identified using SUDS implementation option 2 which meant that the optimal solutions presented in these simulations rarely resulted in a better cost and surface runoff reduction trade-off than the SUDS optimal solutions identified using SUDS implementation options 1 and 3.
- The hypothetical situation (see Section 7.4.8) demonstrated how the SUDS-optimisation-framework could potentially be applied to inform decision makers in the process of developing a SUDS solution. The use of the optimisation framework provided a programme

for the development of an SUDS solution which balanced the costs of construction with the costs of maintenance and allow for easy identification of the point at which the cost of further SUDS solution construction would not provide significant benefit in terms of surface runoff volume reduction.

- The outcomes of these scenarios could provide valuable information to decision makers. The information provided could inform decisions makers as to the variations in stormwater surface runoff and peak flow reductions, highlighting where it is possible to achieve substantial reductions in both, whilst also managing the financial cost outlay.

Chapter Eight: Conclusion and Recommendations

8.1 Conclusion

The aim of the thesis was to develop a Decision-Support-System (DDS) also referred to as the SUDS-optimisation-framework, to identify the optimal SUDS solutions for implementation in the selected study watershed in consideration of the financial outlay required for the selected SUDS. The overall aim of the study was achieved with the production of the DDS based on the Borg multi-objective evolutionary algorithm in combination with the Jeddah-SWMM. The location selected for the conducting of this research study was an urban watershed within Jeddah City, KSA. This location was selected due to it being a typical representation of a developed urban area in an arid environment. Overall, the study area selected was $5km^2$ with 86% of the urban area being classified as highly developed. The study watershed was divided into 12 subcatchments on the basis of terrain, flow networks and the existing drainage system. The subcatchments were comprised of a variety of building types and densities and, due to the variation in the types of buildings and their distribution within the urban environment, no two subcatchments had the same distribution of land cover/use type. This added an interesting dimension to the study as it provided a secondary scope of examining how the optimal SUDS solutions identified varied with different urban infrastructure development. In the following sub-sections, the main research findings are presented as bullet points.

8.1.1 Factors that Affect the Use of SUDS in Arid and Semi-Arid Regions (ASARs)

A review of published literature informed the conclusions drawn regarding the factors that may potentially affect the use of SUDS in ASARs, namely:

(i) The precipitation patterns, including the timing, duration and intensity of rainfall events.
(ii) The extent of urban development and whether the SUDS is to be implemented in an existing developed area (retrofitted) or implemented as part of the development process when a new urban area is constructed.
(iii) The geomorphological features of the watershed (which influences the patterns of water flow through a catchment).
(iv) The suitability of different SUDS options to the study environment is variable; there was found to be a highly limited number of studies which had been conducted within an

environment of similar climatic patterns and, therefore, the potential functionality of different SUDS options was found to be difficult to quantify.

(v) The effects of CC may have a significant impact on the future functionality of different SUDS options.

This review contributed to the achievement of objective 1 (see Section 1.4) in an in-depth and detailed manner.

8.1.2 Suitable Stormwater Simulation Model for SUDS Selection and Placement

These outcomes contributed to the achievement of objective 2 (see Section 1.4) and highlighted the limitation and advantages of the existing stormwater simulation models which had been applied to similar scenarios.

(i) Reviewing the literature showed that the Stormwater Management Model (SWMM) would be appropriate for assessing the impact of SUDs in the Jeddah City watershed due to its flexibility and the range of SUDS options which could be included.

(ii) It was also found that the attributes and capabilities of this model are insufficient for identifying optimum SUDS types and location for the different investigated scenarios. Therefore, the need to combine SWMM with an optimisation algorithm was recognised.

(iii) Due to the lack of currently published studies investigating a similar climatic environment, it was determined that further information would need to be gathered to inform the development of the model's parameters.

8.1.3 SUDS in Arid and Semi-Arid regions: Survey by Questionnaire

These findings fulfilled objective 4 (see Section 1.4) and also provided information which contributed towards the achievement of objectives 5 and 6.

(i) The responses to the questionnaire highlighted that, due a lack of previous implementation of SUDS in similar environments, the provided cost estimates, were highly variable due to their being based on expert opinion rather than experience. This means that there is a degree of uncertainty associated with the calculated financial costs, which are unlikely to be resolved without substantial implementation of SUDS in these environments.

(ii) The questionnaire responses indicated that there was a slightly divided opinion among experts as to which SUDS options would be the most suitable for Jeddah City. The

respondents indicated that green roofs (GRs), permeable pavements (PPs), bio-retention units (BRs), swales (SWs), infiltration trench (ITs) and rain gardens (RGs), respectively, would potentially be suitable for implementation in this scenario. However, analysis of selected areas showed the available locations for applying the different SUDS types mentioned, except ITs and SWs. In addition, these findings were quite similar to those of the literature review, which indicated that GRs, PPs, RGs and BRs are most likely to be appropriate for the scenario and, thus, these SUDS were selected for this study.

(iii) It was also found that GRs and PPs have lower maintenance, operation and construction cost than RGs and BRs.

8.1.4 Parameterising and Calibrating SWMM for the Study Watershed

The findings reported in this section contributed towards the attainment of objectives 2, 3 and 6 (see Section 1.4).

(i) The input parameters were partially dependent upon the methodology choices, such as the equation selected for infiltration and the routing method. Other parameters are necessary regardless of methodology choices.

(ii) It was found that the Jeddah-SWMM model provided an accurate and detailed representation of the patterns of water flow within the area of study

(iii) The Jeddah City watershed is an ungauged catchment; therefore, it was determined that empirical formulae needed to be applied to derive the flow data from other hydrological response data, including rainfall.

(iv) The SCS-CN method and the production of synthetic unit hydrographs were used to estimate the flow patterns in the Jeddah City catchment.

(v) It was found that the calibrated Jeddah-SWMM model predictions are reasonably accurate and, thus, can serve as the basis for testing and analysing SUDS solutions in Jeddah City.

8.1.5 Selection of Appropriate Optimisation Algorithm and Setting-up of the SUDS Optimisation Framework

The following reported conclusions were direct contributors to the achievement of object 2 and contributed towards the attainment of objectives 3 and 5.

(i) Reviewing the literature, an algorithm called Borg multi-objective evolutionary algorithm (Borg-MOEA) was identified as the most appropriate optimisation technique for this application.

(ii) The use of BORG in combination with SWMM allows the identification of optimum solutions that are the most likely to be successful in meeting the objective of this study, namely the provision of a SUDS solution to stormwater management in Jeddah City, whilst also considering the trade-off between successful stormwater management solutions and the cost of solution implementation and maintenance.

(iii) It was found to be unnecessary to examine both peak flow and stormwater runoff volume as a reduction in stormwater runoff volume had a subsequent impact on reducing the peak flow volume.

(iv) In total, 37 decision variables were included as this provided sufficient information to explore potential solutions whilst also increasing the likelihood of adequate exploration of the solutions space and convergence on the Pareto-optimal front.

8.1.6 SUDS Optimisations in the Study Watershed

(i) The most frequently selected SUDS option was found to be PPs. It is suggested that this option was selected most frequently due to its relatively lower cost and the efficiency in managing stormwater surface flow; therefore, representing the high cost benefit trade-off option. Thus, the outputs of the model scenarios are highly suggestive of PPs as being the most appropriate solution to sustainable management of stormwater surface runoff in Jeddah City.

(ii) The use of RGs was found to be the second most effective SUDS option for reducing the total stormwater surface runoff

(iii) SUDS option 1 was found to be the most cost-effective of the different implementation options.

(iv) It was found that all scenarios led to reduce a stormwater runoff with average flow volume reduction of 17%.

(v) The influence of CC was considered in some simulations by using an estimated future rainfall pattern under CC in the Jeddah watershed. It was observed that, when the system was optimised under the CC rainfall scenario, then the performance of the SUDS solutions decreased, with a corresponding influence on the percentage of total and peak flow reduction. It is suggested that this is due to the modelled rainfall event under CC being

significantly more intense than other modelled events; thereby the performance of implemented solutions will correspondingly decrease.

(vi) The influence of climate change (CC) was modelled in some simulations by using an estimated future rainfall pattern under CC in the Jeddah watershed. It was observed that, when CC effects were included within the rainfall scenario, the performance of the SUDS solutions decreased. The reduction in the performance of the SUDS solutions had a corresponding influence on the percentage of total and peak flow reduction, whereby the magnitude of these reductions were lower than observed for other scenarios. Thus, the application of the same SUDS solutions under scenarios including CC effects, in comparison to the same scenarios without CC effects were not as effective in addressing the stormwater management problem. It is suggested that this is due to the modelled rainfall event under CC being significantly more intense than other modelled events; thereby the performance of implemented solutions will correspondingly decrease. This highlights the importance of including CC effects within development scenarios to ensure that solutions are designed which perform optimally not only under the current conditions, but also under future conditions expected to occur due to the influence of CC.

(vii) Regarding the hypothetical scenario that was developed and tested by the DDS (scenario details in Section 7.4.8), it was found that this scenario gave a good understanding about how the framework works by providing suitable solutions among many available options, whilst adhering to a financial budget.

These outcomes contributed to the achievement of objectives 5 and 6 (see section 1.4). In combination, all of the outcomes reported in the preceding sections directly contributed towards the attainment of one or more objectives which when they were all achieved allowed the overall aim of the study to be completed. All of the objectives for the research study, which are given in full in section 1.4, were achieved throughout the course of the research conduction, thereby permitting robust and in-depth conclusions to be made.

8.2. Recommendations for Future Research

Whilst this study considered a range of aspects relating to the use of models for SUDS selection, including factors influencing model setup and calibration to factors influencing the selection and optimisation of SUDS solutions, there are some limitations that will need to be addressed in future research. Considerations for future development of the model include:

A. The potential for including other impacts of SUDS, such as the influence on the urban heat island effect, air pollution and social concerns, within the calculations. These considerations could potentially influence the outcome of the trade-off between the financial cost and the benefits which are derived.

B. The developed DSS incorporated SUDS options into the SWMM model in a parallel formation. This means that there was no consideration given to flow from one type of SUDS to subsequent SUDS. There is the potential that the implementation of SUDS options in a linear (series) format may have a substantial influence on reduction of stormwater surface flow and potentially present more optimal solutions.

C. The hydrologic model used for the SWMM model was a relatively simplistic representation of the study area watershed and, as such, only allowed for limited variation in the positioning of the SUDS in the subcatchments. This was partially due to the study area being an ungauged catchment with a lack of similar gauged catchments which could be used as a proxy. The development and incorporation of a more detailed hydrologic model would enable a greater degree of flexibility and variation in the positioning of the SUDS within the subcatchments and assessment on the watershed flow in the catchment. This would also produce a more detailed outcome of the effect of SUDS on watershed flow and may enable the identification of more optimal SUDS solutions and the production of more accurately modelled scenarios.

D. The subcatchments into which the study area was divided were relatively large. In future work, if the subcatchments were further divided into smaller subcatchment units, then a more detailed output would result, which, in turn, could identify areas of concern that would benefit greatly from the incorporation of specifically designed SUDS solutions. However, dividing into smaller subcatchments is complex and requires more time and resources, which were limited for this study.

E. The DSS was developed to address the issue of stormwater surface runoff in terms of solely considering the volume of runoff produced as a trade-off with the financial costs of implementation and maintenance. However, stormwater management is also linked to the water quality of surrounding waterways from the discharge of stormwater runoff. The model could be improved by incorporating the factor of water quality improvements/degradation under the

implementation of SUDS solutions; this could also impact the relative costs of the SUDS solutions when considering the potential for increasing or reducing strategies to improve water quality. This would aid in understanding how different developmental solutions could potentially impact the reduction of pollutant loads in stormwater runoff and how this impacts the downstream environment.

F. There is the potential for including additional SUDS options into the DSS. The SWMM model has the ability to include up to eight different types of SUDS solutions; however, the tested model and framework only included four. There are several other types of SUDS options that could potentially contribute significantly towards stormwater management in ASARs; however, in order to effectively assess this potential, they would need to be incorporated into future iterations of this model and framework.

G. Finally, one highly important area where future research will be necessary to improve the outputs of this model is with regard to the cost of SUDS implementation and maintenance in ASARs. This is information that will become more widely available as SUDS solution begin to be implemented in such environments, but it may be possible to gather additional data in the meantime by conducting more extensive surveys and interviews with experts in this field. Additionally, it is noted that value depreciations may also impact the current cost functions that are incorporated within the model and it may become necessary to develop a sensitivity analysis to be incorporated within the Pareto-optimal trade-off front to account for the influence of this cost function.

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Appendices

Appendix A: The Jeddah Watershed Data

Different types of input data were needed for modelling the case study (Jeddah City) in SWMM. These data were categorised into three main types: land use map, soil map and climatological data (discussed in Chapter Three). The following sub-sections include details of data collected and used for this study and include the full details of SCS Curve Number Method Techniques and procedures that were selected and used for calculations of flow estimations.

A-1 Geological Map

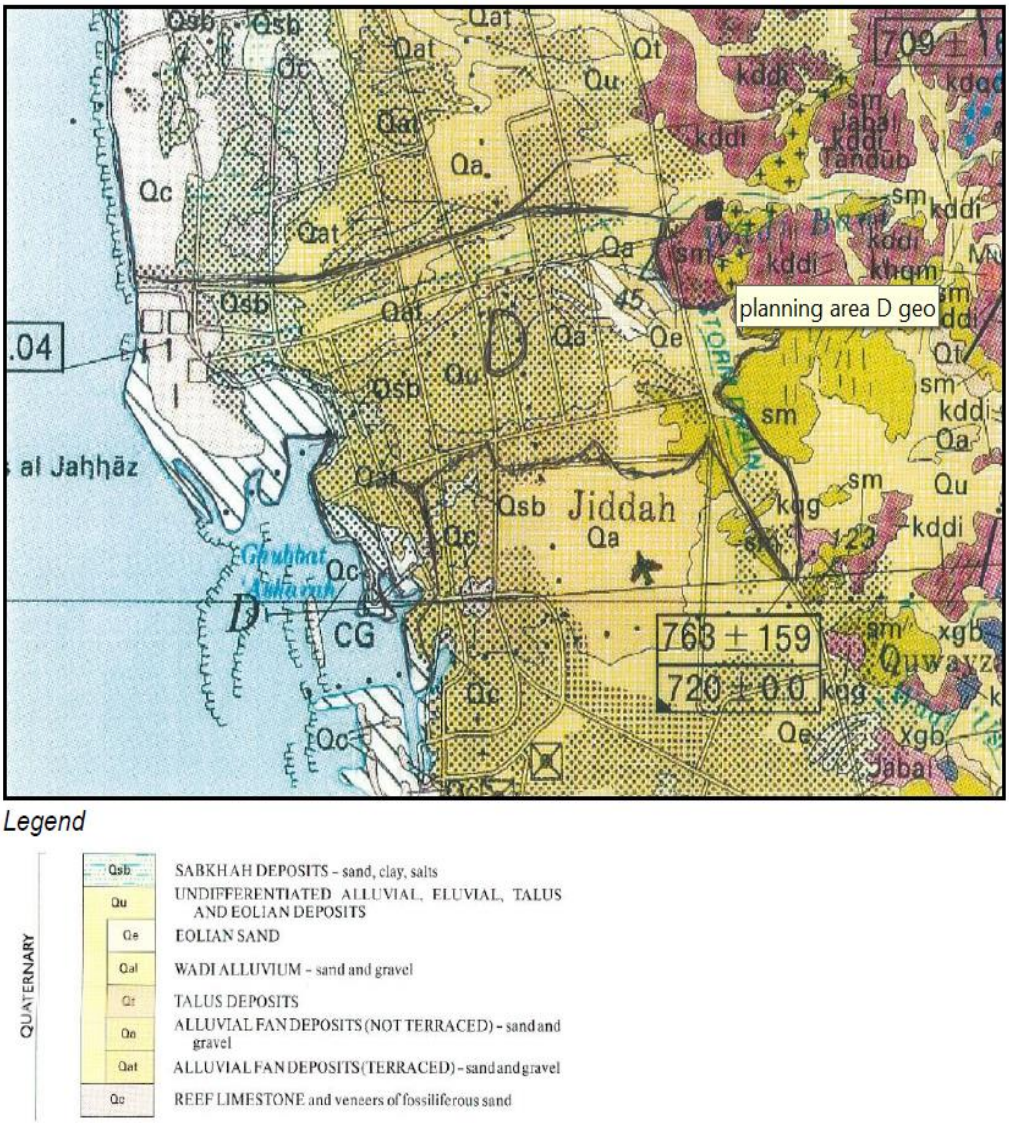


Figure A-1 Planning Area D's geology informations (AECOM, 2014 & Saudi geological Suvey)

A-2 Historical Rainfall Data

Sub-daily historical rainfall data (hourly) which were observed at Airport (41024) rain gauge in Jeddah City are shown in the following figures.

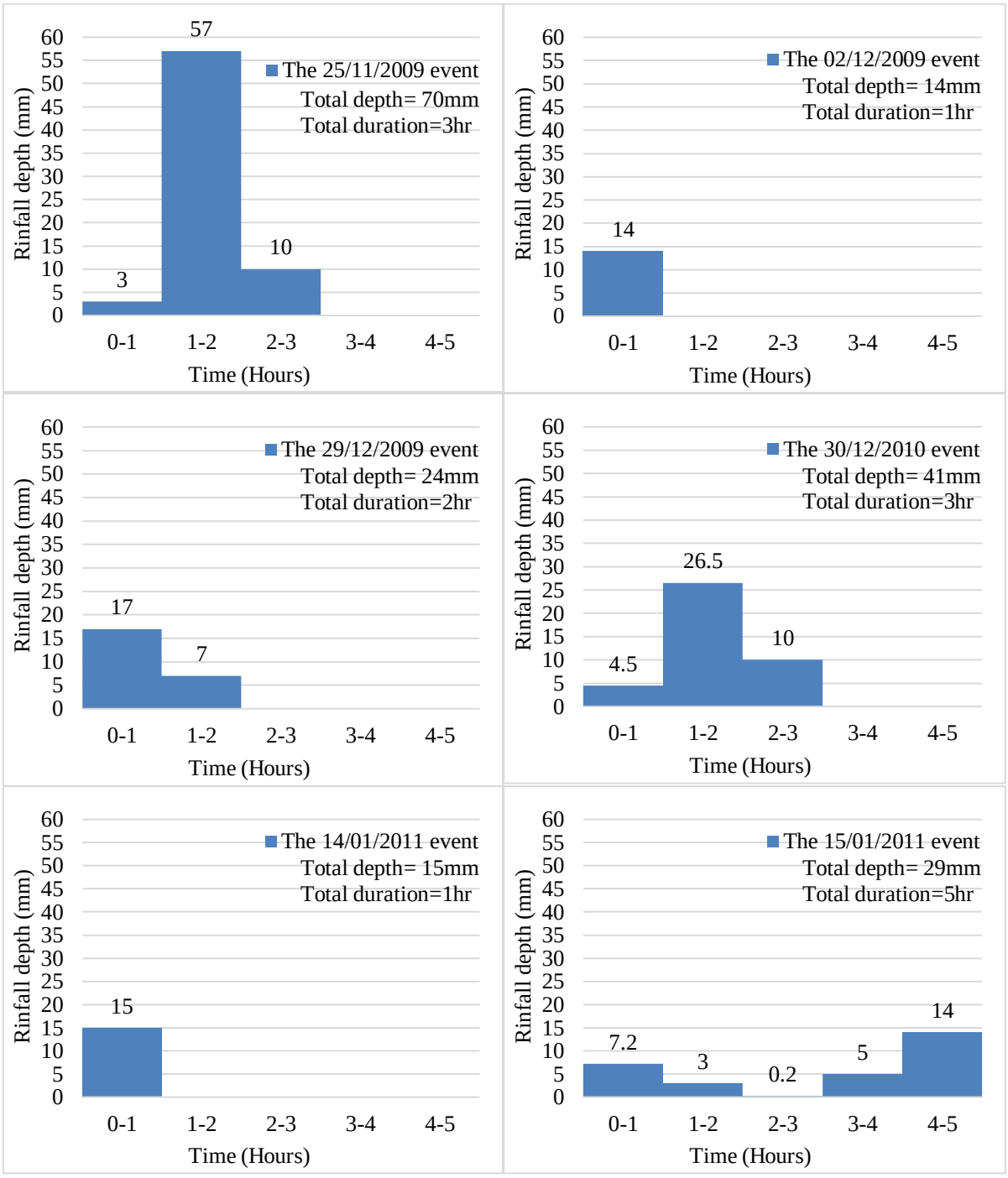


Figure A-2 The rainfall distribution hyetographs for historical rainfall events

A-3 Techniques and Procedures for Calculations of Flow Estimations

A-3-1 SCS Curve Number Method (SCS-CN)

Introduction

The SCS method has been commonly applied to small and medium-sized catchments to estimate rainfall-runoff based on principles and assumptions made about rainfall intensity and soil infiltration capacity and how they vary in both time and space (Yu, 1998). The SCS-CN method is appropriate for the Jeddah City study as it utilises land use, soil types and terrain characteristics (all data of which are available) in combination with the runoff CN (determined for the study site in Chapter 4) to estimate rainfall-runoff (Liu and Li, 2008). Liu and Li (2008) found that the application of the SCS method to a small catchment in China produced rainfall-runoff estimations which had an accuracy of greater than 75% when compared with measured runoff. However, some studies have criticised the traditional SCS-CN method due to the lack of accounting for the influence of soil moisture content on the potential for rainfall infiltration (Shaw and Walter, 2009). This lack of accounting arises due to the relatively simplistic assumptions made by the SCS-CN method whereby it is assumed that no rainfall surface runoff occurs until a rainfall threshold is met, beyond which the magnitude of rainfall surface runoff increases as the amount of rainfall increases (Shaw and Walter, 2009). This potentially limits the accuracy of the rainfall-runoff calculated by the application of this method (Eli and Lamont, 2010). However, other studies have demonstrated that the more accurate the calculated CN, then the more accurate the resultant rainfall-runoff flows determined by the SCS method are (Fan et al., 2013; Kowalik and Walega, 2015). Thus, even with the known limitations of the SCS-CN method, it still remains one of the most commonly applied methods for the determination of rainfall-runoff flow with multiple studies demonstrating that it can be applied with a high level of accuracy. For example, Yao et al. (2018) applied the SCS-CN method to calculate the rainfall-runoff risk characteristics in an urban area of Beijing, whilst simultaneously applying robust methods to ensure that the calculated CNs accurately reflected the study environment, thereby increasing the accuracy of the calculated rainfall-runoff flows.

The application of the SCS-CN method results in the production of synthetic unit hydrographs (SUHs), which are dimensionless and produce a single smoothed peak which simulates the rainfall-runoff flow attributed to one unit of runoff volume (Bhunya et al., 2003). A study conducted by Jang et al. (2007) assessed the use of the SCS-CN method with SUHs in

combination with the SWMM model and found that its use to estimate the rainfall-runoff flow in an ungauged urban environment provided a relatively accurate portrayal , which could subsequently be utilised as a baseline when using an SWMM model to predict the impact of urban stormwater drainage improvement scenarios (Jang et al., 2007). Similar studies have also found that, despite the critiques of the use of SCS-CN and SUHs, it still remains a methodology of sufficient accuracy to enable the estimate of rainfall-runoff flows in ungauged catchments with limited dataset availability (Lastra et al., 2008). Therefore, given the data availability for this study in Jeddah City, it was determined that the use of the SCS-CN method and SUHs would provide the most accurate estimation of rainfall-runoff flows in the absence of measured flow patterns so long as the calculation of the CN was undertaken in a methodical and precise manner.

Description of Method

When rainfall is diverted and absorbed by vegetation, when it transmutes into surfaces, runs into storage or simply evaporates, it does not become run-off and is thus classed as 'losses'. Such losses are denoted in the SWMM model by using the SCS-CNapproach. For this, the CN is needed, as is the initial abstraction (Ia) and the calculated percentage space of the subcatchment area whose surface is impervious.

Excessive precipitation is assessed by the SCS-CN model as a use of cumulative precipitation, antecedent moisture, land use and soil cover, for which the following equation is used (USACE, 2000);

$$P_e = \frac{(P-I_a)^2}{(P-I_a+S)} \quad \text{(A-1)}$$

Where:

P_e is accumulated precipitation excess at time t;

P is accumulated rainfall depth at time t;

I_a is the initial abstraction (=initial loss)

S is potential maximum retention, which is a measure of the ability of a catchment to abstract and retain rainfall.

By analysing the results of numerous experimental catchments of limited size, the following I_a empirical association was developed by SCS (SCS, 1986):

$$I_a = 0.2S \quad \text{(A-2)}$$

The maximum retention (S) and catchment characteristics are related through an intermediate parameter which is CN, as:

$$S = \frac{25400 - 254CN}{CN} \quad \text{(A-3)}$$

The gamut of CN values runs from 100 for water bodies to around 30 for soils that are permeable, with high levels of infiltration.

A-3-2 Development of Run-off Curve Numbers for Selected Study Watershed

How the CN is chosen is dependent on an appraisal of the key hydrological soil group, how the land is used, and the previous moisture condition of the soil. Identification of this study's soil group was through the soil characteristics in the selected area, as noted in Section 3.3.2. The use of the land and its percentage coverage was discerned via a land use map; ArcGIS was then employed to analyse it. Soil conditions were measured by taking into account Jeddah's location, data regarding rainfall and estimates of infiltration; the soil was assessed as condition two. Following this analysis, and considering the type of soil, the designated use of the land and previous levels of soil moisture, five distinct CNs were calculated and chosen for every subcatchment within the area of study. An estimation of CN0.20 values was made from the table built by SCS (1986) (Tables A-3 & A-4). For roofs, roads, parking spaces, CN0.20 of 98 was delegated, while for CN0.20 of 79, 69 was allocated to open areas and backyard, as was a CN0.20 of 74 and 86. How underdeveloped areas might be allocated is dependent on the classification of soil types. Table A-1 below indicates the CN estimation results.

Table A-1 Subcatchment Curve Number Estimates for Selected Areas

	Sub-Catchment	%Roof (CN98)	%Road (CN98)	%Parking (CN98	backyard (CN89)	Space (CN83)	Un-D*1 (CN87)	Weighted CN0.20	S	Initial Abstraction (mm)
Soil C	S1	38.6	24.9	8.5	2.9	7	17.1	93.8	16.7	3.3
	S2	49.4	18.7	14.2	3.3	8.4	5.9	95.7	11.4	2.3
	S3	46.8	16.3	12	4.9	8.9	11.1	95.0	13.4	2.7
	Sub-Catchment	**% Roof (CN98)**	**Road (CN98)**	**Parking (CN98**	**backyard (CN85)**	**Space (CN79)**	**Un-D*1 (CN82)**	**Weighted CN0.20**	**S**	**Initial Abstraction (mm)**
	S4	52.4	16.4	11.8	3.7	8.3	7.4	94.8	14.1	2.8
Soil B	S5	53.2	19.3	11.5	4.2	9.2	2.67	95.3	12.4	2.5
	S6	39.2	23.2	11.7	2	6.7	17.3	93.8	16.8	3.4
	S7	59.6	18	12.8	4.2	5.4	0	96.4	9.4	1.9
	S8	53.4	25.8	10.7	3.3	4.3	2.5	96.4	9.6	1.9
	S9	56.2	20.4	11.3	3.1	8.6	0	95.6	11.8	2.4
	S10	50.5	27.3	11.4	2.6	7.9	0	95.9	11.0	2.2
	Sub-Catchment	**% Roof (CN98)**	**Road (CN98)**	**Parking (CN98**	**backyard (CN89)**	**Space (CN86)**	**Un-D*1 (CN87)**	**Weighted CN0.20**	**S**	**Initial Abstraction (mm)**
Soil C	S11	13.8	39.3	10.3	1.6	34.1	0	92.9	19.5	3.9
	S12	21.9	33.3	11.9	8.2	16.9	7.9	94.5	14.9	3.0

A-3-3 Time to Peak and Peak Flow Calculation

Description of Method

The SCS UH model can be defined as a single-peaked, dimensionless UH, which represents the UH discharge – U_T – as a ration of the peak discharge, q_p(also known asU_P), for any time t, a fraction of T_P, the time to UH peak. McCuen, R. H. (1998) proposes the UH peak and the time of the UH peak to be connected by:

$$q_p = \frac{484\ A\ Q}{T_P} \tag{A-4}$$

A: area in mi^2

T_P: Time to peak in hours

Q: The run-off depth equal to 1 in

Constancy of 484 (the conversion constant or peak flow constant) indicates that 3/8 of the UH area is under the rising limb. Larger early peaks may result from difficult terrain and urban zones, therefore peaking factor values may settle at around 600. Similarly, flat, swamp-like areas are likely to hold and keep water, which results in a staggered, lower peak. Such conditions yield values of 300 or less (SCS 1972; Wanielista, et al. 1997; McCuen, R. H. 1998). The constant 484 may thus not apply to watersheds in general. Potential peaking factor values are shown in Table A-2, as are the ratios linking recession limb length to rising limb. Nevertheless, recording the reasons why the constant of 484 might be changed would be essential, as such an action would alter the configuration of the unit hydrograph. When the unit hydrograph's shape is altered, the ratios of volumes under the respectively rising and falling sides of the original unit hydrograph must be borne in mind, as the original is dimensionless, and the end volume has to stay at one inch.

As the chosen area is an extremely flat, urban space, and numerous prior studies of Areas encompassing Jeddah claim SCS typical constant values, the chosen approach for this study is SCS typical value.

Equation A-4, which is also given by SCS, in SI units, posits the relation of UH peak and the time of UH peak by:

$$q_p = \frac{CA}{T_P} \tag{A-5}$$

A is the catchment area; C is a Conversion Constant (or peak factor) (2.08 in SI unit). The time of the peak is associated with the length of time of the excess precipitation unit as:

$$T_P = \frac{\Delta t}{2}\ t_{log} \tag{A-6}$$

Where Δt = the excess precipitation duration.

t_{log} = the catchment lag.

The equations that enable T_P and Up to locate the UH peak can be solved if there is specification of the lag time. If T_P and U_P are known, UH can be determined via the dimensionless from Table A-8

A.3.3 Lag Times – For Selected Area

It is not easy to calculate the timing parameter, as it is somewhat subjective, but this parameter has a large degree of influence on the unit hydrograph's values. The definition of "lag time" by USACE (2000) is the length of time from the central mass of excessive rainfall to the hydrograph peak. "Time of Concentration (T_C)" has been depicted as the length of flow time

from the catchment's hydraulically remotest point to the catchment's outlet. This SCS lag equation is an empirical method, estimating lag time directly. The SCS has evolved this method empirically. It has also been advocated by SCS (1972) that this equation should be used on basins smaller than 2000 acres that are regarded as somewhat homogenous. If catchments are ungauged, SCS proposes the UH lag time may be estimated as 0.6 times theT_C. A large amount of equations have been suggested for the estimation of Tc (McCuen et al., 1984). Numerous hydrology text books have detailed these extensively, and so further description is not added here, as a lot of inputs need to be calculated. Prakash (2004) proposes, nevertheless, that it is expedient to utilise a minimum of three separate techniques to calculate the T_C, and within the total range of the three assessed Figures, make a considered judgement of the end value (Prakash, 2004). SCS lag time was considered more desirable, as it is more consistent with the chosen SCS UH model and the area chosen is considerably smaller than 2000 acres.

Description of Method

A short description of the SCS lag time method is detailed below, with the full details being available in SCS (1985). The SCS lag equation is:

$$t_{log} = \frac{2.587 * L^{0.8} (\frac{1000}{CN} - 9)^{0.7}}{1900 * H^{0.8}} \quad (3\text{-}7)$$

Where tlag = lag time in hours; L = Hydraulic catchment length (m); CN = Hydrological area-weighted CN (no units); and H = Average catchment land slope (%); For the SCS lag time equation (3-7), it is necessary to obtain L, CN, and H.

Result of flow estimation Calculations

For every subcatchment of the case study watershed, L was measured in GIS for each subcatchment. The path of the flow was calculated from observations of the delineated subcatchment (detailed in Section 4.2, Chapter Four). Following this, CNs were created by working out the percentage area in every subcatchment that was allocated a specific CN (98, 89, 87, 82 and 79). A weighted average of CN0.20 was computed for the subcatchments. A digital elevation model (DEM) was then constructed for the slope with the Surface Analysis tool in ESRI's Spatial Analyst application. The slope DEMs then yielded a statistical mean for each subcatchment, using the Zonal Statistics tool in Spatial Analyst. Additionally, Eq.(A-2)

and Eq.(A-3) were used to work out maximum retention and initial abstraction. Equation (A-7) was then used to find Tlog then time to peak (Tp) and peak flow were calculated according to Eq.(A-6) and Eq.(A-5) (time to peak and peak flow for one-unit cm), Also, time to base was calculated (Tb= 2.67 Tp) and the results are shown in Table 3-4. The actual hydrograph was then calculated and drawn by applying excess rainfall (historical rainfall, see Table 3-2) and following procedure Eq.(A-1). This was done for each subcatchment. The calculations were done on Excel spreadsheet. Full hydrographs of all historical rainfall events can be found in Section B-1 within calibration results.

Table A-2 Shows results of SCS calculations

Sub-Catchment	Area (km^2)	Length (m)	Initial Width (m)	Slope (%) (m/m)	Weighted CN0.20	Maximum Retention (S)	(Ia) (mm)	Lag Time – Base (hr)	Tp (hr)	Up (m^3/s)	Tb (hr)
S1	0.28	818	347.3	2.33	93.8	16.7	3.3	0.27	0.77	0.8	2.1
S2	0.43	1088	398.8	1.50	95.7	11.4	2.3	0.39	0.89	1.0	2.4
S3	0.36	1101	327.6	1.53	95.0	13.4	2.7	0.40	0.90	0.8	2.4
S4	0.25	942	263.3	1.53	94.8	14.1	2.8	0.36	0.86	0.6	2.3
S5	0.54	1280	423.6	1.08	95.3	12.4	2.5	0.53	1.03	1.1	2.7
S6	0.80	1506	528.4	1.36	93.8	16.8	3.4	0.58	1.08	1.5	2.9
S7	0.42	1277	326.5	1.21	96.4	9.4	1.9	0.47	0.97	0.9	2.6
S8	0.57	1694	338.1	1.08	96.4	9.6	1.9	0.63	1.13	1.1	3.0
S9	0.13	465	283.8	1.45	95.6	11.8	2.4	0.20	0.70	0.4	1.9
S10	0.14	438	316.1	2.02	94.8	14.1	2.8	0.17	0.67	0.4	1.8
S11	0.04	295	139.7	1.54	92.9	19.5	3.9	0.15	0.65	0.1	1.7
S12	0.89	1817	489.0	1.05	94.5	14.9	3.0	0.74	1.24	1.5	3.3
T. Area	4.85km^2										

A-4 List of Tables Used for Estimation of Flow Calculations

Table A-3 Peak factors of hydrograph and limb ratio (Wanielista et al., 1997)

General Description	Peaking Factor	Limb Ratio (Recession to Rising)
Urban areas; steep slopes	575	1.25
Typical SCS	484	1.67
Mixed urban/rural	400	2.25
Rural, rolling hills	300	3.33
Rural, slight slopes	200	5.5
Rural, very flat	100	12.0

Table A-4 Soil group definition (NRCS, 2009)

Group	Meaning	Saturated Hydraulic Conductivity (in/hr)
A	Low runoff potential. Water is transmitted freely through the soil. Group A soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures.	> 1.42
B	Moderately low runoff potential. Water transmission through the soil is unimpeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures.	0.57 – 1.42
C	Moderately high runoff potential. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures.	0.06 - 0.57
D	High runoff potential. Water movement through the soil is restricted or very restricted. Group D soils typically have greater than 40 percent clay, less than 50 percent sand, and have clayey textures.	< 0.06

Table A-5 SCS curve numbers for urban areas

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Cultivated land				
Without conservation treatment	72	81	88	91
With conservation treatment	62	71	78	81
Pasture or range land				
Poor condition	68	79	86	89
Good condition	39	61	74	80
Meadow				
Good condition	30	58	71	78
Wood or forest land				
Thin stand, poor cover, no mulch	45	66	77	83
Good cover[2]	25	55	70	77
Open spaces, lawns, parks, golf courses, cemeteries, etc.				
Good condition: grass cover on 75% or more of the area	39	61	74	80
Fair condition: grass cover on 50-75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential[3]				
Average lot size (% Impervious[4])				
1/8 ac or less (65)	77	85	90	92
1/4 ac (38)	61	75	83	87
1/3 ac (30)	57	72	81	86
1/2 ac (25)	54	70	80	85
1 ac (20)	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads				
Paved with curbs and storm sewers[5]	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

Source: .SCS Urban Hydrology for Small Watersheds, second edition. (TR-55), June 1986. Footnotes:

1. Antecedent moisture condition II. Ia = 0.2S
2. Good cover means protected from grazing and litter and brush cover soil

Table A-6 SCS soil group and infiltration rates (AECOM, 2014)

Soil Group	Description	Range of loss rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.30 – 0.45
B	Shallow loess, sandy loam	0.15 – 0.30
C	Clay loams, shallow sandy loams, soils low in organic content, and soils usually high in clay	0.05 – 0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00 – 0.05

Table A-7 Manning' coefficient for overland flow (McCuen, et al. 1996)

Surface	**n**
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Table A-8 Ratios for dimensionless unit hydrograph and mass curve (used for estimation flow)

Time Ratios (t/tp)	Discharge Ratios (q/qp)	Mass Curve Ratios (Qa/Q)	Time Ratios (t/tp)	Discharge Ratios (q/qp)	Mass Curve Ratios (Qa/Q)
0	0	0.0000	5.1	0	1
0.1	0.03	0.0010	5.2	0	1
0.2	0.1	0.0060	5.3	0	1
0.3	0.19	0.0120	5.4	0	1
0.4	0.31	0.0350	5.5	0	1
0.5	0.47	0.0650	5.6	0	1
0.6	0.66	0.1070	5.7	0	1
0.7	0.82	0.1630	5.8	0	1
0.8	0.93	0.2280	5.9	0	1
0.9	0.99	0.3000	6	0	1
1	1	0.3750	6.1	0	1
1.1	0.99	0.4500	6.2	0	1
1.2	0.93	0.5220	6.3	0	1
1.3	0.86	0.5890	6.4	0	1
1.4	0.78	0.6500	6.5	0	1
1.5	0.68	0.7000	6.6	0	1
1.6	0.56	0.7510	6.7	0	1
1.7	0.46	0.7900	6.8	0	1
1.8	0.39	0.8220	6.9	0	1
1.9	0.33	0.8490	7	0	1
2	0.28	0.8710	7.1	0	1
2.1	0.2435	0.8895	7.2	0	1
2.2	0.207	0.9080	7.3	0	1
2.3	0.177	0.9210	7.4	0	1
2.4	0.147	0.9340	7.5	0	1
2.5	0.127	0.9435	7.6	0	1
2.6	0.107	0.9530	7.7	0	1
2.7	0.092	0.9600	7.8	0	1
2.8	0.077	0.9670	7.9	0	1
2.9	0.066	0.9720	8	0	1
3	0.055	0.9770	8.1	0	1
3.1	0.0475	0.9805	8.2	0	1
3.2	0.04	0.9840	8.3	0	1
3.3	0.0345	0.9865	8.4	0	1
3.4	0.029	0.9890	8.5	0	1
3.5	0.025	0.9910	8.6	0	1
3.6	0.021	0.9930	8.7	0	1
3.7	0.018	0.9940	8.8	0	1
3.8	0.015	0.9950	8.9	0	1
3.9	0.013	0.9960	9	0	1
4	0.011	0.9970	9.1	0	1
4.1	0.0098	0.9974	9.2	0	1
4.2	0.0086	0.9978	9.3	0	1
4.3	0.0074	0.9982	9.4	0	1
4.4	0.0158	0.9986	9.5	0	1
4.5	0.005	0.9990	9.6	0	1
4.6	0.004	0.9992	9.7	0	1
4.7	0.003	0.9994	9.8	0	1
4.8	0.002	0.9996	9.9	0	1
4.9	0.001	0.9998	10	0	1
5	0	1			

A-5 Data of Existiong Storm Drainage Network

Existing stormwater drainage used to develop stormwater flow networks in the Jeddah-SWMM model are shown in Table A-9 (Data obtained in form of vector (point polyline).

Table A-9 The conduit properties for each identified conduit within selected study site within Jeddah City.

Conduit Properties											
Conduit ID	**Type of Conduit**	**Shape**	**Inlet Node (ID)**	**Outlet Node (ID)**	**Length (m)**	**h (fmm)**	**b (mm)**	**Upstream Invert (m AD)**	**DownStram Invert (m AD)**	**10 Years Design**	
										Flow d	**flow rate**
C19	PIPE	CIRC	Ja5	Ja4	400	1000	1000	1.3	1.1	1.99	1.932
C4	PIPE	CIRC	Ja4	Outlet1	635.52	1800	1800	1.1	-1.3	2.576	2.329
C1	PIPE	CIRC	J1a	J2a	616.09	900	900	1.4	1.3	1.077	1.034
C2	PIPE	CIRC	J2a	J3a	589.68	1000	1000	1.3	1.2	1.99	1.932
C3	PIPE	CIRC	Ja3	Ja4	232.77	1000	1000	1.2	1.1	1.99	1.932
C5	PIPE	CIRC	D_b1300	D_b1400	260.77	900	900	2.12	1.6	1.077	1.034
C6	PIPE	CIRC	D_b1400	Est.1	654	1000	1000	1.6	-0.6	1.99	1.932
C18	PIPE	RECT	-	900733	179	3000	1500	-0.6	-0.89	- 2.325 7.494	7.494
C8	PIPE	RECT	900731	Est.1	259.19	3000	1500	-0.51	-0.6	- 2.325 7.494	7.494
C7	PIPE	CIRC	D_B: 1500	900731	173.52	1800	1800	-0.31	-0.51	2.576	2.329
C10	PIPE	CIRC	0	900731	753.5	1800	1800	2.63	-0.51	- 2.547 9.004	9.004
C9	PIPE	CIRC	900728b	0	403.66	800	800	3.6	2.944	1.233	0.577
C11	PIPE	CIRC	901142	0	379.36	1800	1800	3.32	2.63	2.599	7.738
C12	PIPE	CIRC	900716	901142	608.78	1600	1600	6.73	6.29	2.581	7.737
C14	PIPE	CIRC	901601	901607	347.71	1000	1000	8.12	8.09	1.751	0.189
C13	PIPE	CIRC	901607	900716	31.01	1600	1600	6.86	6.73	2.869	7.724
C15	PIPE	CIRC	901600	900716	391.21	1600	1600	9.01	6.73	2.581	7.737
C16	PIPE	CIRC	901614	901601	373.4	800	800	9.01	8.92	0.861	-0.001
C17	PIPE	CIRC	901616	901600	387.3	800	800	9.19	9.01	0.353	0

A-6 Intensity – Duration – Frequency (IDF) Curves

AECOM's Jeddah stormwater programme has developed Intensity – Duration – Frequency (IDF) curves for small development sites that would require intensity of rainfall. Following thorough analysis of the parameters involved in making the IDF, AECOM produced IDF curves for the Jeddah Coastal Plain as follows:

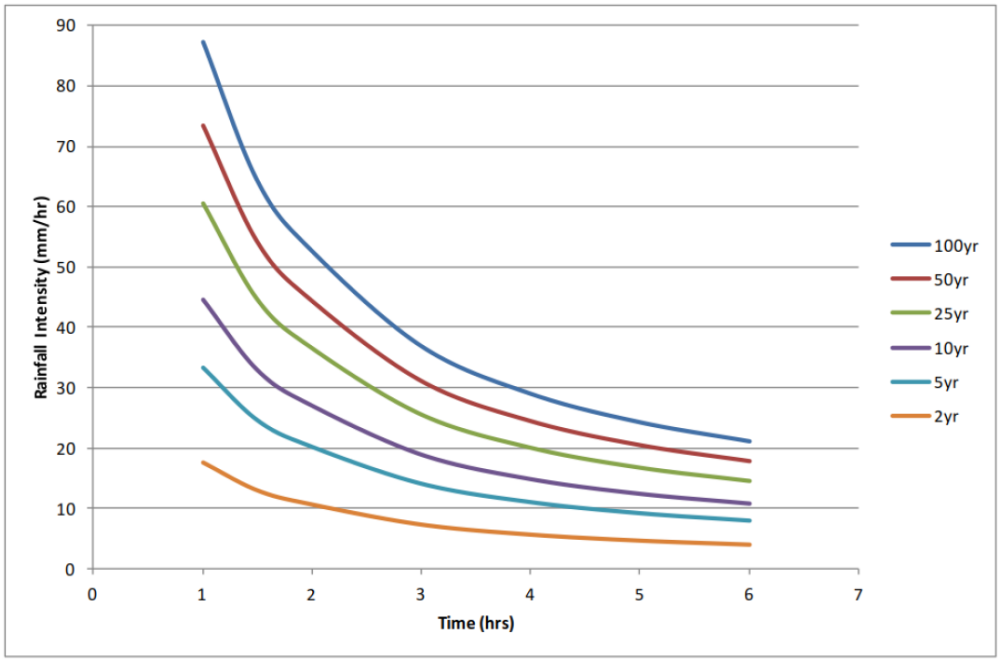


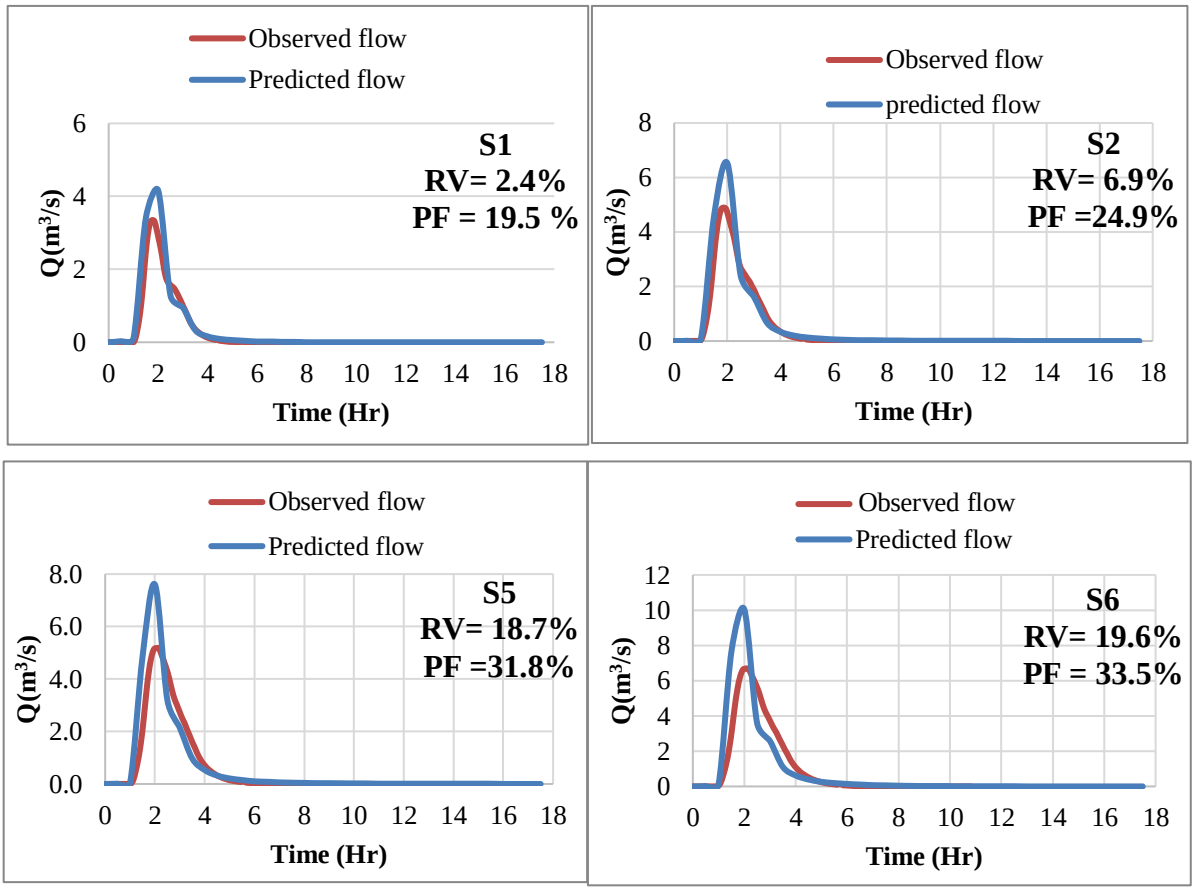
Figure A-3 IDF curve for the Jeddah Coastal Plain (AECOM, 2014)

Appendix B: The Jeddah Watershed Hydrologic Models (Jeddah-SWMM Model)

This appendix includes information related to the Jeddah SWMM-model and includes results of calibration and verification of the model and the SWMM Input File.

B-1 Results of Calibration and Verification

B-1-1 Calibration for the 25/11/2009 event



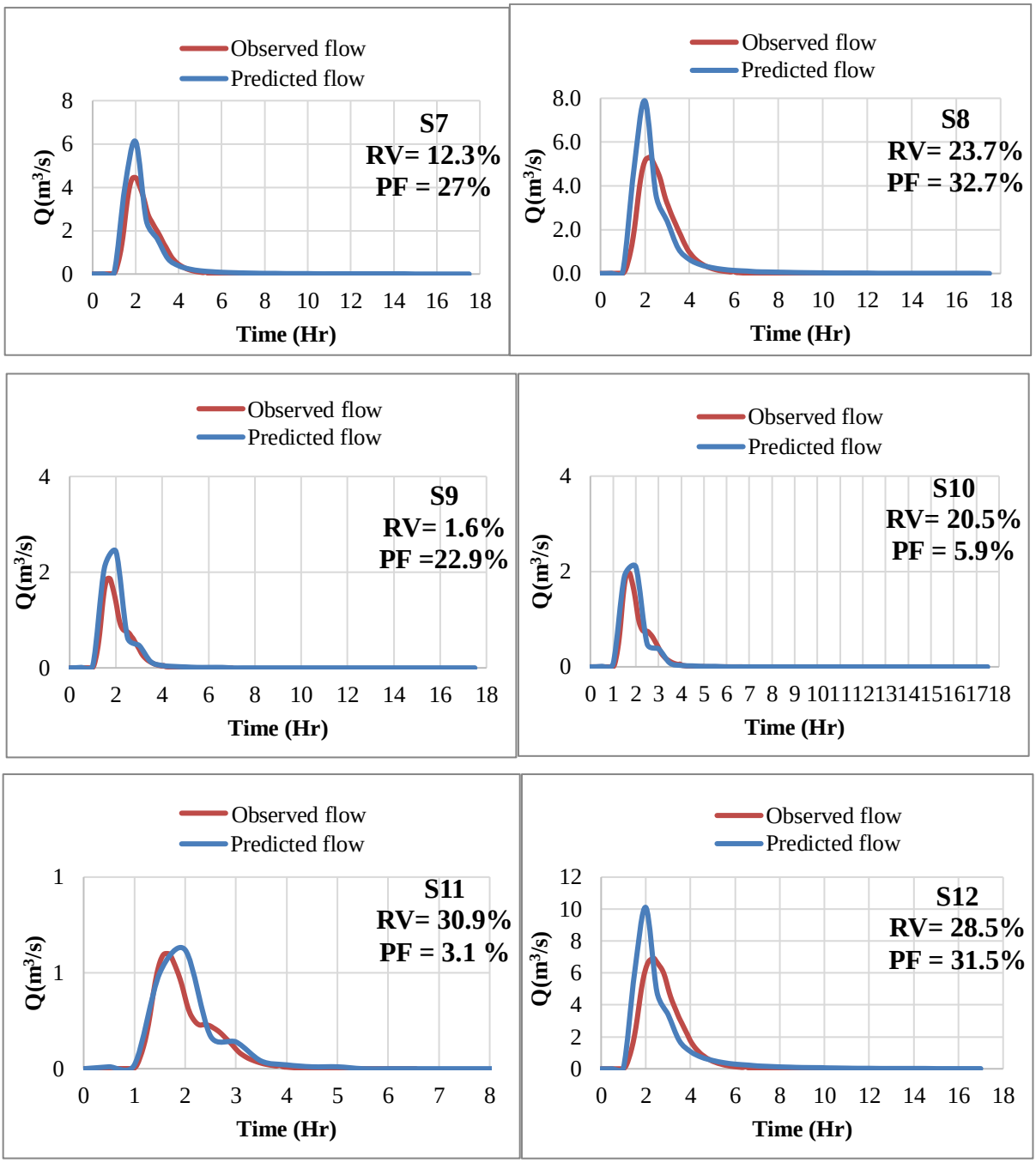


Figure B-1 Calibration outputs of the 25/11/2009 event across twelve subcatchments using default parameter

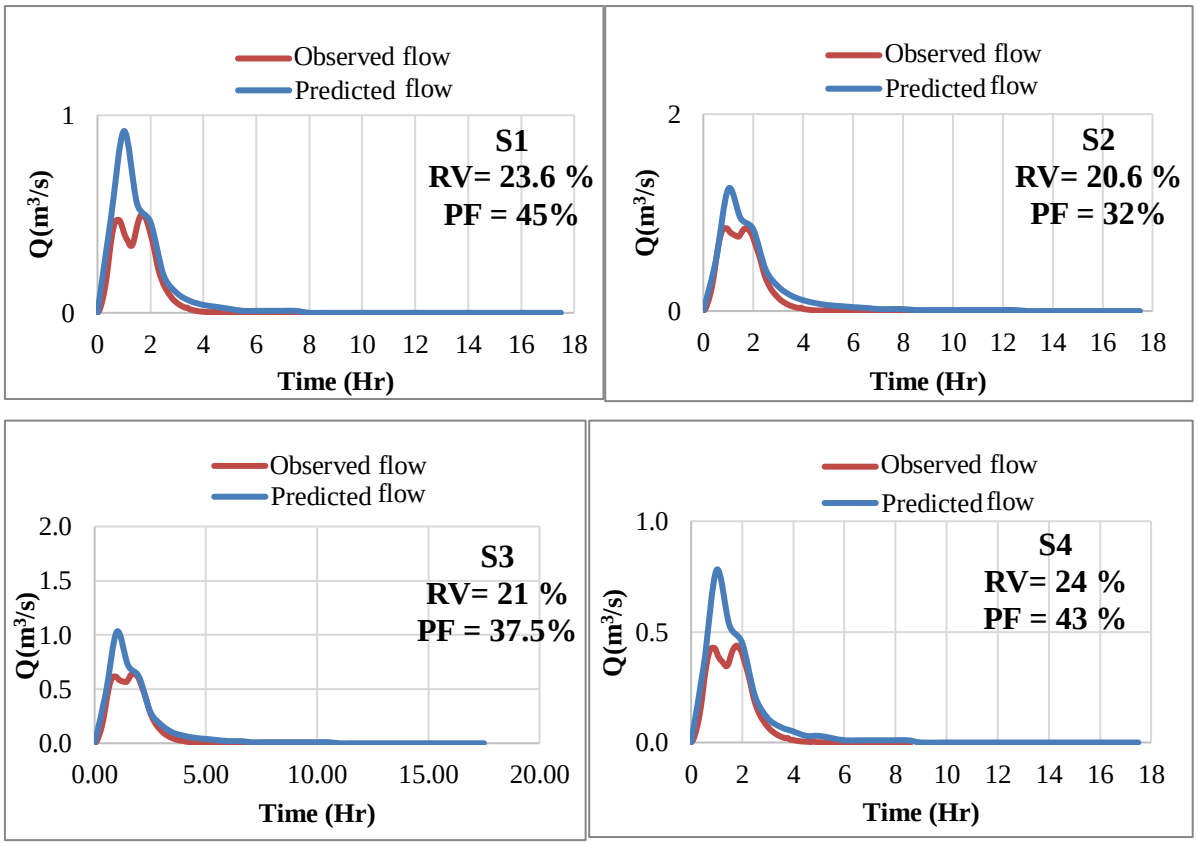
Table B-1 The values of the calibrated parameters for the Jeddah-SWMM model for the 25/11/2009 event.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	90		S7	CN	91	
	Manning's n	0.013	0.19		Manning's n	0.015	0.13
	Depression storage (mm)	0.9	9.4		Depression storage (mm)	1.4	12.5
	%zero	20	NA		%zero	12	NA
S2	CN	91		S8	CN	91	
	Manning's n	0.015	0.16		Manning's n	0.015	0.13
	Depression storage (mm)	1.4	9.2		Depression storage (mm)	1.4	11.6
	%zero	15	NA		%zero	12	NA
S3	CN	90		S9	CN	89	
	Manning's n	0.015	0.16		Manning's n	0.013	0.15
	Depression storage (mm)	1.3	9.8		Depression storage (mm)	1.2	13
	%zero	15	NA		%zero	10	NA
S4	CN	89		S10	CN	90	
	Manning's n	0.015	0.15		Manning's n	0.014	0.15
	Depression storage (mm)	1.6	12.4		Depression storage (mm)	1.2	13
	%zero	10	NA		%zero	15	NA
S5	CN	89		S11	CN	91	
	Manning's n	0.015	0.15		Manning's n	0.015	0.2
	Depression storage (mm)	1.7	13		Depression storage (mm)	1.1	8
	%zero	10	NA		%zero	25	NA
S6	CN	88		S12	CN	91	
	Manning's n	0.01	0.2		Manning's n	0.015	0.2
	Depression storage (mm)	1.6	14.8		Depression storage (mm)	1.7	9
	%zero	15	NA		%zero	10	NA

Table B-2 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 25/11/2009 event

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m^3/s)			Total volume (m3)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
25/11/2009	3hr	70 mm	S1	3.4	4.2	19.5	19646	19170	-2.4
	3hr	70 mm	S2	4.9	6.5	24.9	28357	30456	6.9
	3hr	70 mm	S3	3.9	5.1	23.9	22486	23940	6.1
	3hr	70 mm	S4	2.8	3.7	24.9	16057	16758	4.2
	3hr	70 mm	S5	5.2	7.6	31.8	30076	37008	18.7
	3hr	70 mm	S6	6.7	10.1	33.5	39215	48798	19.6
	3hr	70 mm	S7	4.5	6.1	27.0	25715	29322	12.3
	3hr	70 mm	S8	5.3	7.9	32.7	30295	39708	23.7
	3hr	70 mm	S9	1.9	2.4	22.9	10859	10692	-1.5
	3hr	70 mm	S10	2.0	2.1	5.9	11507	9144	-20.5
	3hr	70 mm	S11	0.6	0.6	3.1	3503	2772	-20.9
	3hr	70 mm	S12	6.9	10.1	31.5	39187	54774	28.5

B-1-2 Calibration for the 29/12/2010 event



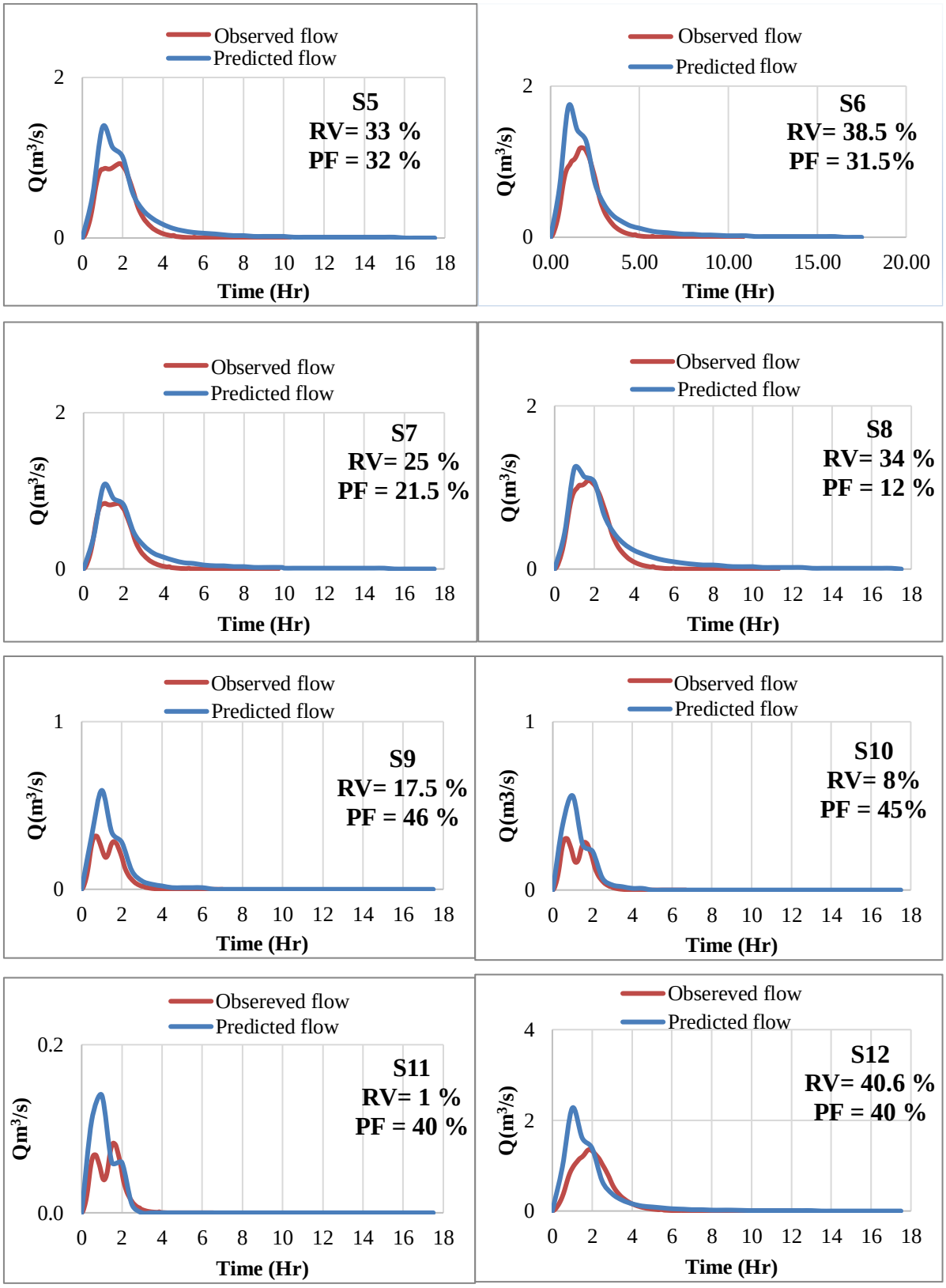


Figure B-2 Calibration outputs of the 29/12/2010 event across twelve subcatchments using default parameter

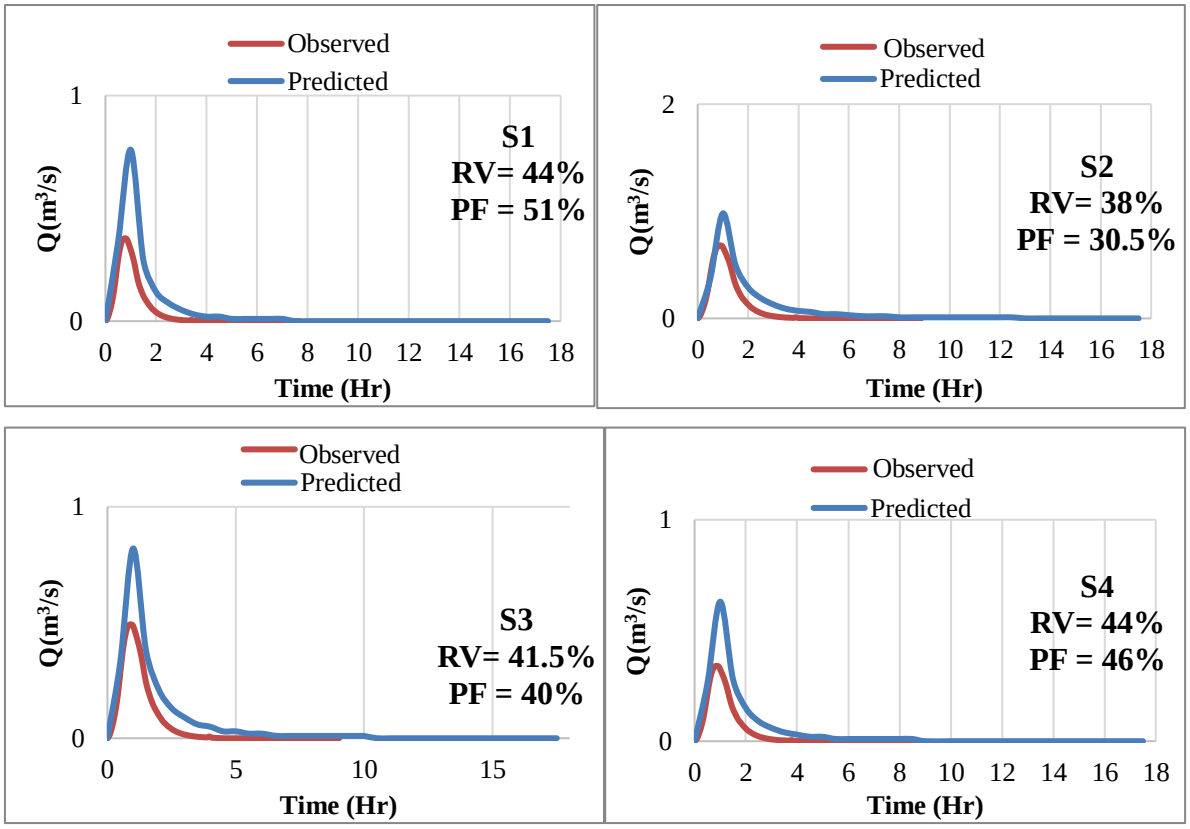
Table B-3 The values of the calibrated parameters for the Jeddah-SWMM model for the 29/12/2010 event.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	**90**		**S7**	CN	**91**	
	Manning's n	0.02	0.25		Manning's n	0.02	0.15
	Depression storage (mm)	1.7	9.4		Depression storage (mm)	1.5	11.5
	%zero	**7**	NA		%zero	**5**	NA
S2	CN	**91**		**S8**	CN	**91**	
	Manning's n	0.02	0.2		Manning's n	0.02	0.15
	Depression storage (mm)	1.6	8.2		Depression storage (mm)	1.5	14.6
	%zero	**7**	NA		%zero	**5**	NA
S3	CN	**90**		**S9**	CN	**91**	
	Manning's n	0.018	0.2		Manning's n	0.018	0.2
	Depression storage (mm)	1.7	9.8		Depression storage (mm)	1.7	11.5
	%zero	**10**	NA		%zero	**10**	NA
S4	CN	**90**		**S10**	CN	**91**	
	Manning's n	0.018	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.8	10.4		Depression storage (mm)	1.6	11.5
	%zero	**10**	NA		%zero	**15**	NA
S5	CN	**90**		**S11**	CN	**89**	
	Manning's n	0.018	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.8	11		Depression storage (mm)	1.7	9.3
	%zero	**10**	NA		%zero	**15**	NA
S6	CN	**89**		**S12**	CN	**90**	
	Manning's n	0.02	0.2		Manning's n	0.016	0.2
	Depression storage (mm)	1.7	11.6		Depression storage (mm)	2	9.2
	%zero	**5**	NA		%zero	**10**	1.1

Table B-4 Results of the Jeddah- SWMM hydrologic model for each subcatchment includes the deviation in peak flow rate and flood volume for the 29/12/2010 event

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr %	Observed	Predicted	FV-Erorr %
29/12/2010	2hr	24 mm	S1	0.50	0.9	45.9	4210	5202	23.6
	2hr	24 mm	S2	0.84	1.2	32.1	6964	8766	20.6
	2hr	24 mm	S3	0.64	1.0	37.5	5248	6642	21.0
	2hr	24 mm	S4	0.44	0.8	43.9	3681	4842	24.0
	2hr	24 mm	S5	0.93	1.4	32.8	7199	10872	33.8
	2hr	24 mm	S6	1.19	1.7	31.5	8384	13662	38.6
	2hr	24 mm	S7	0.84	1.1	21.5	6667	8892	25.0
	2hr	24 mm	S8	1.09	1.2	12.0	7811	11862	34.1
	2hr	24 mm	S9	0.32	0.6	46.1	2642	3204	21.3
	2hr	24 mm	S10	0.31	0.6	45.2	2638	2862	8.5
	2hr	24 mm	S11	0.08	0.1	40.8	686	684	-0.3
	2hr	24 mm	S12	1.36	2.3	40.2	8794	14796	40.6

B-1-3 Calibration for the 14/01/2011 event



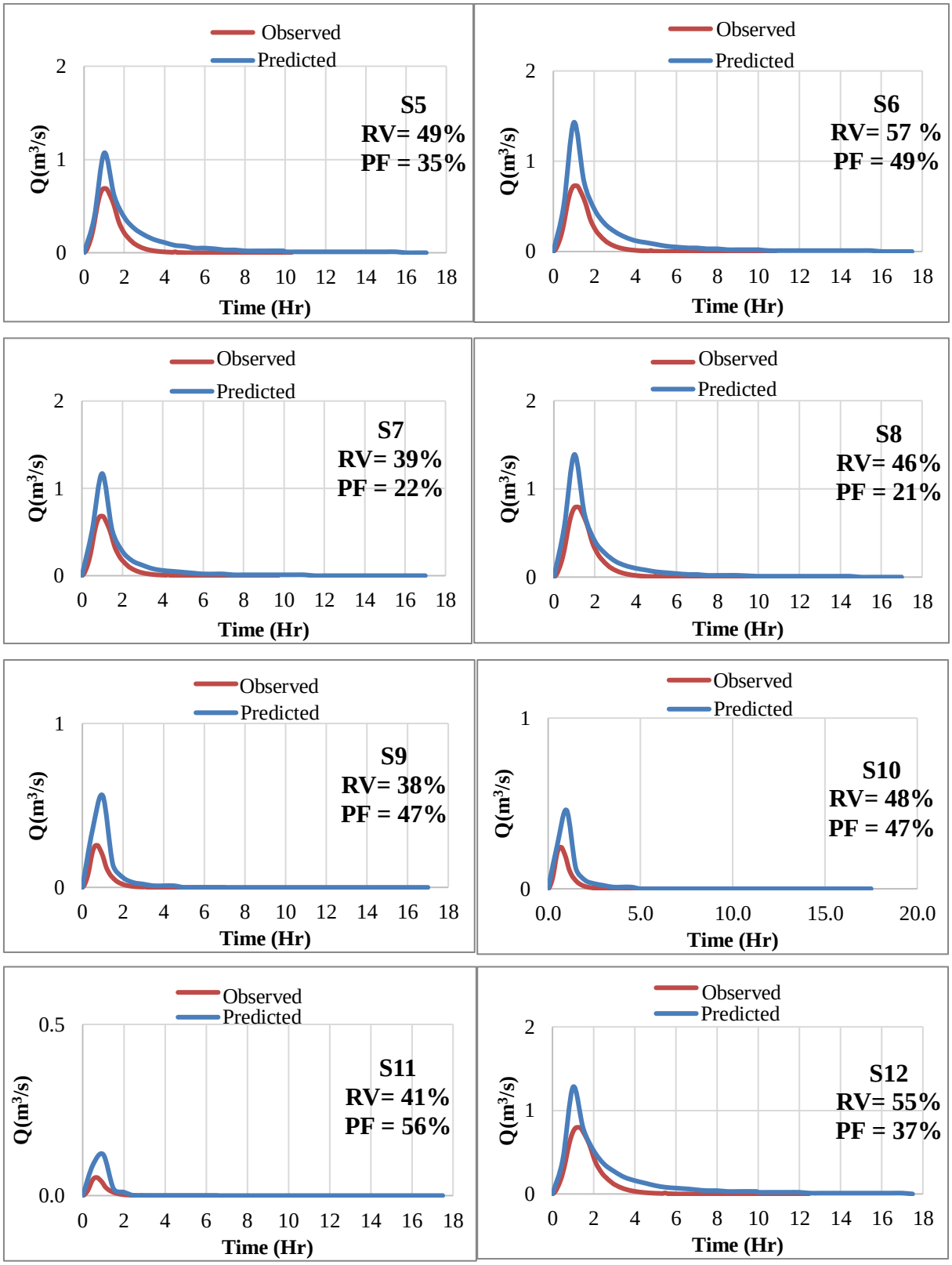


Figure B-3 Calibration outputs of the 14/01/2011 event across twelve subcatchments using default parameter

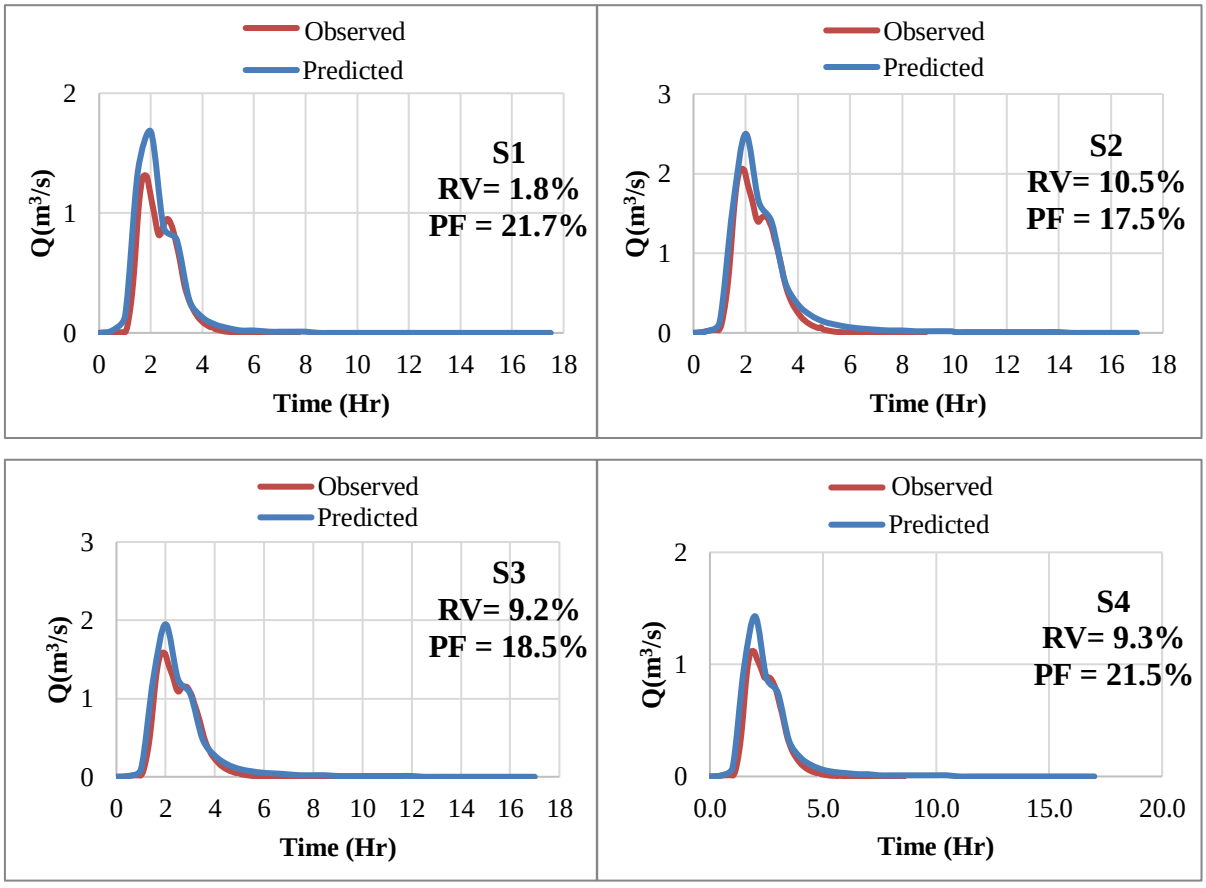
Table B-5 The values of the calibrated parameters for the Jeddah-SWMM model for the 14/01/2011 event.

Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	**90**		**S7**	CN	**92**	
	Manning's n	0.022	0.15		Manning's n	0.02	0.15
	Depression storage (mm)	1.7	8.4		Depression storage (mm)	1.7	13
	%zero	**5**	NA		%zero	**10**	NA
S2	CN	**92**		**S8**	CN	**92**	
	Manning's n	0.022	0.15		Manning's n	0.02	0.15
	Depression storage (mm)	1.7	9.2		Depression storage (mm)	1.8	12.5
	%zero	**10**	NA		%zero	**10**	NA
S3	CN	**91**		**S9**	CN	**92**	
	Manning's n	0.02	0.15		Manning's n	0.02	0.15
	Depression storage (mm)	1.8	8.8		Depression storage (mm)	1.7	12.5
	%zero	**10**	NA		%zero	**10**	NA
S4	CN	**91**		**S10**	CN	**92**	
	Manning's n	0.02	0.15		Manning's n	0.022	0.15
	Depression storage (mm)	1.7	11.5		Depression storage (mm)	1.8	12.5
	%zero	**10**	NA		%zero	**10**	NA
S5	CN	**91**		**S11**	CN	**89**	
	Manning's n	0.02	0.15		Manning's n	0.018	0.15
	Depression storage (mm)	1.9	12		Depression storage (mm)	1.5	8
	%zero	**12**	NA		%zero	**15**	NA
S6	CN	**90**		**S12**	CN	**91**	
	Manning's n	0.02	0.15		Manning's n	0.02	0.15
	Depression storage (mm)	1.8	11.5		Depression storage (mm)	2	9
	%zero	**5**	NA		%zero	**7**	1.1

Table B-6 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 14/01/2011 event

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
14/01/2011	1hr	15 mm	S1	0.4	0.8	51.7	1766	3168	44.3
	1hr	15 mm	S2	0.7	1.0	30.5	3278	5310	38.3
	1hr	15 mm	S3	0.5	0.8	40.0	2367	4050	41.5
	1hr	15 mm	S4	0.3	0.6	46.0	1636	2970	44.9
	1hr	15 mm	S5	0.7	1.1	35.6	3317	6624	49.9
	1hr	15 mm	S6	0.7	1.4	49.0	35106	8280	57.6
	1hr	15 mm	S7	0.7	0.9	22.5	32822	5382	39.0
	1hr	15 mm	S8	0.8	1.0	21.3	38280	7146	46.4
	1hr	15 mm	S9	0.3	0.5	47.7	1234	1998	61.9
	1hr	15 mm	S10	0.2	0.5	47.0	1172	1746	32.8
	1hr	15 mm	S11	0.05	0.1	56.0	254	432	41.2
	1hr	15 mm	S12	0.8	1.3	37.7	3837	8712	55.9

B-1-4 Calibration for the 30/12/2010 event



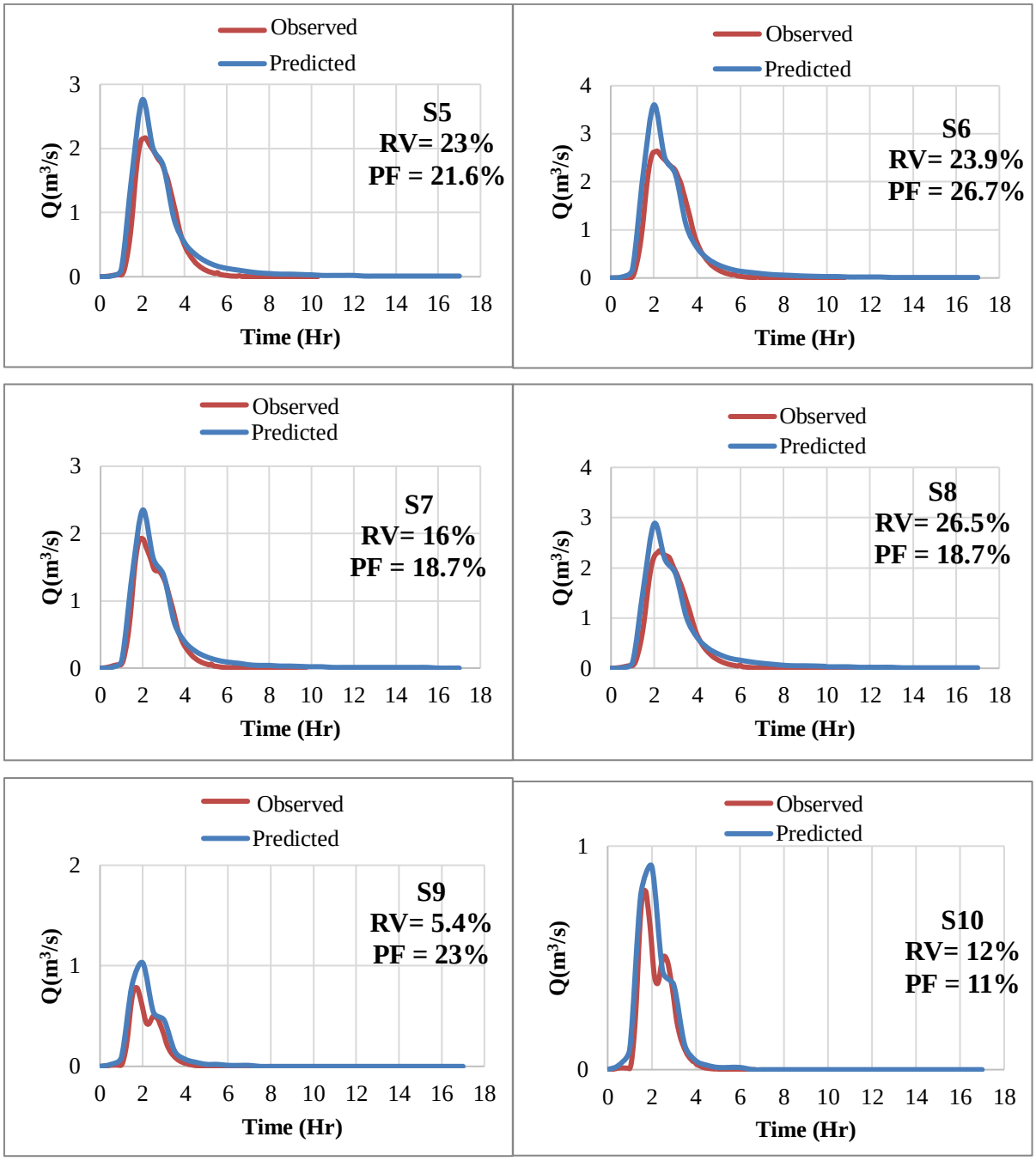


Figure B-4 Calibration outputs of the 30/12/2010 event across twelve subcatchments using default parameter

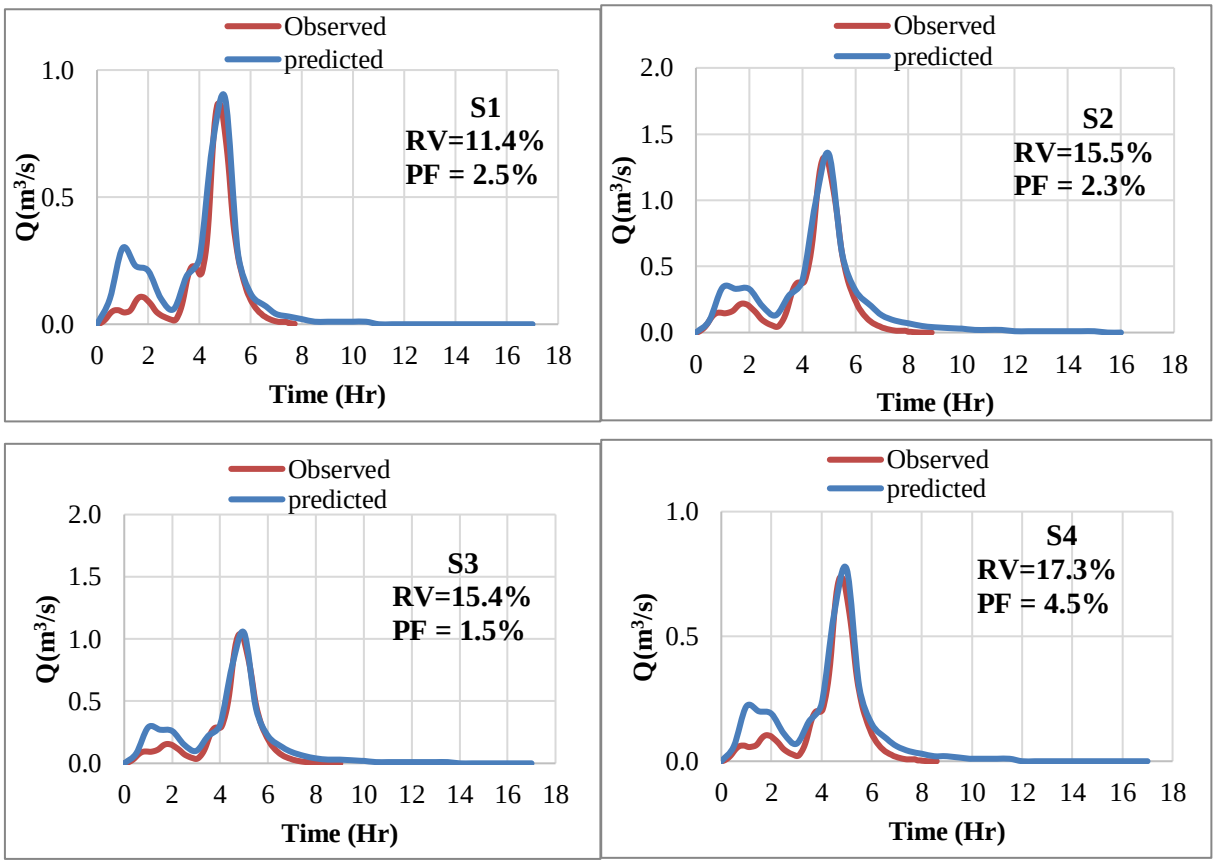
Table B-7 The values of the calibrated parameters for the Jeddah-SWMM model for the 30/12/2010 event.

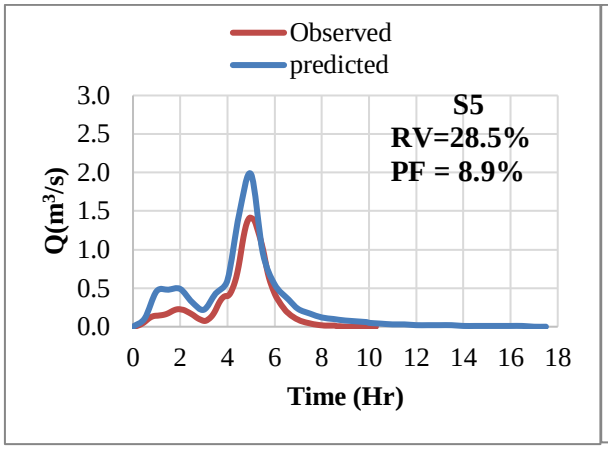
Sub-catchment	Parameter	Impervious surfaces	pervious surfaces	Sub-catchment	Parameter	Impervious surfaces	pervious surfaces
S1	CN	**89**		**S7**	CN	**90**	
	Manning's n	0.016	0.2		Manning's n	0.018	0.17
	Depression storage (mm)	1.6	10.4		Depression storage (mm)	1.7	13
	%zero	**10**	NA		%zero	**10**	NA
S2	CN	**91**		**S8**	CN	**90**	
	Manning's n	0.02	0.18		Manning's n	0.018	0.17
	Depression storage (mm)	1.6	10.2		Depression storage (mm)	1.7	12.5
	%zero	**10**	NA		%zero	**10**	NA
S3	CN	**90**		**S9**	CN	**90**	
	Manning's n	0.02	0.19		Manning's n	0.018	0.2
	Depression storage (mm)	1.7	10		Depression storage (mm)	1.5	13.5
	%zero	**12**	NA		%zero	**10**	NA
S4	CN	**90**		**S10**	CN	**91**	
	Manning's n	0.02	0.17		Manning's n	0.02	0.2
	Depression storage (mm)	1.7	13.5		Depression storage (mm)	1.6	13.5
	%zero	**13**	NA		%zero	**10**	NA
S5	CN	**91**		**S11**	CN	**90**	
	Manning's n	0.02	0.2		Manning's n	0.016	0.19
	Depression storage (mm)	1.8	13.5		Depression storage (mm)	1.5	8.5
	%zero	**8**	NA		%zero	**15**	NA
S6	CN	**88**		**S12**	CN	**90**	
	Manning's n	0.02	0.18		Manning's n	0.02	0.19
	Depression storage (mm)	1.6	13.5		Depression storage (mm)	2	10.4
	%zero	**7**	NA		%zero	**12**	1.1

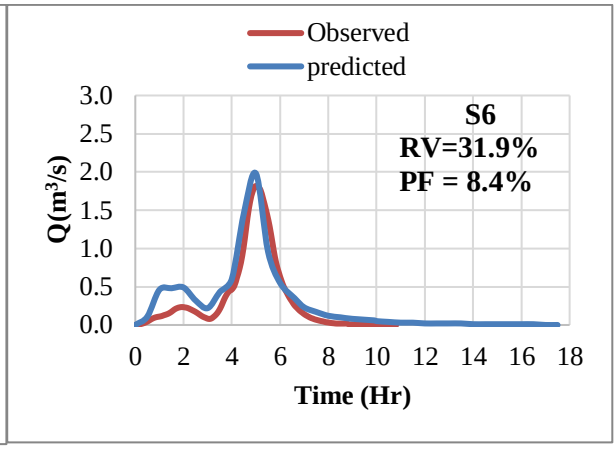
Table B-8 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 30/12/2010 event

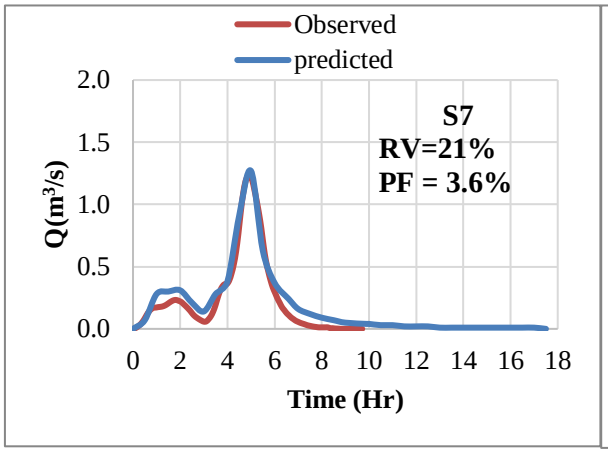
Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
30/12/2010	3hr	41 mm	S1	1.3	1.7	21.7	9614	9792	1.8
	3hr	41 mm	S2	2.1	2.5	17.5	14630	16362	10.6
	3hr	41 mm	S3	1.6	2.0	18.6	11375	12528	9.2
	3hr	41 mm	S4	1.1	1.4	21.6	80669	8892	9.3
	3hr	41 mm	S5	2.2	2.8	21.6	15364	19998	23.2
	3hr	41 mm	S6	2.6	3.6	26.7	19175	25200	23.9
	3hr	41 mm	S7	1.9	2.4	18.0	13548	16146	16.1
	3hr	41 mm	S8	2.3	2.9	18.7	15927	21690	26.6
	3hr	41 mm	S9	0.8	1.0	23.9	5582	5904	5.8
	3hr	41 mm	S10	0.8	0.9	11.8	5781	5076	-13.9
	3hr	41 mm	S11	0.2	0.2	-1.6	1748	1386	-26.1
	3hr	41 mm	S12	3.0	3.5	14.8	19524	27468	28.9

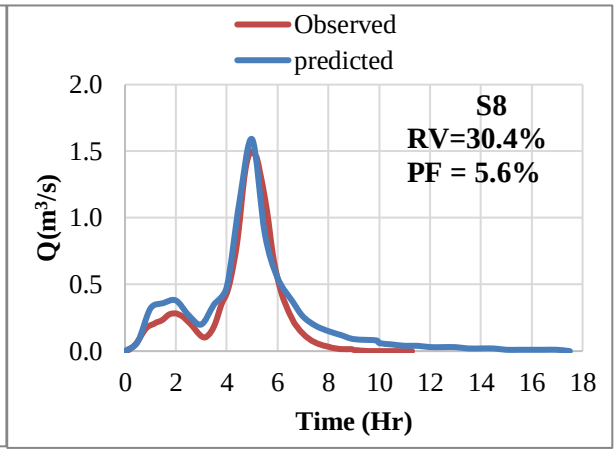
B-1-5 Verification for the 15/01/2011 event

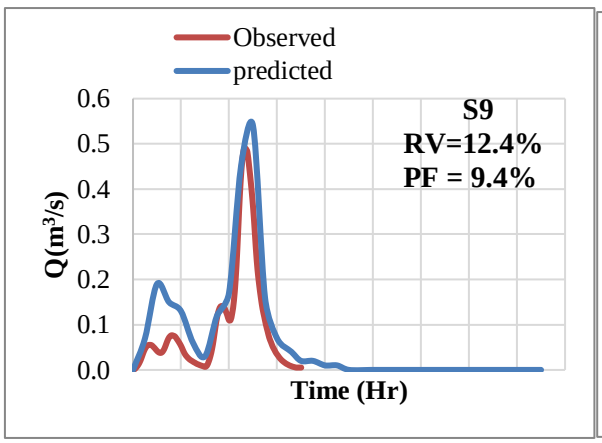


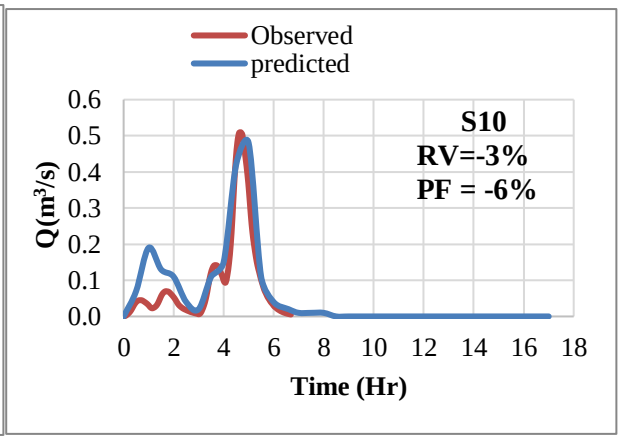

Observed
predicted
S5
RV=28.5%
PF = 8.9%
Q(m³/s)
Time (Hr)

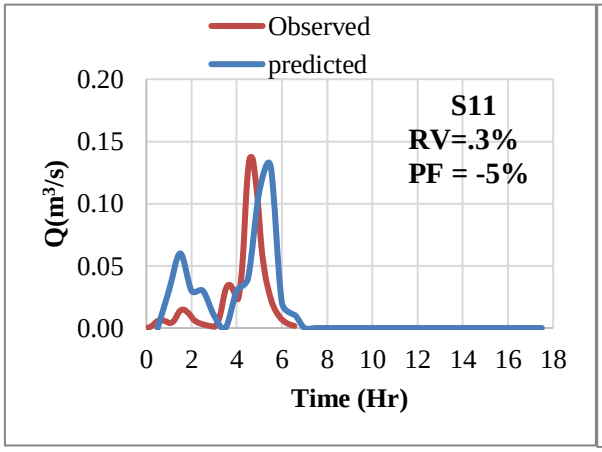

Observed
predicted
S6
RV=31.9%
PF = 8.4%
Q(m³/s)
Time (Hr)


Observed
predicted
S7
RV=21%
PF = 3.6%
Q(m³/s)
Time (Hr)


Observed
predicted
S8
RV=30.4%
PF = 5.6%
Q(m³/s)
Time (Hr)


Observed
predicted
S9
RV=12.4%
PF = 9.4%
Q(m³/s)
Time (Hr)


Observed
predicted
S10
RV=-3%
PF = -6%
Q(m³/s)
Time (Hr)


Observed
predicted
S11
RV=.3%
PF = -5%
Q(m³/s)
Time (Hr)

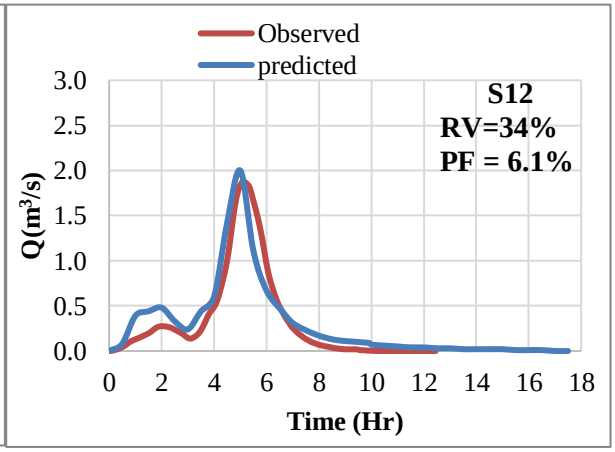
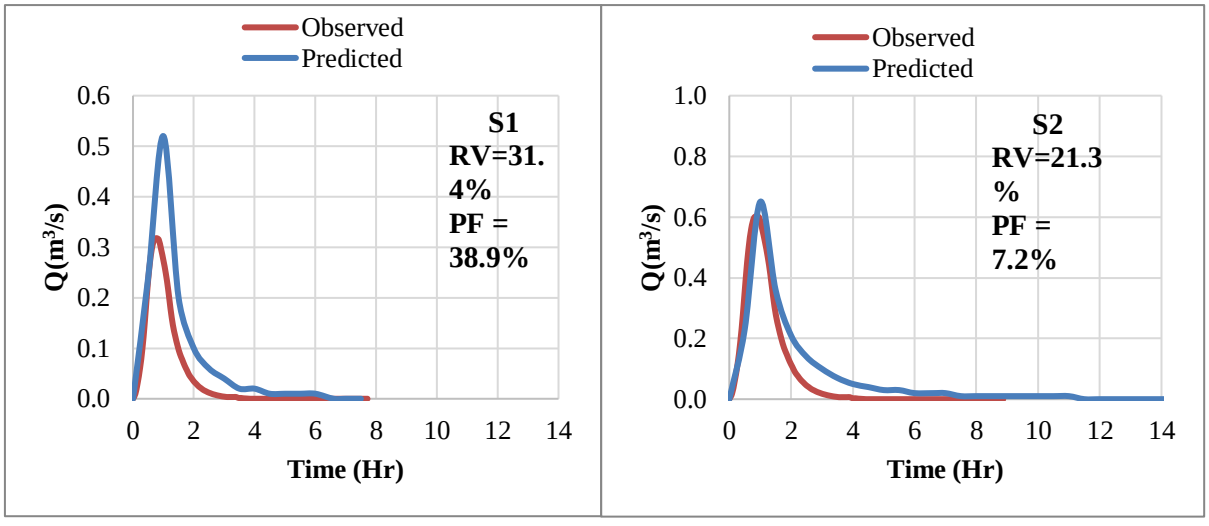

Observed
predicted
S12
RV=34%
PF = 6.1%
Q(m³/s)
Time (Hr)

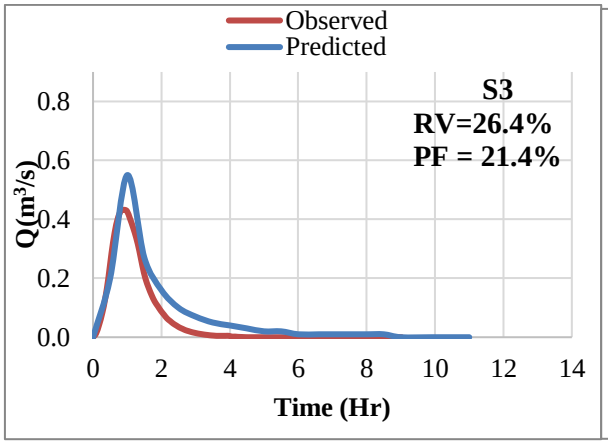
Figure B-5 Verfication outputs of the 15/01/2011 event across twelve subcatchments using calibrated parameters

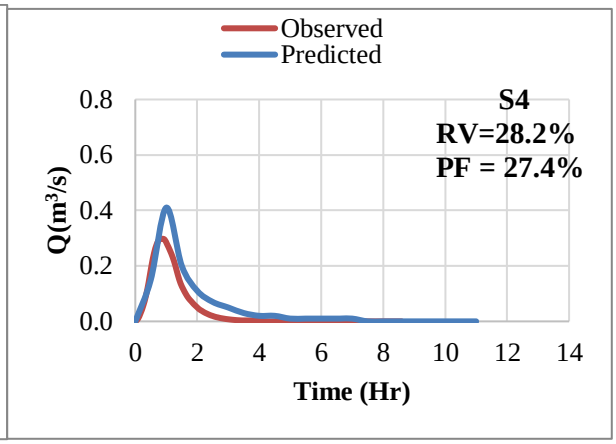
Table B-9 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 15/01/2011 event

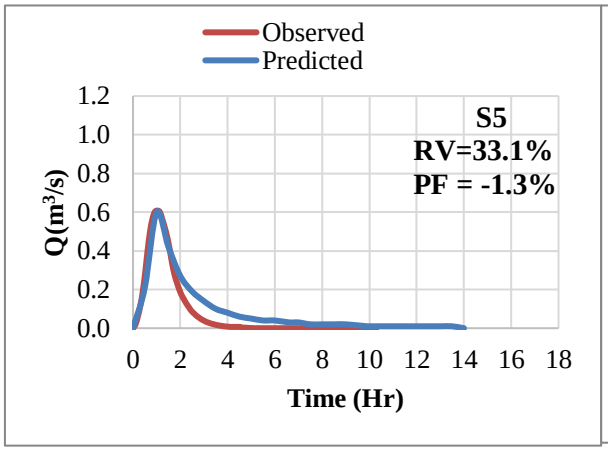
Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m^3/s)			Total volume (m^3)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
15/01/2011	5hr	29 mm	S1	0.9	0.9	2.5	5822.4	6570.0	11.4
	5hr	29 mm	S2	1.3	1.35	2.3	9294.5	10998.0	15.5
	5hr	29 mm	S3	1.0	1.05	1.5	7098.7	8388.0	15.4
	5hr	29 mm	S4	0.7	0.8	4.5	5002.6	6048.0	17.3
	5hr	29 mm	S5	1.4	1.6	8.9	9673.5	13536.0	28.5
	5hr	29 mm	S6	1.8	2.0	8.4	11603.5	17028.0	31.9
	5hr	29 mm	S7	1.2	1.3	3.6	8772.8	11106.0	21.0
	5hr	29 mm	S8	1.5	1.6	5.6	10293.2	14796.0	30.4
	5hr	29 mm	S9	0.5	0.5	9.4	3530.6	4032.0	12.4
	5hr	29 mm	S10	0.5	0.5	-6.2	3574.6	3456.0	-3.4
	5hr	29 mm	S11	0.1	0.1	-5.8	903.1	900.0	-0.3
	5hr	29 mm	S12	1.9	2.0	6.1	12017.0	18198.0	34.0

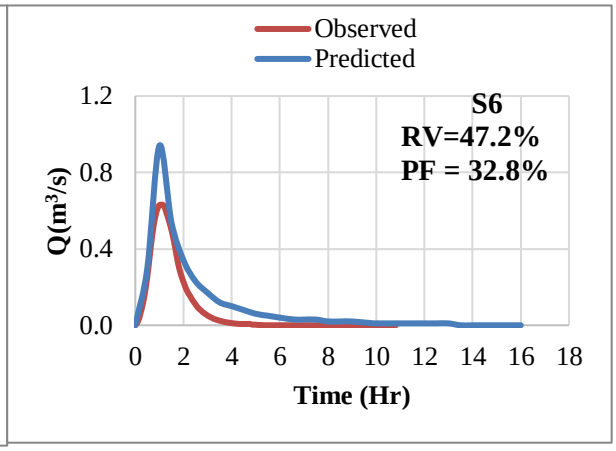
B-1-6 Verification for the 02/12/2009 event

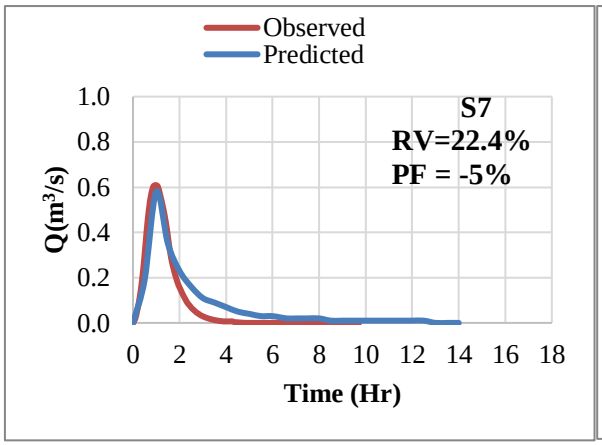


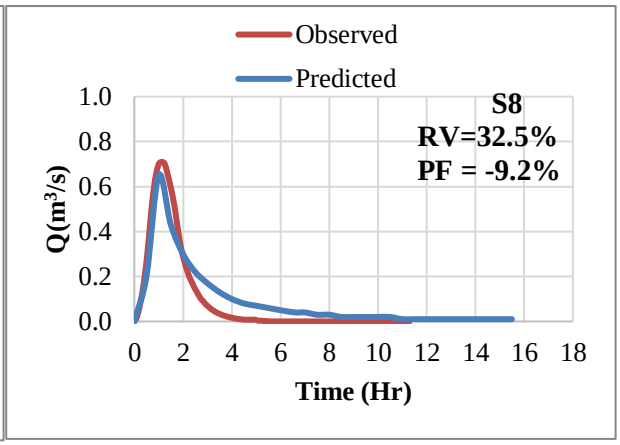

Observed
Predicted
S3
RV=26.4%
PF = 21.4%
Q(m³/s)
Time (Hr)

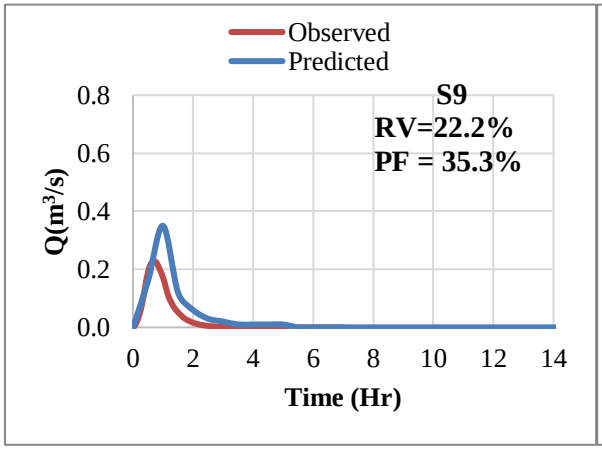

Observed
Predicted
S4
RV=28.2%
PF = 27.4%
Q(m³/s)
Time (Hr)

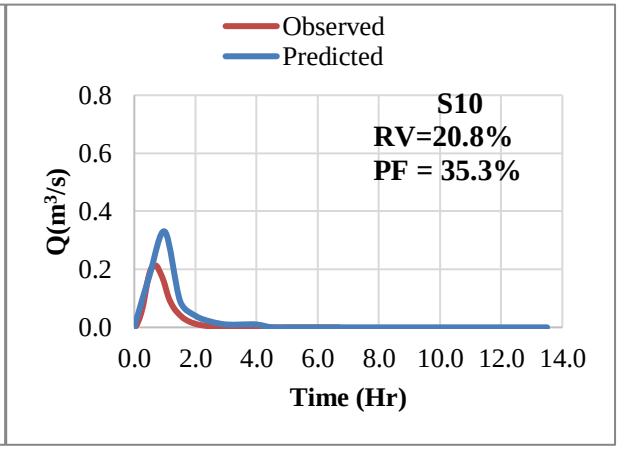

Observed
Predicted
S5
RV=33.1%
PF = -1.3%
Q(m³/s)
Time (Hr)


Observed
Predicted
S6
RV=47.2%
PF = 32.8%
Q(m³/s)
Time (Hr)


Observed
Predicted
S7
RV=22.4%
PF = -5%
Q(m³/s)
Time (Hr)


Observed
Predicted
S8
RV=32.5%
PF = -9.2%
Q(m³/s)
Time (Hr)


Observed
Predicted
S9
RV=22.2%
PF = 35.3%
Q(m³/s)
Time (Hr)


Observed
Predicted
S10
RV=20.8%
PF = 35.3%
Q(m³/s)
Time (Hr)

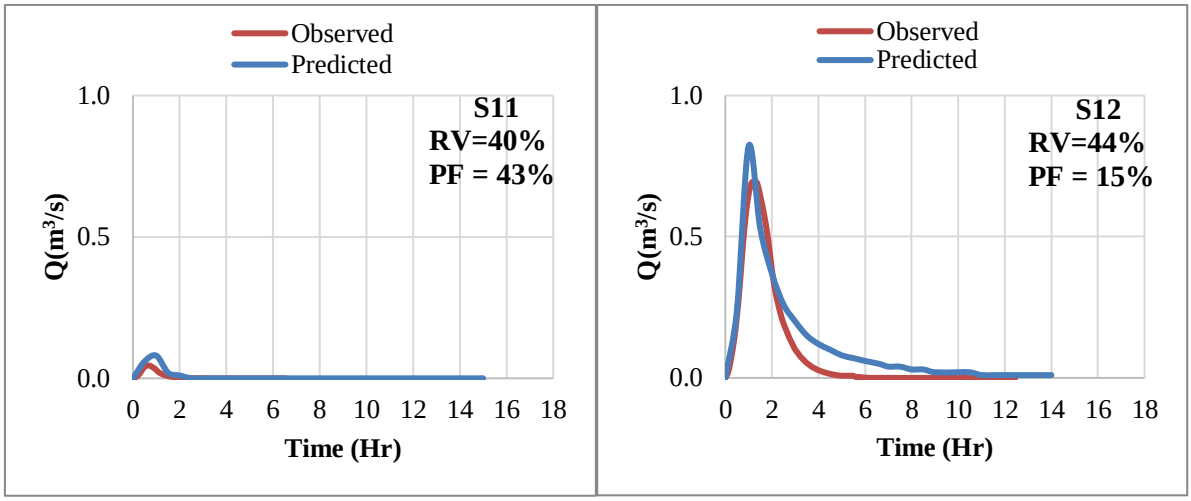


Figure B-6 Verification outputs of the 14/01/2011 event across twelve subcatchments using calibrated parameters

Table B-10 Results of the Jeddah- SWMM hydrologic model for each subcatchment, including the deviation in peak flow rate and flood volume for the 14/01/2011 event

Historical Rainfall Events	Total duration (Hr.)	Total Depth (mm)	Sub-catchments	Peak flow (m3/s)			Total volume (m3/s)		
				Observed	Predicted	PF-Erorr	Observed	Predicted	FV-Erorr
29/12/2010	5hr	14 mm	S1	0.3	0.5	38.9	1530.5	2232.0	31.4
	5hr	14 mm	S2	0.6	0.65	7.2	2903.6	3690.0	21.3
	5hr	14 mm	S3	0.4	0.55	21.4	2080.9	2826.0	26.4
	5hr	14 mm	S4	0.3	0.4	27.4	1433.7	1998.0	28.2
	5hr	14 mm	S5	0.6	0.6	-1.3	2926.8	4374.0	33.1
	5hr	14 mm	S6	0.6	0.9	32.8	3041.0	5760.0	47.2
	5hr	14 mm	S7	0.6	0.6	-5.0	2931.7	3780.0	22.4
	5hr	14 mm	S8	0.7	0.7	-9.2	3416.3	5058.0	32.5
	5hr	14 mm	S9	0.2	0.4	35.2	1091.8	1404.0	22.2
	5hr	14 mm	S10	0.2	0.3	35.3	1027.5	1242.0	17.3
	5hr	14 mm	S11	0.0	0.1	43.5	217.7	306.0	28.9
	5hr	14 mm	S12	0.7	0.8	15.1	3351.4	6066.0	44.8

B-2 SWMM Input fille

The following is the SWMM input file for Scenario 1: 2-year rainfall and SUDS option 1.

```
 [TITLE]
;;Project Title/Notes

[OPTIONS]
;;Option            Value
FLOW_UNITS          CMS
INFILTRATION        CURVE_NUMBER
FLOW_ROUTING        KINWAVE
LINK_OFFSETS        DEPTH
MIN_SLOPE           0
ALLOW_PONDING       NO
SKIP_STEADY_STATE           NO

START_DATE          03/04/2019
START_TIME          00:00:00
REPORT_START_DATE           03/04/2019
REPORT_START_TIME           00:00:00
END_DATE            03/05/2019
END_TIME            12:00:00
SWEEP_START         01/01
SWEEP_END           12/31
DRY_DAYS            0
REPORT_STEP         00:30:00
WET_STEP            00:05:00
DRY_STEP            01:00:00
ROUTING_STEP        0:00:30
RULE_STEP           00:00:00

INERTIAL_DAMPING    FULL
NORMAL_FLOW_LIMITED         BOTH
FORCE_MAIN_EQUATION         D-W
VARIABLE_STEP       0.75
LENGTHENING_STEP            0
MIN_SURFAREA        1.167
MAX_TRIALS          8
HEAD_TOLERANCE      0.0015
SYS_FLOW_TOL        5
LAT_FLOW_TOL        5
MINIMUM_STEP        0.5
THREADS             1

[EVAPORATION]
;;Data Source      Parameters
;;----------------  ----------
CONSTANT            0.0
DRY_ONLY            NO

[RAINGAGES]
;;Name            Format          Interval  SCF       Source
;;--------------  ---------  ------  ------  ----------
RG1               VOLUME          1:00      0         TIMESERIES     2years-Design (26.9mm) 6h


[SUBCATCHMENTS]
```

;;Name	Rain Gage	Outlet	Area	%Imperv	Width	%Slope	CurbLen	SnowPack
S1	RG1	J1a	30.19	75.86	347.3	2.32	0	
S2	RG1	J2a	45.60	85.7	398.8	1.47	0	
S3	RG1	J3a	37.15	79.9	327.6	1.56	0	
S4	RG1	J3a	25.71	84.3	263.3	1.52	0	
S5	RG1	J14b	55.87	88.2	423.6	1.07	0	
S6	RG1	J7b	81.28	76	528.4	1.35	0	
S7	RG1	J2b	42.32	94.6	326.5	1.22	0	
S8	RG1	J5b	57.94	93.3	338.1	1.26	0	
S9	RG1	J10b	15.70	91.3	283.8	1.4	0	
S10	RG1	J10b	13.42	92	316.1	2	0	
S11	RG1	out2	4.51	65.9	139.7	1.54	0	
S12	RG1	J4a	88.85	75.1	489	1.06	0	

[SUBAREAS]

;;Subcatchment	N-Imperv	N-Perv	S-Imperv	S-Perv	PctZero	RouteTo	PctRouted
S1	.018	.2	1.5	9.4	11	OUTLET	
S2	.019	.17	1.6	9.2	11	OUTLET	
S3	.018	.18	1.6	9.6	12	OUTLET	
S4	.018	.17	1.7	12	11	OUTLET	
S5	.018	.18	1.8	12.4	10	OUTLET	
S6	.018	.18	1.7	12.9	8	OUTLET	
S7	.018	.15	1.6	12.5	9	OUTLET	
S8	.018	.15	1.6	12.8	9	OUTLET	
S9	.017	.18	1.5	12.6	10	OUTLET	
S10	.018	.18	1.6	12.6	13	OUTLET	
S11	.016	.19	1.5	8.5	18	OUTLET	
S12	.018	.19	1.9	9.4	10	OUTLET	

[INFILTRATION]

;;Subcatchment	CurveNum		DryTime
S1	90	0.5	7
S2	91	0.5	7
S3	90	0.5	7
S4	90	0.5	7
S5	90	0.5	7
S6	89	0.5	7
S7	91	0.5	7
S8	91	0.5	7
S9	91	0.5	7
S10	91	0.5	7
S11	90	0.5	7
S12	91	0.5	7

[LID_CONTROLS]

;;Name	Type/Layer	Parameters						
BR	BC							
BR	SURFACE	300	.1	0.03	0	5		
BR	SOIL	250	.4	.25	0.15	40	6	75
BR	STORAGE	500	.4	1.44	0			
BR	DRAIN	0	0	0	6	0	0	
GR	GR							

```
GR               SURFACE     0          0.0        0.35       2.6        5
GR               SOIL        100        0.45       0.3        .05        25         15         110
GR               DRAINMAT    25         0.5        0.25

RG               RG
RG               SURFACE     150        .1         0.03       0          5
RG               SOIL        250        .4         0.25       0.15       40         6          75
RG               STORAGE     0          0.75       10         0

PP               PP
PP               SURFACE     1.5        0          .014       1.5        5
PP               PAVEMENT    130        0.16       0          284        58         0          0
PP               SOIL        250        0.45       0.3        0.05       25         15         75
PP               STORAGE     300        0.6        8          0
PP               DRAIN       0          0          0          6          0          0

[LID_USAGE]
;;Subcatchment   LID Process     Number     Area       Width      InitSat    FromImp    ToPerv     RptFile                  DrainTo          FromPerv
;;---------------  ----------------  ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------------- ----------
S1               GR              141.5      100        10         0          9.4        0          *          *          0
S1               BR              170.1      25         2.5        0          3.5        0          *          *          0
S1               PP              270.7      80         4          0          11.5       0          *          *          0
S2               GR              1.4        100        10         0          11.7       0          *          *          0
S2               BR              239.3      25         2.5        0          3.9        0          *          *          0
S2               PP              772        80         4          0          16.6       0          *          *          0
S3               GR              2.9        100        10         0          6.3        0          *          *          0
S3               BR              211.5      25         2.5        0          4.5        0          *          *          0
S3               PP              542.6      80         4          0          15.1       0          *          *          0
S4               GR              89.6       100        10         0          5          0          *          *          0
S4               BR              264.6      25         2.5        0          3.9        0          *          *          0
S4               PP              354.5      80         4          0          14         0          *          *          0
S5               GR              .9         100        10         0          2.6        0          *          *          0
S5               BR              681.4      25         2.5        0          4.1        0          *          *          0
S5               PP              775.9      80         4          0          13         0          *          *          0
S6               GR              9.3        100        10         0          12.9       0          *          *          0
S6               BR              49.8       25         2.5        0          3.5        0          *          *          0
S6               PP              996.1      80         4          0          15.4       0          *          *          0
S7               GR              5.8        100        10         0          3.5        0          *          *          0
```

S7	BR	173.1	25	2.5	0	2.3	0	*	*
0									
S7	PP	664.2	80	4	0	13.5	0	*	*
0									
S8	GR	63.6	100	10	0	2.2	0	*	*
0									
S8	BR	387.8	25	2.5	0	1.8	0	*	*
0									
S8	PP	764.8	80	4	0	11.5	0	*	*
0									
S9	GR	.2	100	10	0	.2	0	*	*
0									
S9	BR	136.2	25	2.5	0	3.8	0	*	*
0									
S9	PP	183.4	80	4	0	12.4	0	*	*
0									
S10	GR	3.1	100	10	0	.4	0	*	*
0									
S10	BR	121.7	25	2.5	0	3.4	0	*	*
0									
S10	PP	141.7	80	4	0	12.4	0	*	*
0									
S11	RG	20.2	100	10	0	16	0	*	*
30									
S11	BR	16.1	25	2.5	0	2.3	0	*	*
15.7									
S11	PP	26.5	80	4	0	15.7	0	*	*
0									
S12	GR	999	100	10	0	21.8	0	*	*
0									
S12	RG	42.6	100	10	0	2.4	0	*	*
2.4									
S12	BR	69.3	25	2.5	0	4.8	0	*	*
0									
S12	PP	999.7	80	4	0	12.7	0	*	*
0									

[JUNCTIONS]

;;Name	Elevation	MaxDepth	InitDepth	SurDepth	Aponded
;;----------	----------	----------	----------	----------	----------
J1a	1.6	0	0	0	0
J2a	1.3	0	0	0	0
J3a	1.2	0	0	0	0
J4a	1	0	0	0	0
J5a	1.5	0	0	0	0
J12b	1.8	0	0	0	0
J13b	1.6	0	0	0	0
J14b	-.6	0	0	0	0
;ID 900731					
J10b	-.51	0	0	0	0
J11b	5	0	0	0	0
;ID 0					
J9b	2.94	0	0	0	0
;ID 900728b					
J7b	3.6	0	0	0	0
;ID 901142					
J8b	6.29	0	0	0	0
;ID 900716					

J6b 6.73 0 0 0 0
;ID 901607
J5b 6.86 0 0 0 0
;ID 901600
J4b 9.01 0 0 0 0
;ID 901616
J1b 9.190 0 0 0 0
;real ID 901614
J2b 9.01 0 0 0 0
;ID 901601
J3b 8.92 0 0 0 0

[OUTFALLS]
;;Name Elevation Type Stage Data Gated Route To
;;---------- ---------- ---------- ---------- -------- ----------
Out1 -.8 FREE NO
Out2 -.89 FREE NO

[CONDUITS]
;;Name From Node To Node Length Roughness InOffset OutOffset InitFlow MaxFlow
;;---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ----------
C1 J1a J2a 616.09 0.01 1.9 1.8 0 0
C2 J2a J3a 589.68 0.01 2 1.9 0 0
C3 J3a J4a 232.77 0.01 1.9 1.1 0 0
C4 J4a Out1 635.52 0.01 1.1 2 0 0
C5 J12b J13b 260.77 0.01 3.08 .81 0 0
C6 J13b J14b 654.30 0.01 .9 2.61 0 0
C7 J11b J10b 173.52 0.01 3.51 2.65 0 0
C8 J10b J14b 259.19 0.01 2.65 2.61 0 0
C9 J7b J9b 403.66 0.01 2.27 2.21 0 0
C10 J9b J10b 753.50 0.01 2.21 2.65 0 0
C11 J8b J9b 379.36 0.01 .74 2.21 0 0
C12 J6b J8b 608.78 0.01 3.56 .74 0 0
C13 J5b J6b 31.01 0.01 3.42 3.27 0 0
C14 J3b J5b 347.71 0.01 1.42 3.42 0 0
C15 J4b J6b 391.21 0.01 1.45 3.56 0 0
C16 J2b J3b 373.40 0.01 2.89 1.42 0 0
C17 J1b J4b 387.30 0.01 2.91 1.45 0 0
C18 J14b Out2 179 0.01 2.61 2.639 0 0
C19 J5a J4a 400 0.01 .9 .8 0 0

[XSECTIONS]
;;Link Shape Geom1 Geom2 Geom3 Geom4 Barrels Culvert
;;---------- ---------- ---------- ---------- ---------- ---------- ---------- ----------
C1 CIRCULAR .4 0 0 0 1
C2 CIRCULAR .4 0 0 0 1
C3 CIRCULAR .4 0 0 0 1
C4 CIRCULAR .4 0 0 0 1
C5 CIRCULAR .4 0 0 0 1
C6 CIRCULAR .4 0 0 0 1
C7 CIRCULAR .4 0 0 0 1
C8 CIRCULAR .4 0 0 0 1
C9 CIRCULAR .4 0 0 0 1
C10 CIRCULAR .4 0 0 0 1
C11 CIRCULAR .4 0 0 0 1
C12 CIRCULAR .4 0 0 0 1
C13 CIRCULAR .4 0 0 0 1

C14	CIRCULAR	.4	0	0	0	1
C15	CIRCULAR	.4	0	0	0	1
C16	CIRCULAR	.4	0	0	0	1
C17	CIRCULAR	.4	0	0	0	1
C18	CIRCULAR	.4	0	0	0	1
C19	CIRCULAR	.4	0	0	0	1

[LANDUSES]

;; ;;Name	Sweeping Interval		Fraction Available	Last Swept
;;----------	----------	----------	----------	
Commercial	0	0	0	
Villa-Zone	0	0	0	
Apartment-Zone	0	0	0	
Street	0	0	0	
Landscape	0	0	0	
Parking	0	0	0	
Garden	0	0	0	
Education-Services		0	0	0
Healthcare	0	0	0	
GovtServices	0	0	0	

[COVERAGES]

;;Subcatchment	Land Use	Percent
;;----------	----------	----------
S1	commercial	10.3
S1	Villa-Zone	55
S1	Street	20.3
S1	Landscape	2.7
S2	commercial	12
S2	Villa-Zone	58
S2	Street	11
S2	Landscape	3.6
S2	Parking	1.5
S2	Healthcare	15.2
S3	commercial	11.2
S3	Villa-Zone	56.5
S3	Street	15.71
S3	Landscape	3.7
S3	Parking	1.5
S4	commercial	7.4
S4	Villa-Zone	66
S4	street	15.7
S4	Govt.Services	2.3
S5	commercial	2.7
S5	Villa-Zone	71
S5	street	18.8
S5	Landscape	2
S5	Education Services	2.9
S6	commercial	3.7
S6	Villa-Zone	36
S6	street	19.74
S6	Landscape	.2
S6	Education-Services	.3
S6	Healthcare	9.5
S6	Gov.tServices	11.8
S7	commercial	6.1
S7	AppartmentZone	72
S7	street	17.5

```
S7              Landscape       1.4
S7              Parking         .7
S7              Education Services      .7
S7              Healthcare      .7
S8              commercial      2.25
S8              Apartment-Zone  66.7
S8              street          25.3
S8              Landscape       .48
S8              Parking         .03
S8              Education-Services      1.78
S8              Healthcare      .16
S8              Govt.Services   .7
S9              commercial      .4
S9              Villa-Zone      79.2
S9              street          20.3
S10             commercial      .6
S10             Villa-Zone      65.1
S10             street          26.1
S10             Healthcare      7.9
S10             GovtServices    .2
S11             Villa-Zone      19.5
S11             street          39.4
S11             Landscape       3.2
S11             Garden          37.9
S12             commercial      42
S12             street          27
S12             Landscape       16
S12             Garden          5.4

[TIMESERIES]
;;Name           Date      Time           Value
;;-------------- ---------- ---------- ----------
2years-Design(26.9mm)6h3/4/2019         1       3.7
2years-Design(26.9mm)6h3/4/2019         2       17.6
2years-Design(26.9mm)6h3/4/2019         3       .7
2years-Design(26.9mm)6h3/4/2019         4       .6
2years-Design(26.9mm)6h3/4/2019         5       .6
2years-Design(26.9mm)6h3/4/2019         6       .6

[REPORT]
;;Reporting Options
SUBCATCHMENTS   ALL
NODES ALL
LINKS   ALL

[MAP]
DIMENSIONS  514170.594      2381010.504     519821.384      2383938.691
Units     Meters

[SYMBOLS]
;;Gage           X-Coord           Y-Coord
;;-------------- ------------------ ------------------
RG1             518587.833        2381397.160
```

Appendix C: Information's related to Survey by Questionnaire

This appendix contains all the information related to the survey through questionnaire, which comprises an email sent to participants, a copy of the questionnaire, consent form, ethical approval and the full tabulation of answers of the questionnaire survey, as presented in Chapter Five.

C-1 A Copy of an email that sent to participants

"Dear Sir/Madam

"Decision Support System for Optimum Selection and Placement of SUDS for Urban Stormwater Management in Arid and Semi-Arid Region (with a case study in Jeddah city): request to participate in a surve".

I have been given your details by (Twitter/ Municipality contact/ University website / other known contact) as a recognised expert in Water management/ civil and environment Engineering, Hydrology (Academic/ municipality / private sector).

I am a PhD student at the University of Birmingham, and my research project is on the implementation of Sustainable Urban Drainage Systems (SUDS) in arid and semi-arid regions. I am working on developing a decision support system framework for the optimum selection and placement of SUDS in these regions. This framework will come up with tradeoff curves between cost-effectiveness and runoff reduction (volume and peak flow) for different combination of SUDS which can be used by researchers and decision-makers to make sustainable decisions and plans for stormwater management in arid and semi-arid urban areas.

Part of the research involves collecting general data and information from experts in the filed on the suitability of different type of SUDS in arid regions, and to obtain information about the costs of building and maintaining such infrastructures. I intend to collect this needed information through a survey in which questioners will be distributed (via email) among practitioners, experts, contractors and engineers working in the area of urban storm water management in KSA; hence why you have been contacted.

I was wondering if you would volunteer to participate in my survey and provide answers to some key questions regarding this research.

The survey would be conducted following the University's Strict Ethical policies – so you could be either be referenced / or remain anonymous within the thesis as you require. Information will be

encrypted and kept securely on University of Birmingham's servers. You may also withdraw your information up to 1st of November 2019.

I do hope you will be able to assist. If you are happy to participate in this survey, please complete and sign the attached consent form and return it to me. I will send you the questionnaire once I receive your signed consent form.

Many Thanks and Best regards,

Mr Abdulrahman Almalki

PhD research Student

Department of Civil Engineering.

University of Birmingham B15 2TT

[redacted]

[redacted]"

C-2 Consent Form

''Dear Sir/Madam

"Decision Support System for Optimum Selection and Placement of Sustainable Urban Drainage Systems (SuDs) for Urban Stormwater Management in Arid and Semi-Arid Region"

Research Participation Information & Consent Form – Part 1

Introduction

I am a PhD student at the University of Birmingham, and my research project is on the implementation of Sustainable Urban Drainage Systems (SuDs) in arid and semi-arid regions. SUDS are drainage systems that are considered to be environmentally beneficial, causing minimal or no long-term detrimental damage. I am working on developing a decision support system framework for the optimum selection and placement of SUDS in these regions. This framework will come up with tradeoff curves between cost-effectiveness and runoff reduction (volume and peak flow) for different combination of SUDS which can be used by researchers and decision-makers to make sustainable decisions and plans for stormwater management in arid and semi-arid urban areas.

Part of the research involves collecting general data and information from experts in the filed on the suitability of different type of SUDS in arid regions, and to obtain information about the costs of building and maintaining such infrastructures. I intend to collect this needed information through a survey in which questioners will be distributed among practitioners, experts, contractors and engineers working in the area of storm water management in Kingdom of Saudi Arabia (KSA); hence why you have been contacted.

Confidentiality

Participation in this research is **voluntary**. All information's will be kept confidential and will only be used by me and the supervision team. The answers and notes will be digitised, encrypted and stored on the University of Birmingham's servers (BEAR Datashare). The answers provided will be summarized and reported in my dissertation and any subsequent publications without mentioning any individual names or companies. You can withdraw from the research after you have completed and submitted the questioner; if you choose to do this you will be asked whether any data you have given that is specific to you can be used in the research, or whether you would like it destroyed.

The deadline for participant withdrawal and to withdraw data from the study should be before 1st of November 2019.

Participating in the survey

If you are happy to participate in the survey, you will be required to read both parts of this consent form, and sign part 2. You should retain Part 1 for your records and send me Part 2 via email which will be retained by the project supervision team. I will email you the questionnaire once I receive your signed consent form. If you require any further information or clarification, please do not hesitate to contact us.

Principal Investigator:
Dr.Soroosh Sharifi

Co Investigator:
Dr. Michael Burrow

Researcher:
Mr Abdulrahman Almalki

Participation Information and Consent Form – Part 2

Participant name:……

Organization:……

- I agree to take part in the above named project for University of Birmingham research, and to participate in this research. The research procedures have been explained to me and described in writing. Please initial as appropriate.

Yes, I agree to participate ☐

- I understand and agree that I can withdrawal from the research at any time prior to taking part in the survey, without having to give a reason. Similarly, I can withdrawal from the research after taking part in the survey; if I choose to do this I will be asked whether any data I have given that is specific to me can be used in the research, or whether I would like it destroyed. I understand and agree that the deadline date for withdrawal of data from the study is before 1st of November 2019.

Yes, I agree ☐

For the purpose of reference, I agree to the following may be used

My/our name(s) ☐ OR MY/our name cannot be used ☐

Job actual role title(s) ☐ OR A generic equivalent job role ☐

(e.g. "Senior Architect")

My/our organisations name ☐ OR A generic organisation title ☐

(e.g. "A leading KSA Consultancy")

I confirm that the research procedures of this project have been explained to me and described in writing.

Yes, I agree ☐

Signature of participant:…….. Date:……..

Researcher name: Abdulrahman Seraj Almalki

Signature of researcher:…… Date:……

C-3 A full copy of the distributed questionnaire

Survey Questionnaire. - Decision Support System for Optimum Selection and Placement of Sustainable Urban Drainage Systems (SUDS) for Urban Stormwater Management in Arid and Semi-Arid Region

Thank you for agreeing to participate in the survey. The survey questionnaire is formed of 2 parts. Part 1 focuses on questions related to the suitability of different SUDS types in Jeddah City (KSA). The second part is related to the building and maintenance costs of different type of SUDS. Feel free to answer, part 1, part 2 or both parts depending on your experience and background.

Name:

Organization:

City:

Part 1: Questions

Theme1: The Suitability of SUDS in Jeddah
❖ **Q1:** Is the current drainage system in Jeddah City fit for purpose (i.e. does it prevent flooding)? Why?
❖ **Q2:** SUDS have been proposed as a method of controlling flooding whilst reducing environmental impacts, do you think that this would be the outcome if they were used in Jeddah City? Why/Why not?
❖ **Q3:** The use of SUDS is not widespread in Jeddah City, can you think of any reasons why this so?

Theme 2: Appropriate type of SUDS for Jeddah

- **Q4:** The popular type of SUDS available include Green roof, Bio-retention, swales, rain garden, previous pavement, Rainwater harvesting, Infiltration Trench. Can you list in order the SUDS that you think are more appropriate for Jeddah?

1-	**2-**
3-	**4-**
5-	**6-**
7-	

- **Q5:** Review of the literature shows that green roofs, permeable pavement, green gardens and bio-retention areas have all been suggested as SUDS that would be appropriate for Jeddah City. Do you think any one of these SUDS has merits over the others? Why?

- **Q6:** Do you think any of the SUDS listed in the previous questions would be inappropriate for implementation in Jeddah City? Why?

Theme 3: Challenges of SUDS implementation

- **Q7:** Where do you think Green roof should be installed? On Private houses or Commercial buildings or Government buildings? (Why or why not?)

- **Q8.** Do you think that SUDS could be retrofitted in Jeddah City? Why/Why not? Can you identify any particular challenges to this undertaking?

- **Q9.** Asides from the previous questions, can you think of any challenges to the use of SUDS in Jeddah City? How do you think these challenges could be overcome?

Theme 4: Opinion and Comments
❖ **Q10.** In your opinion what information needs to be gathered to facilitate the implementation of SUDS in Jeddah City?
❖ **Q11.** Any other comments on the use of SUDS in Jeddah City?

Part 2: SUDS Cost Estimation

SUDS Type	**New fit / retrofit**	**Unit**	**Cost ريال, SR**		**Maintenance Frequency (per year)**	**Cost per Maintenance**	**Additional Operational Costs (per year)**
			Materials	Construction (labour, permits etc)			
Green Roofs (Average thickness of 0.4 m)	New fit	/m^2					
	Retrofit	/m^2					
Permeable Pavement (Average thickness of 0.5 m)	New fit	/m^2					
	Retrofit	/m^2					
Rain Garden (Average thickness of 0.5 m)	New fit	/m^2					
	Retrofit	/m^2					
Bio-retention area(Average thickness of 0.5 m)	New fit	/m^2					
	Retrofit	/m^2					

C-4 Ethical Review Aproval (ID: ERN_19-1054)

Re: "Decision support system for optimum selection and placement of Sustainable Urban Drainage systems (SUDs) in arid and semi-arid regions"

Application for Ethical Review ERN_19-1054

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

I would like to remind you that any substantive changes to the nature of the study as described in the Application for Ethical Review, and/or any adverse events occurring during the study should be promptly brought to the Committee's attention by the Principal Investigator and may necessitate further ethical review.

Please also ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research Ethics/Links-and-Resources.aspx) are adhered to and referred to in any future applications for ethical review. It is now a requirement on the revised application form (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research Ethics /Ethica -Review-Forms.aspx) to confirm that this guidance has been consulted and is understood, and that it has been taken into account when completing your application for ethical review.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at

Kind regards

Research Ethics Manager

Research Support Group

C Block Dome

Aston Webb Building

University of Birmingham

Edgbaston B15 2TT

C-5 The full tabulation of the questionnaire survey for each question under each theme.

Theme One: Suitability of SUDS	
Participants Code	**Survey Questionnaire: Question One**
All participants except (B3-P.Eng. & C3-Gov.)	▪ All participants are agreed that the current drainage system is not fit for purpose because it cannot prevent flooding. ▪ *A2-AC* mentioned that although the municipality of Jeddah solutions have focused on building many dams in the east side of city, this solution not enough. ▪ *B2- P.Eng* said that the existing network inside the city is not fit for purpose because the pipe diameters are very small (i.e. 250-300mm) and there is no proper maintenance and cleaning of existing networks before and during the rainy season. ▪ *A6-AC* said that the implemented solution is not a comprehensive plan that tackles the root of the problem. It is, rather, an "urgent" solution! ▪ *A5-AC, B3-P.Eng, B3-P.Eng* mentioned that the municipality working on improving the current system and proposed system will reduce the flooding impact after implementation for the designed storm return periods. ▪ *C1-Gov* said that there is no infrastructure for stormwater in most neighbourhoods, but there is something called streams that may be used to drain rainwater. Also, the impact of poor drainage infrastructure is apparent when it rains on Jeddah city in the winter, so that some roads become submerged. ▪ *C2-Gov* said that, due to expansion in the city's boundaries as a result of population growth, the system does not, therefore, it covers the entire city of Jeddah.
(B3-P.Eng.)	▪ The current system meets the level of service requirements chosen for the city, i.e. once in 5 yrs and once in 10 yrs. There are several areas where the enhancement of the existing SW system could help improve the level of comfort and convenience during a rain event.
C3-Gov.	▪ *C3-Gov.* "I think the situation is good for the floods that come from outside Jeddah (flash flood) due to the construction of the dams, but, inside the city, there is still a need for an ideal drainage system. Most of the residential neighbourhoods were not covered by a drainage network."
	Survey Questionnaire: Question Two
All participants except (A6-AC) (D1-Cont. & C3-Gov.)	▪ All participants except *A6-AC* and *C1-Cont* said that, yes, SUDS would be the outcome if they were used in Jeddah City. And all of them said this is because it can reduce floods, and have many benefits. The following are the different justifications by participants: ▪ A1- AC. "Jeddah is located in a floodplain area of major wadis (valleys) which mean SUDS are needed for controlling flood hazards. Also *A4- AC.* ▪ *A3-AC.* "Yes, I think it will serve in controlling flooding and will even provide alternative solutions to irrigation of landscaped areas around the city." ▪ *A5-AC.* "SUDS have many benefits besides reducing flow volume, such as improving landscape, increased social benefits by building green gardens and reducing imperviousness. ▪ *B1-P.Eng.* "Yes, it can be used as long as the maintenance regime is satisfactory." ▪ *B2-P.Eng.* "It will improve the environmental impact as it will prevent ponding areas, which will decrease stagnant water and mosquitoes."

	▪ *B3-P.Eng.* "Using SUDS will definitely result in delivering cost-effective solutions. However, choosing the right SUDS for the right drainage solution of an area depends on a number of local factors related to the future development plans of that area." ▪ *B4-P.Eng.* "The SUDS would help attenuate flooding impacts by temporarily storing water locally in an urban city like Jeddah, provided this forms part of the city's integrated wider drainage system. " ▪ *C1-Gov.* "The SUDS idea itself is a novelty, but it is an auxiliary option not an alternative option. Also, I think that the priority for Jeddah now is first working on the implementation of the planned drainage infrastructure and then the application of SUDS if necessary." ▪ *C2-Gov.*"Yes, I think so. It can be used to remove pollutants from surface water prior to discharge to watercourses or aquifers. Also, the city of Jeddah is not completely covered by a sewage network, which leads to increased pollution of groundwater." ▪ *C4-Gov.* "Yes, especially green roof." ▪ *C5-Gov.* "Yes, but SUDS could be an auxiliary option not an alternative option.
(A6-AC)	▪ "Yes and no. Yes, if it was carefully planned/designed to meet the multiplicity of sustainability goals and is resilient when a natural disaster strikes. No if it is creating other issues (i.e., upkeep, inviting anti-social behaviours through creation of a crime-inviting environment). SUDS are not efficient if they will lead to constant landscape manicuring to meet the preferences of the public, which means more reliance on labourers and more greenhouse gas emissions. Adopting eco-friendly SUDS requires adopting local materials and native plants with minimum upkeep commitments, and, of course, plants that are resistant to submerging during storm events."
C3-Gov.	"There is a need for a smart drainage system to protect the city from the rainwater inside Jeddah because most residential areas do not have a drainage system, so I would like your suggestion to be perfect and applicable within the city of Jeddah!"
D1-Cont	"SUDS might have less efficiency for Jeddah because the existing planning is done randomly in most areas of Jeddah and because rainfall is limited and not continuous
	Survey Questionnaire: Question Three
	Most of the answers were because of lack of planning, and whether future planning should involve SUDS. Also, whether they should supported by the government (municipality).
A1-AC, A2-AC, A4-AC, A5-AC & C2-Gov.	▪ Because of municipality priorities and regulations ▪ *A1-AC.* "The use of SUDS should be supported by the government and by decision makers in the Municipality of Jeddah." ▪ *A2-AC.* "I think the people in Jeddah don't have an understanding about the SUDS solutions." ▪ *A4-AC.* "The current plan for Jeddah city is involves old designs in many areas of the city." ▪ *C2-Gov.* "Due to regulation as well as rapid urbanisation and expansion in cities in recent decades."
A3-AC	▪ "Because the main drainage system is not used properly nor is it enough. So, SUDS are not even in use."
A6-AC	▪ "Many of the municipality engineers (decision-makers) in charge of stormwater management actually have no idea what SUDS, LIDs or GIs are."

	▪ "There are only a few studies, almost nearly none, regarding the feasibility of SUDS and similar practices done for the arid region (Jeddah) and adopted to our culture, which are additional reasons why they are not implemented."
B1-P.Eng.	▪ "SUDS requires maintenance and understanding of its benefits by Jeddah city. The use of SUDS is not widespread because traditional design and construction is preferred. In addition to this, the attraction of mosquitoes to ponds also affects SUDS application."
B2-P.Eng.	▪ "Jeddah is a very old and historical city and was planned based on a very limited number of population; now it is under huge development and widely expanding." ▪ "Due to time constraints, the priority now (for the municipality) is to protect the city from floods, to protect lives and properties."
B3.P.Eng.	▪ "The choosing of the right SUDS for a particular site (zone) should be done at the master planning stage."
B4.P.Eng.	▪ "Because, Jeddah city does not receive regular rainfall, some SUDS, such as green roof, will require regular maintenance (e.g. watering)."
C1-Gov.	▪ I think awareness is one of the most important reasons. Awareness must be directed towards decision makers and individuals.
D1-Cont.)	▪ "The methodology used and selected for infrastructure construction for Jeddah is primitive and undeveloped." ▪ "There is a lack of research in the field of SUDS and limited financial support for this sector of business."
C4-Gov.	▪ "Because of the hot weather for Jeddah and because SUDS have high cost."
C5-Gov	▪ "Because of the hot weather's effect on grass."
Theme 2: Appropriate type of SUDS for Jeddah	
	Survey Questionnaire: Question Four
	Survey Questionnaire: Question Five
(A1-AC), (A3-AC)	Permeable pavement is the most suggested method in accordance to the Jeddah environment. In addition, *A3-AC* said because of its ease of installation, it's already in use and people know of it. The other SUDS are applicable, but need more focus from manufacturers and users to make it a norm.
(A2-AC)	▪ "Permeable pavement for now and bio-retention and green gardens in the future." (Better planning)
(A4-AC)	▪ "Permeable pavement is suitable for the Jeddah environment which is located in a very hot region and does not need irrigation. In addition, there are many areas across Jeddah city suitable to implement permeable pavement." ▪ "Also, bio-retention has merits because it is easy to construct for Jeddah and does not need a large area."
A5-AC	▪ "Green roof has merit because it is an easy adoption. The city is developed and, therefore, there are many existing roofs in the city. If green roof is applied, it would cover a huge area within the city."

A6-AC	▪ "I think those solutions at the city scale in which the city government can initiate applicable design planning codes and nominate which SUDS have merits over the others. For instance, bio-retention, swales, infiltration trench, or check dams for harvesting at the scale of the city can be implemented if following the conditions I explained earlier."
B1-P.Eng.	▪ "Permeable pavement, bio-retention and swales could be adopted due to their easy adoption by Jeddah's construction practice."
B2-P.Eng.	▪ "Bio-retention areas have merits over others for Jeddah city because the topography of the city has a steep slope from east to west, so this SUDS will slow down water velocity inside the stormwater network whilst other SUDS will be impacted by hot weather, humidity and the soil nature of the city."
B3-P.Eng.	▪ "Considering the rain pattern in Jeddah the use of permeable pavements and rain gardens in currently undeveloped areas should be considered as a priority- this will reduce the size (and costs) of future drainage infrastructure."
B4-P.Eng	▪ "Permeable pavement/green gardens would have merits over green roofs in areas where the groundwater table is low. In road carriageways, infiltration trenches/bio-retention swales in road medians would be more suitable than permeable pavement due to the CAPEX and OPEX and regular maintenance work carried out by a number of utility providers."
C1-Gov.	▪ "Green gardens are the best solutions because they serve the city in many ways and do not require much to implement."
C2-Gov.	▪ "Green roof, for their high absorption and storing rainfall. Filter pollutants from rainfall provide insulation, help lower urban air temperatures and combat urban temperature. Also, it raises the percentage of vegetation cover in Jeddah, which will have a big impact on the climate."
C3-Gov.	▪ "Permeable pavement will be appropriate because it helps the water to infiltrate down and, therefore, the water does not stay on the surface."
C4-Gov.	▪ "All of them are a good selection because it can reduce floods."
C5-Gov. & D1.Cont.	▪ *C5.Gov*. "RG covers a big area." ▪ *D1. Cont.* "Rain garden has merit over other SUDS because it has a positive effect on reducing temperature Also, because it can capture water and the water can be reused for irrigation. In addition, its adoption cost is low and its maintenances is easy."
	Survey Questionnaire: Question Six
A1-AC, A2-AC, A5-AC	All agree that none of them is inappropriate. All of them are appropriate for Jeddah
A3-AC	▪ "I think bio-retention might not be as applicable as the other SUDS, basically because of the additional costs and construction it will incur."
A4-AC	▪ "None of them is inappropriate. But the decision-makers need to look at the maintenance and operation side to get a sufficient SUDS for Jeddah."

A6-AC, ***C4-Gov.*** ***C5-Gov.***	▪ *A6-AC*. "Permeable pavement in many areas that have serious water-table issues." (water table is high/ground water issues) ▪ *C4-Gov* did not mention any reason. ▪ *C5-Gov*. "Because the pp cost is high if we need to apply it along the flood path."
B1-P.Eng.	▪ "None of them is an inappropriate."
B2-P.Eng. & B3, P.Eng.	▪ They both mentioned that green garden may be appropriately implemented, but: ▪ *B2- P.Eng* said it should be done with special care to avoid damage to grass and green areas because of the hot weather and high water table. ▪ *B3-P.Eng* said it would be helpful if the research team could find some examples of similar experiences and lessons learnt in other parts of the world with climate conditions similar to Jeddah.
B4-P.Eng	▪ Said that, provided there are adequate regulations in place for compliance, all SUDS would be appropriate. Otherwise they would not be appropriate.
C1-Gov.	▪ Said green roofs, because there is no framework to apply it in the city of Jeddah and there is also a problem related to costs (M&O).
C2-Gov.	▪ Said infiltration trench, which is localised and needs more area, which is not usually available in Jeddah due to population density.
C3-Gov.	▪ "I think the green roof is not appropriate due to the rainfall in Jeddah is not continuous and comes at long intervals."
D1.Cont.	▪ "Bio- retention because, in the event of scarcity of rain for a long term, stagnation will occur in the water and make a swamp for bacteria and insects."
Theme Three: Challenges of SUDS implementations	
	Survey Questionnaire: Question Seven
A1-AC, A2-AC, A4-AC, C2-Gov.	▪ All of them said green roof should be installed on commercial, compounds and government buildings. ▪ *A1-AC*. "Due to the effective area for harvesting, but we don't have enough and continuous rainfall." ▪ *A2-AC*. "The high cost may prevent using it on private buildings." ▪ *C2-Gov*. "Commercial buildings or government buildings, because the design of private buildings may not be appropriate and the owners may not accept this. On the other hand, the spaces in government and commercial buildings are very suitable."
A3-AC	▪ "It should be installed everywhere and companies need to act quickly to be professionals in it and provide this service at competitive prices with various designs and quality. Government buildings should make it a MUST in all their branches."
A5-AC, **B2-P.Eng.** ***C5-Gov.***	▪ *A5-AC* and *B2-P.Eng* both said GR should be installed on private houses, ▪ *A5-AC* said there is a concern about supporting the people to adopt it on their own houses (in terms of budget). Also, it needs a robust and efficient maintenance and operation system due to Jeddah's environment.*B2-P.Eng* said definitely on private houses because it needs special care which may not be provided in other types of buildings. ▪ *C5-Gov*. "Because there are many private houses."

A6-AC	▪ "Commercial buildings where the city can enforce regulations to keep up with city planning, and, of course, government buildings. However, green roofs cannot be installed unless there is cooperation between the city and house owners to do so." (Build a green roof and in return you get such and such).
B1-P.Eng	▪ "Experimentation should be started on commercial buildings, which are well-maintained."
B3- P.Eng	▪ "At the moment, I am not very sure on the use of roof gardens. It would be helpful if the research team could find some examples of similar experiences and lessons learnt in other parts of the world with climate conditions similar to Jeddah. Therefore, I cannot answer where GR should be installed."
C1-Gov.	▪ "I think it depends on the government (decision-maker) and then the private sector because they bear part of the responsibility to preserve the environment."
C3-Gov.	▪ "The green roof is not appropriate for Jeddah, as I mentioned, because of its water needs, but, in the south-western region, it will be appropriate where there is a lot of rainfall. If necessary, you can start in the government buildings first then the commercial buildings and finally the private."
D1.Cont.	▪ "Government buildings because they have annual maintenance contracts with permanent cleaning contracts in buildings. This is one of the most important points that must be available for green roofs. Also, government buildings have a large water source that can be of benefit for irrigating a green roof." ▪ "Also, it is known that green roofs increase the efficiency of the building, which reduces the cost of energy running the building."
	Survey Questionnaire: Question Eight
A1-AC, A2-AC, A3-AC, A4-AC, B1-P.Eng, B4-P.Eng	▪ *A1-AC, A2-AC, A3-AC, A4-AC* all answered yes, it can retrofitted Regarding challenges which might face retrofitting SUDS in Jeddah, these are: ▪ *A1-AC*. "It depends on the government and decision-makers and the complexity of the Jeddah environment." ▪ *A3-AC*. "Yes, it can be retrofitted and it can also be done with minimum cost if designed and implemented correctly with skilled labour. The main challenge is to find the right and qualified labour and construction company and also design firms that can do this huge job." ▪ *A4-AC*. "SUDS can be retrofitted, especially for areas that do not have traditional design. The challenges are related to the budget and the priorities for the Jeddah municipality." ▪ *B1-P.Eng*. "I believe all methods except green roofs can be easily adopted / retrofitted. The biggest challenge is that of using SUDS in the design and endorsement by the authorities." ▪ B4-P.Eng. "Yes, provided there are adequate regulations and design guidelines in place for compliance. The main challenge would be public participation due to reluctance of residents, lack of awareness of design requirements and promotion of retrofit SUDS to tackle a range of issues related to design and methodology."
A5-AC	▪ "Retrofitting is not difficult if decision-makers (the Municipality of Jeddah) agree it and providing all requirements for this kind of project, such as studying the project in terms of its beneficial, cost, and time, are in place."

A6-AC	▪ "No, it cannot be retrofitted for the next 10 years or even more. The cost of redoing the current infrastructure, the state of the economy that has paused and cancelled many big projects, and the educational background of most of the decision-makers from stormwater management and urban planning backgrounds will hinder the implementation of such solutions. There are more urgent infrastructure projects in the list of priorities of the city (such as transportation, housing) that need to be taken care of now more than SUDS. In addition, some of these practices at the urban scale will require enforcing "right of way" acts. This, as a result, will create boundless urban traffic/parking issues in a city that is car friendly only."
B2-P.Eng	▪ "No, I don't think so because SUDS still have a very limited use in Jeddah city because of the hot weather, high water table and the aggressive soil of the city."
B3- P.Eng	▪ "Yes, but it requires the private developers to be engaged at the master planning stage."
C1-Gov.	▪ "Depends on budgets, labour, specialist companies for implementation. If these things are available, then they can be retrofitted."
C2-Gov.	▪ "No specific idea, there is a need to study the situation more in Jeddah city inform all sides."
C3-Gov.	▪ ----------
C4-Gov	▪ "Yes, it can be retrofitted, especially RG and GR."
C5-Gov	▪ "Yes, especially GR, but it needs an action by decision-makers to apply it."
D1.Cont.	▪ "Topography of the area and planning according to their needs, climate analysis of the region and defined rainfall rate."
	Survey Questionnaire: Question Nine
A1-AC	▪ "Jeddah has highly populated slums or random housing areas which lack of modern planning." ▪ "We need in-depth environmental studies and a challenging master plan."
, A2-AC	▪ "We need more environmental and hydrogeological studies covering all parameters of the city water balance. On the other hand, we need more knowledge about new methods of SUDS in arid and semi-arid areas. (I think this study affords us the best methods that can be used in arid countries like Saudi Arabia)."
, A3-AC	▪ "The amount of waste water, type of waste water, amount of precipitation in different city locations, water level during wet season and dry seasons, etc."
, A4-AC	▪ "The most important challenges faced in using SUDS in Jeddah are maintenance and operation of different types of SUDS. Such as green roof and rain garden need irrigation and extra care because the weather is very hot and rainfall is not continuous. So, maintenance and operation might consume extra cost. Therefore, given the maintenance and operation are efficient, we can apply SUDS easily in Jeddah City."
A5-AC	▪ "The challenges are related to the cost of maintenance and operation because the weather is hot Also, there are challenges related to the existing traditional plan for the city. This makes difficulties to build different types of SUDS. " ▪ "There is a need to adopt a robust and efficient maintenance and operation system due to Jeddah's environment. These challenges can be overcome by developing a master plan for Jeddah."

A6-AC	▪ "Expert marketplace (researcher, planners and designer, companies)."
B1-P.Eng	▪ "SUDS should be part of the mainstream media and government should back it up because Jeddah city will benefit from the widespread use of SUDS."
B2-P.Eng	▪ "Hot weather, humidity, high water table and aggressive soil are the main challenges. These can be overcome by providing special care by choosing plants and structure protection which suit this type of environment and providing frequent maintenance to increase the lifecycle of SUDS."
B3-P.Eng	• "We need time to study and select the right SUDS for the right zone (master planning area), the commitment and engagement of Jeddah city stakeholders (roads, municipality, urban planning, private developers, etc.) in terms of time, Space requirements and adoptability."
B4-P.Eng	▪ "Public awareness to educate on the benefits of SUDS would be also another challenge. The students in schools and universities can be used as ambassadors to enhance the public awareness and in promoting SUDS."
C1-Gov.	▪ "I believe that one of the most important solutions to overcome the challenges is the participation of the private sector to apply SUDS for the cities."
C2-Gov.	▪ "Incomplete infrastructure, rapid urban growth, and erratic rainfall in arid and semi-arid areas. To overcome these challenges, there is a need to conduct more specialised studies, accelerate the completion of infrastructure, enact regulations."
C3-Gov.	▪ "In my opinion, the most appropriate thing for the city of Jeddah is for the drainage network and tunnels to absorb the floods and then divert them to huge reservoirs for reuse in the irrigation of public parks or being recharged in dry aquifers."
C4-Gov, C5-Gov	▪ Both worried about cost, which they thought would be high, especially in terms of M&O.
D1-CONT	▪ "Randomly planning of some neighbourhoods, which are built in the streams and valleys." ▪ "Not to analyse the topography of the area before designing the infrastructure." ▪ "The rate of rainfall resulting from future climate changes."
Theme Four: Opinion and Comments	
	Survey Questionnaire: Question Ten
A1-AC	▪ Geological, hydrogeological data, DEM analysis, groundwater maps, soil types analysis, hazards maps and vulnerability maps.
A2-AC	▪ Hydrological and hydrogeological data, land use maps (urban and non-urban zones), DEM data, climate data, surface and subsurface drainages and network systems.
A3-AC	▪ Amount of wastewater, type of wastewater, amount of precipitation in different city locations, water level during wet season and dry seasons, etc.
A4-AC	▪ Gathering all information needs relating to implement SUDS, such as land use map, soils map and Jeddah topography. ▪ Intensive studies by researchers, decision-makers and specialists to see and estimate how SUDS are beneficial for Jeddah city.
A5-AC	▪ Elevations, slopes, land cover map, weather information and budget.

A6-AC	▪ A comprehensive study of feasibility for a proposed landscape plan by: a) Landscape Architects (SUDS plan on a regional scale and design at urban scale, including soft and- hardscape specification); b) Engineers (rainwater algorithm and SUDS specification design); c) Ecologists (design for ecosystem and biodiversity); d) Urban Planners (adopting SUDS to current urban regulations); and e) Architects (including SUDS in structure and building codes), ▪ Standardising practices and construction materials (experiments), ▪ Longitudinal research experiments (social landscape, performance and cost efficiency studies).
B1-P.Eng	▪ The suppliers and designers should arrange a seminar / workshop to attract various ideas and clients should back it up.
B2-P.Eng	▪ Soil investigation reports to include recommendations to protect stormwater structure and lowering of the water table, technical data sheets for plants and trees which can grow and live in this kind of environment and M&O guidance for structures and green areas with frequent maintenance tables for each item.
B3-P.Eng	▪ Future master planning with detailed land use plans of governmental and private developments. ▪ Design of future road works and finished grading plans.
B4-P.Eng	▪ Identify the SUDS opportunities and regional companies develop local markets for them to expand the business. Promote targeted communication initiatives for public awareness.
C1-Gov.	--------
C2-Gov.	▪ Maximum network load or discharge (threshold), level of groundwater in Jeddah city and the effect when applying SUDS; advantages and disadvantages of the environmental situation before applying any type of SUDS.
C3-Gov.	▪ First, the most affected areas that were not covered by the drainage network. Second, the map of the current drainage system and what is the problem? Third, the maps of slopes, topography and geology of Jeddah.
C5-Gov	▪ Make a report about areas affected by flooding.
D1-CONT	---------
	Survey Questionnaire: Question Eleven
A1-AC	▪ "I think officials in the government should consider adopting the latest SUDS techniques in Jeddah to avoid flash floods and groundwater rise problems."
A2-AC	▪ "In my opinion, we need new arrangements and laws recommending the SUDS and government organisations to make these laws effective.
A3-AC, A6-AC, B4-P.Eng	▪ None
A4-AC	▪ "Government (municipality) or decision-makers should give SUDS more attention for Jeddah."
A5-AC	▪ "Municipalities, academics and the private sector should cooperate and spend time to look at SUDS for Jeddah to see how they could be applied for Jeddah and which type of SUDS are the best."

B1-P.Eng	▪ "SUDS is a need of all major urban environments and Jeddah should take a lead."
B2-P.Eng	▪ "By using proper techniques, engineering design and qualified contractors, SUDS could be implemented in Jeddah city."
B3-P.Eng	▪ "I would be very interested to be kept informed of the ongoing progress in this research."
C3-Gov.	▪ "I would like you to focus on the permeable pavement and rainwater harvesting through the subsurface tunnels."
D1-CONT	▪ "Not to drain the rainwater to the sea and to benefit from it."

Appendix D: Code of SUDS Optimisation Framwork and Simulation results

Programing Code

In order to use the SUDS optimisation model (the Borg MOEA and the SWMM hybrid model), the following codes were developed on MATLAB during the research:

D-1 Linking SWMM Model with MATLAB Script

Two steps have been taken under this section

```
% 1- Creat SWMM the input file
 % 2- Run SWMM
    1-  Creat input file:
Function []=Create_INP(x)
% This function creates SWMM inputfiles
fopen('Jeddah_run.inp','w');
fopen('Jeddah_run.rpt','w');
fopen('Jeddah_run.out','w');
fclose('all');
fi=fopen('Jeddah_temp.inp','r');
% open another new file to save the outcome
fo=fopen('Jeddah_run.inp','w');
% scan the input file line by line
txtcell=textscan(fi,'%s','delimiter','\n');
%find the line number that has the string [LID_USAGE]
idx = ~cellfun('isempty',strfind(txtcell{1},'[LID_USAGE]'));
% find the row number that contatins [LID_USAGE]
k = find( idx );
for i=k+3:k+3+36
   i;
   txtcell{1}{i} = regexprep(txtcell{1}{i},'#',num2str(x(i-k-2)));
end
for i=1:length(txtcell{1})
   fprintf(fo,'%s\n', strcat(txtcell{1}{i}));
end
fclose(fi);
```

```
fclose(fo);
end
    2-  Run SWMM
This function lets SWMM to be run via MATLAB
   !swmm5 Jeddah_run.inp Jeddah_run.rpt Jeddah_run.out
```

D-2 Fitness Function:

D.2.1 Cost Function

```
Function [obj3] =CostCalc(x)
% Calculates the third Objective which is the Cost Function
N_GR=0;
N_RG=0;
N_BR=0;
N_PP=0;
j=1;
for i=1:10
   N_GR=N_GR+x(j);
   N_BR=N_BR+x(j+1);
   N_PP=N_PP+x(j+3);
   j=j+3;
end
N_GR+x(34);
N_RG=x(31)+x(35);
N_BR=N_BR+x(32)+x(36);
N_PP=N_PP+x(33)+x(37);

GR_cost=(N_GR*100)*1034;
RG_cost=(N_RG*100)*1098;
BR_cost=(N_BR*25)*1122;
PP_cost=(N_PP*80)*553;

Obj3=GR_cost+RG_cost+BR_cost+PP_cost;
end
```

D.2.2 Flow Volume and Peak Flow Functions (Objective Functions)

```
Function [ objs ] = EVO_SB( x )
    nvars = 37;
    nobjs = 3;
    % 1- Creat SWMM the input file (D-1)
    Create_INP(x);
    % 2- Run SWMM (D.1)
    !swmm5 Jeddah_run.inp Jeddah_run.rpt Jeddah_run.out
    % 3- Calculate first Objective which is the reduction in Total flooding   % at all junctions
    % read report file to find total flooding in all junctions
    data=textread('Jeddah_run.rpt', '%s','delimiter', '\n');
    H=[];
    % flooding calculation
    for k=1:size(data,1)
       TF = strcmp(data(k),'subcatchment runoff summary'); %Flooding refers to all subcatchment
outlet
       if TF == 1
         for j=k+8:size(data,1)
            while strcmp(data(j),'')==0
             k1=char(data(j));
             k2=k1(104:110);              % for peak runoff change to (114:118)
             k2=str2num(k2);
             H=[H k2];
             j=j+1;
             end
            break
         end
         break
       end
    end
    %flood reduction in all subcatchment outlet
    objs(1,1)=sum(H);
    % 4- Calculate second Objective which is reduction in flood Volume

%     objs(1,2) = [];
```

```
    % 5- Calculate third Objective which is the cost
        objs(1,2)=CostCalc(x);
end
```

D-3. Main Code of the Borg MOEA that Optimise a multiobjective problem

After building objectives functions and defining SWMM inputs files, the following code is then used to run an optimisation problem (SUDs-Optimisation-Framwork) so as to find optimum selection.

```
clc
clear
tic
% Maxs is a vector that shows the maximum allowable number for the
% different type of SUDS in each subcatchment (for SUDS option 1)
Maxs= [177, 262, 272, 436, 485, 772, 181, 513, 543, 104, 328, 367, 124, 793, 776, 778, 847, 1000,
136, 358, 667, 115, 390, 765, 2, 182, 186, 5, 175, 197, 125, 25, 53, 1000, 386, 999, 1000];
[vars, objs, runtime] = borg(37, 2, 0, @EVO_SB, 10000, 0.01*ones(1,2), zeros(1,37),Maxs);
 Toc
% if need to set minimum number of SUDS, setting change to:
 [vars, objs, runtime] = borg(37, 2, 0, @EVO_SB, 6000, 0.01*ones(1,2), Mins, Maxs);
toc
```

D-4 Results of Simulation

The scenarios that were studied in this reaserch are presented In Table 7-4, Chapter Seven. Given the number of simulation scenarios that were conducted (18 in total), as mentioned, it was not feasible to report all simulation outputs. Therefore, this section is about the simulation outcome of all scenarios that not reported in chapter seven.

D-4-1 Scenario 2: 6-hour 2-year rainfall and SUDS option 2

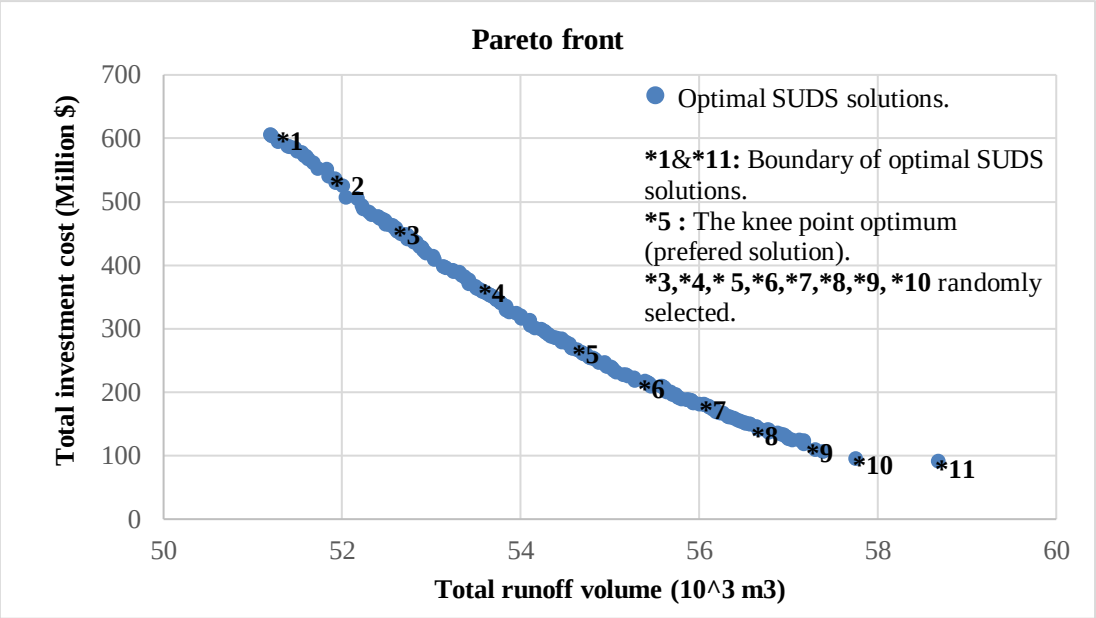


Figure D-1 Pareto-optimal front of SUDS solutions for scenario 2: 6-hour, 2-year rainfall event & SUDS option 2.

Table D-1 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 2 (6-hour 2year rainfall and SUDS option 2).

ID of SUDS solution	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	601	51200	44.3
*2	553	51700	43.8
*3	465	52500	42.9
*4	371	53400	42.0
*5	270	54600	40.7
*6	219	55300	39.9
*7	181	56000	39.1
*8	151	56500	38.6
*9	125	57000	38.0

*10	95.8	57800	37.2
*11	91.4	58680	36.2

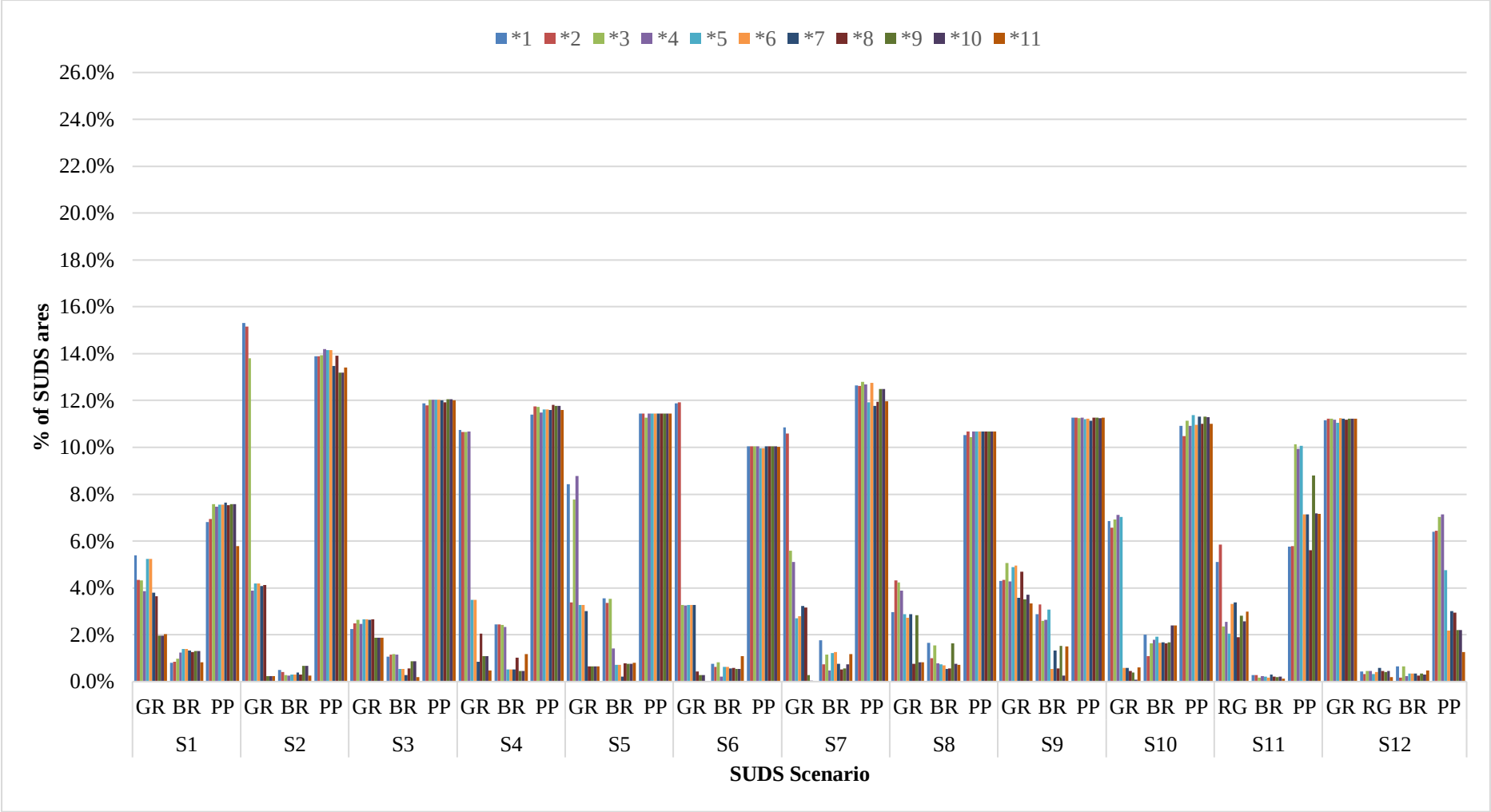


Figure D-2 SUDS percentage coverage in each sub-catchment for scenario 2's selected optimal solution

D-4-2 Scenario 5: 6-hour 10-year rainfall and SUDS option 2

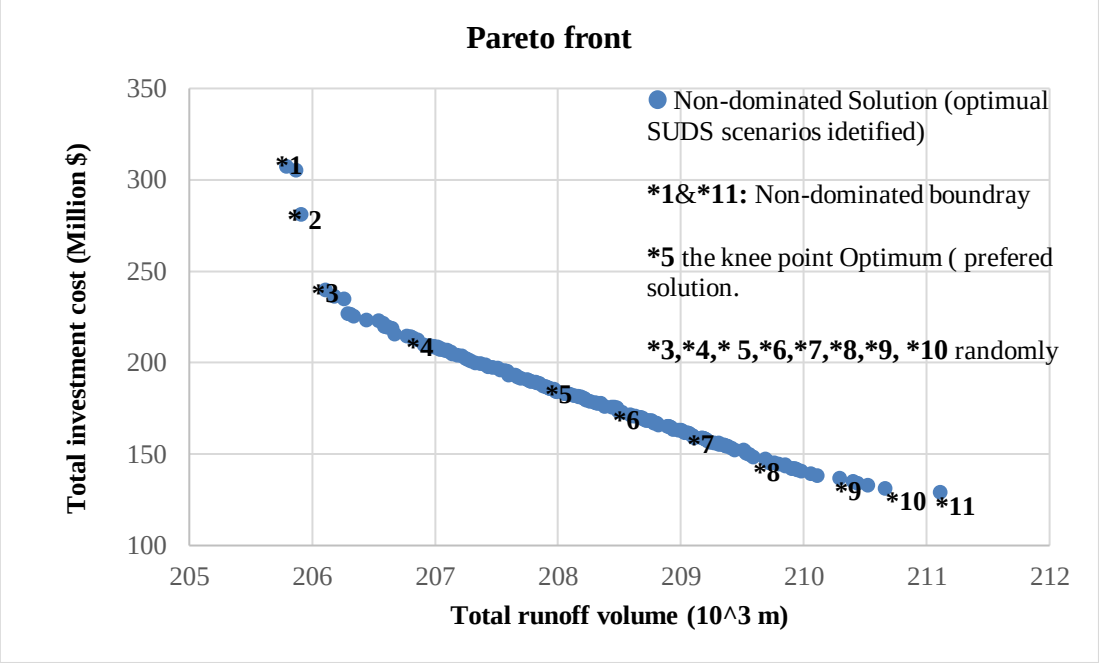


Figure D-3 Pareto-optimal front of SUDS solutions for scenario 5: 6-hour, 10-year rainfall event & SUDS option 2.

Table D-2 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 5 (6-hour 10-year rainfall and SUDS option 2).

ID of SUDS solution	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	307	205790	27.9
*2	281	205900	27.9
*3	240	206100	27.8
*4	213	206800	27.6
*5	184	207900	27.4
*6	173	208500	27.0
*7	161	209000	26.8
*8	148	209600	26.6
*9	136	210300	26.3
*10	131	210700	26.2
*11	129	211110	26.0

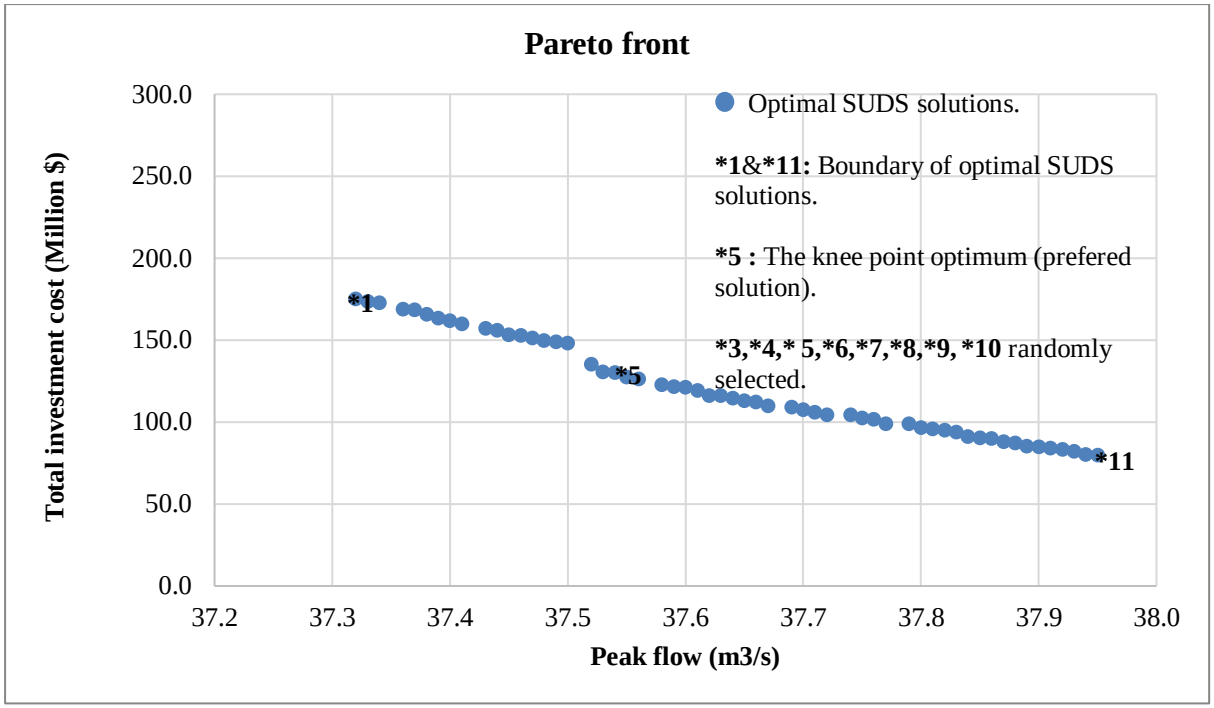


Figure D-4 Pareto-optimal front of SUDS solutions for scenario 5 using peak flow and cost objective functions

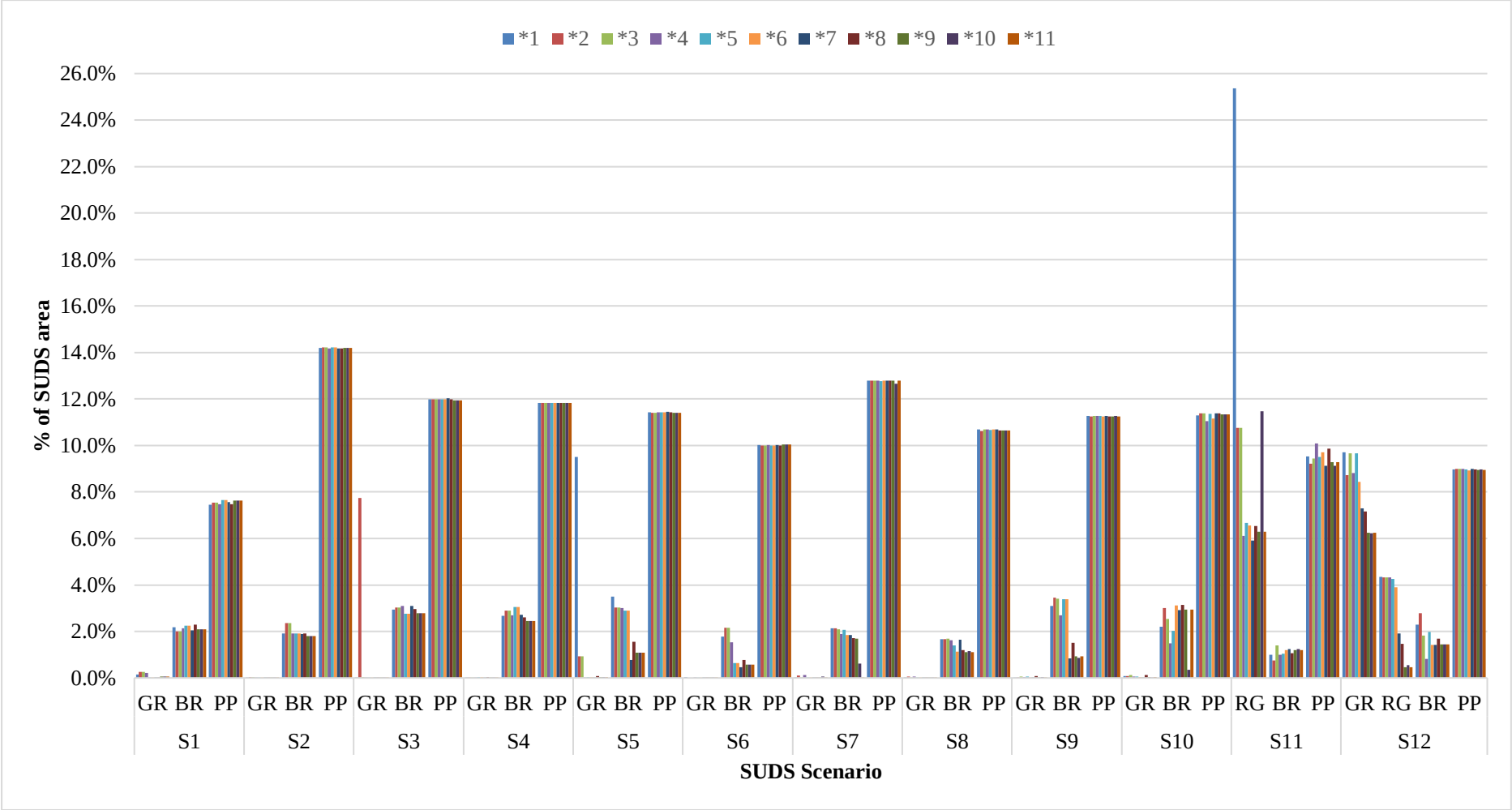


Figure D-4 SUDS percentage coverage in each subcatchment for scenario 2's selected optimal solutions.

D-4-3 Scenario 8: 6-hour 25-year rainfall and SUDS option 2

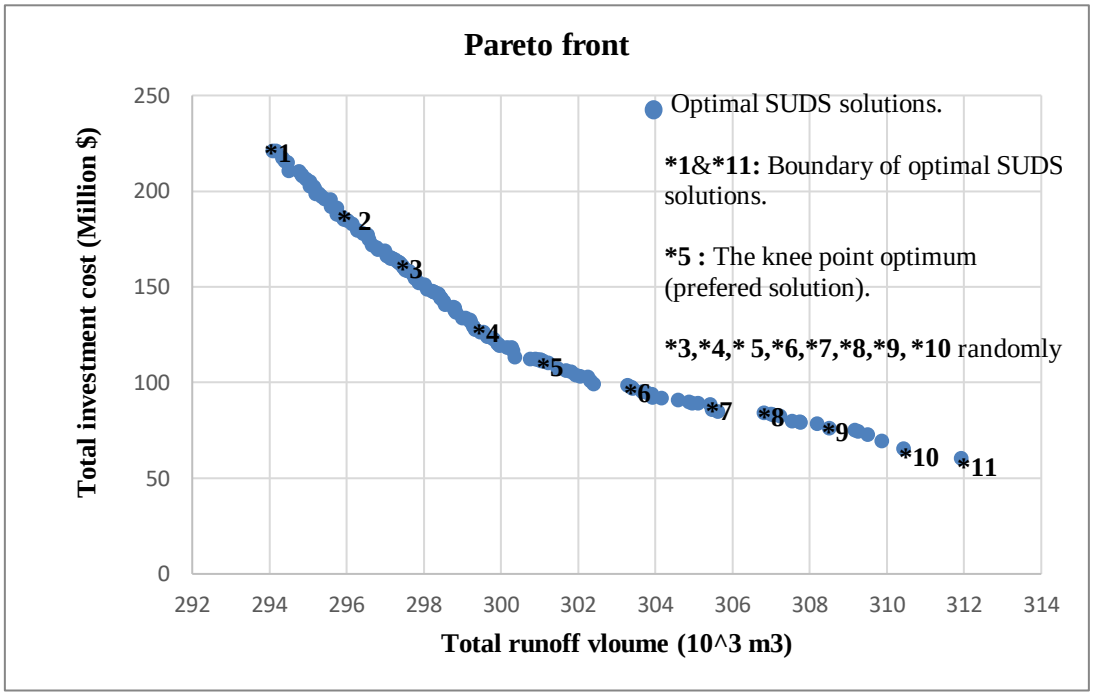


Figure D-5 Pareto-optimal front of SUDS solutions for scenario 8: 6-hour, 25-year rainfall event & SUDS option 2.

Table D-3 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 8 (6-hour 25-year rainfall and SUDS option 2).

ID of SUDS solution	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	221	294090	26.9
*2	188	295800	26.4
*3	165	297100	26.1
*4	134	299000	25.6
*5	113	300400	25.3
*6	99	303300	24.6
*7	89	305100	24.1
*8	84	306800	23.7
*9	78	308200	23.4
*10	65	310400	22.8
*11	60	311920	22.4

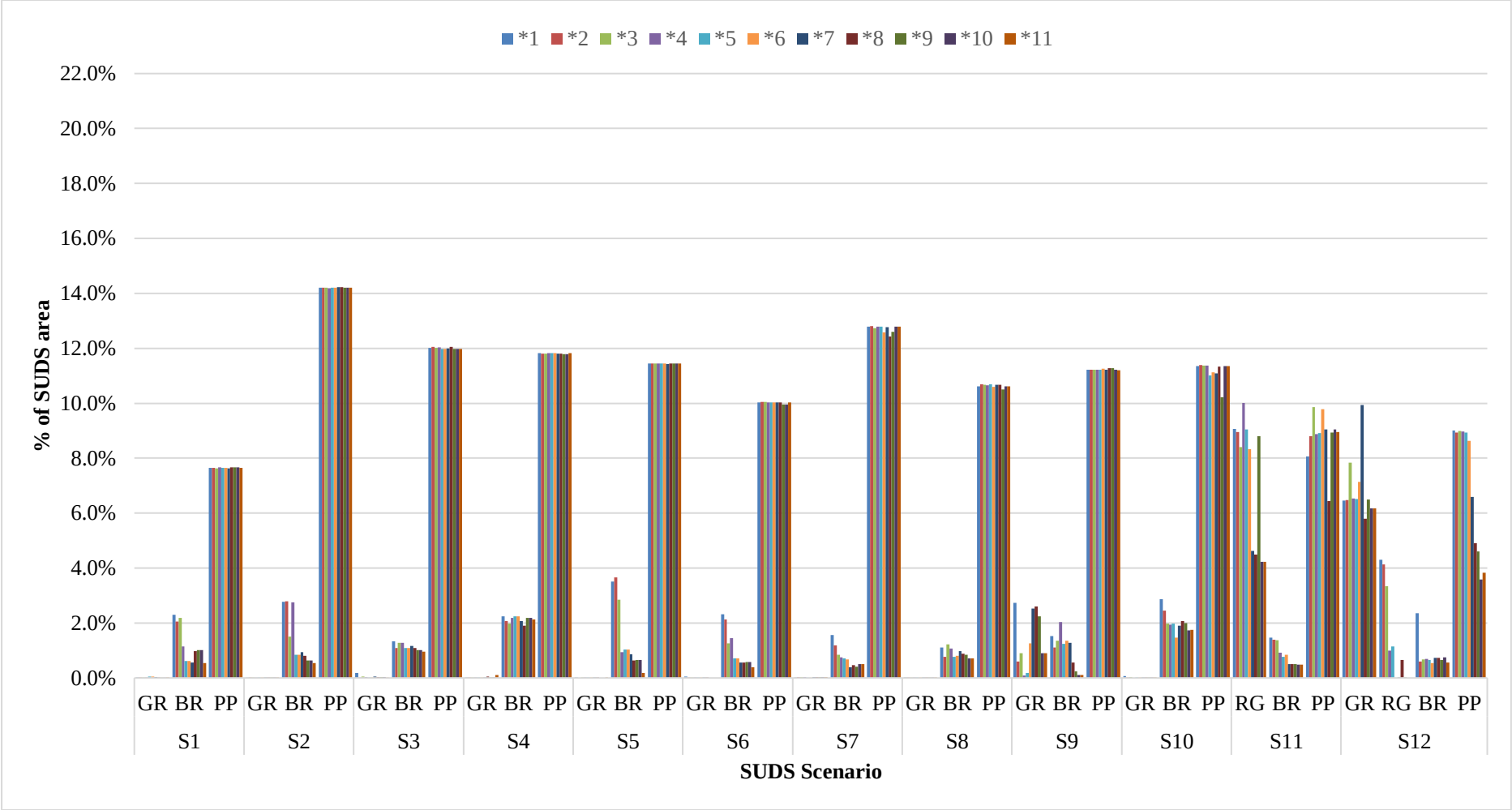


Figure D-6 SUDS percentage coverage in each sub-catchment for scenario 8's selected optimal solutions.

D-4-4 Scenario 11: 6-hour 100-year rainfall and SUDS option 2

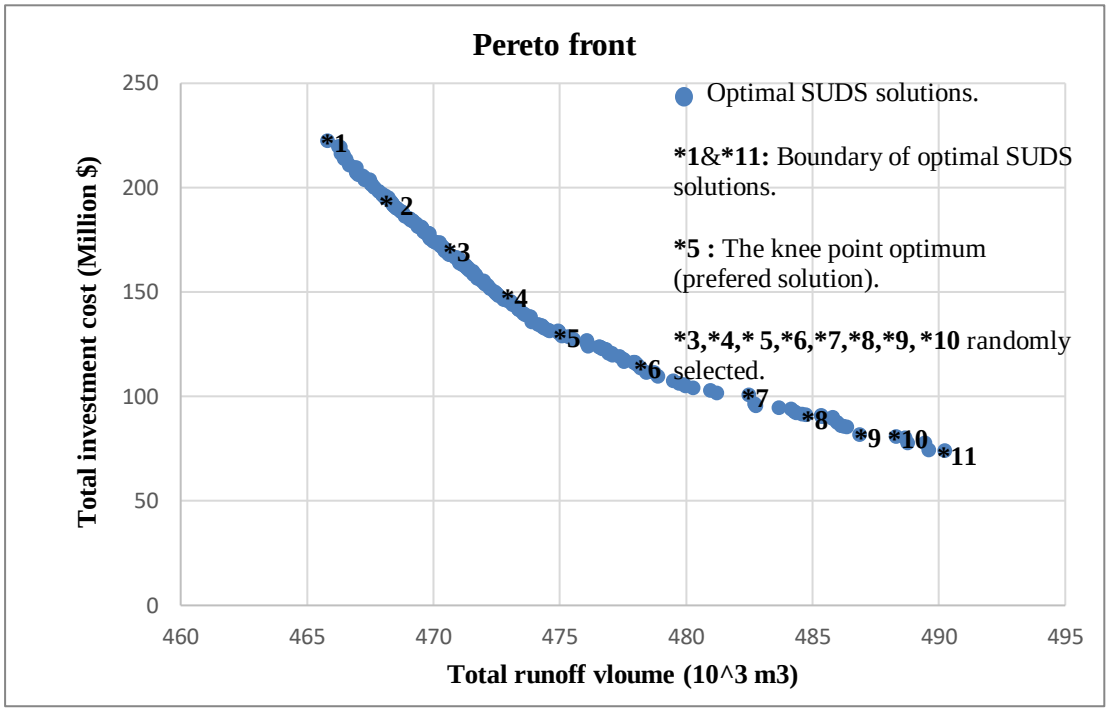


Figure D-7 Pareto-optimal front of SUDS solutions for scenario 11: 6-hour, 100-year rainfall event & SUDS option 2.

Table D-4 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 11 (6-hour 100-year rainfall and SUDS option 2).

ID of SUDS solution	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	222	465800	21.8
*2	200	467650	21.5
*3	174	470.08	99.9
*4	150	472470	20.7
*5	131	474600	20.4
*6	117	477550	19.9
*7	101	482480	19.0
*8	92	484360	18.7
*9	85	486360	18.4
*10	81	488310	18.1
*11	74	490230	17.7

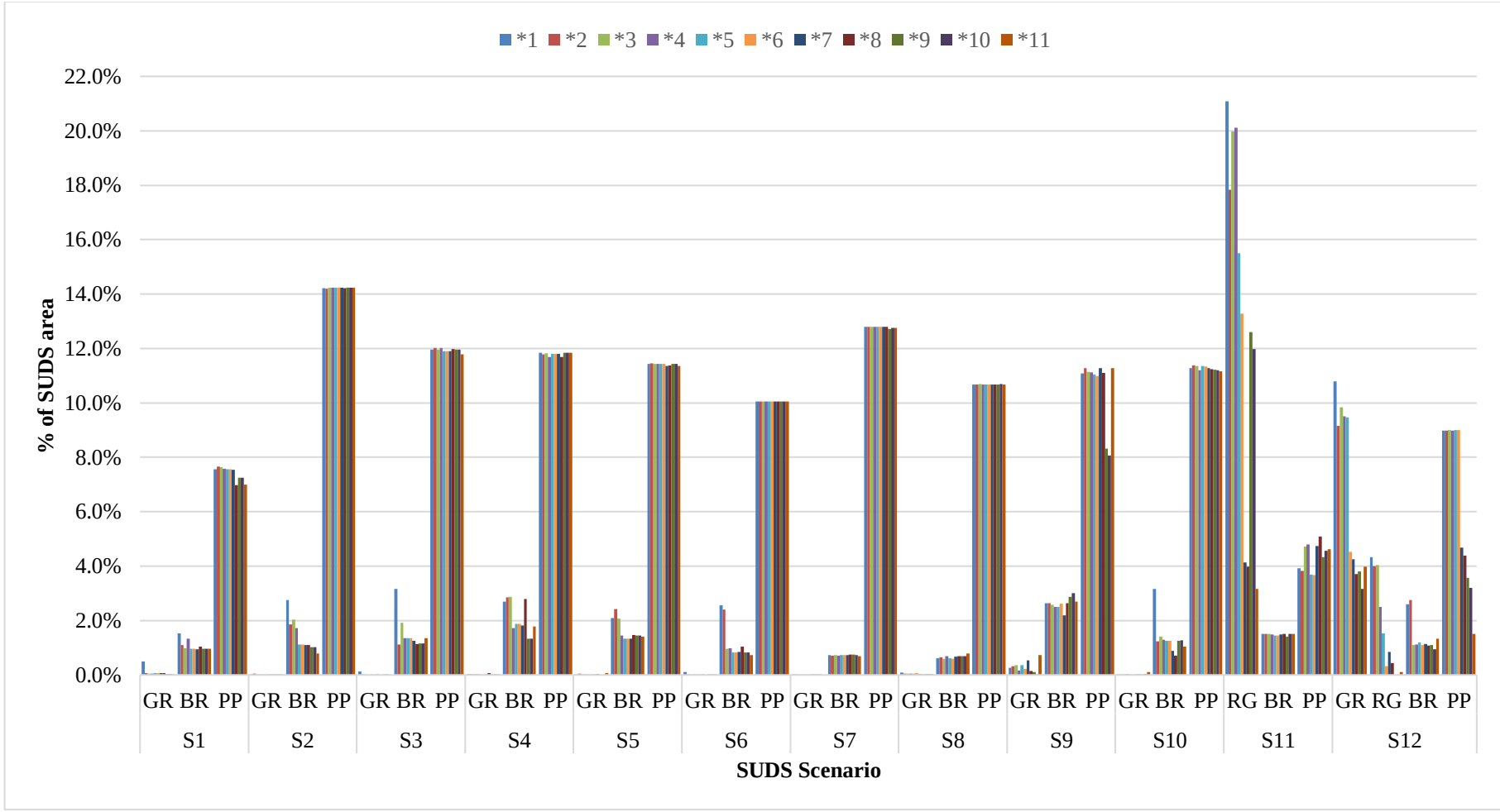


Figure D-8 SUDS percentage coverage in each sub-catchment for scenario 11's selected optimal solutions.

D-4-5 Scenario 14: 6-hour 100-year + 30%CC rainfall and SUDS option 2*

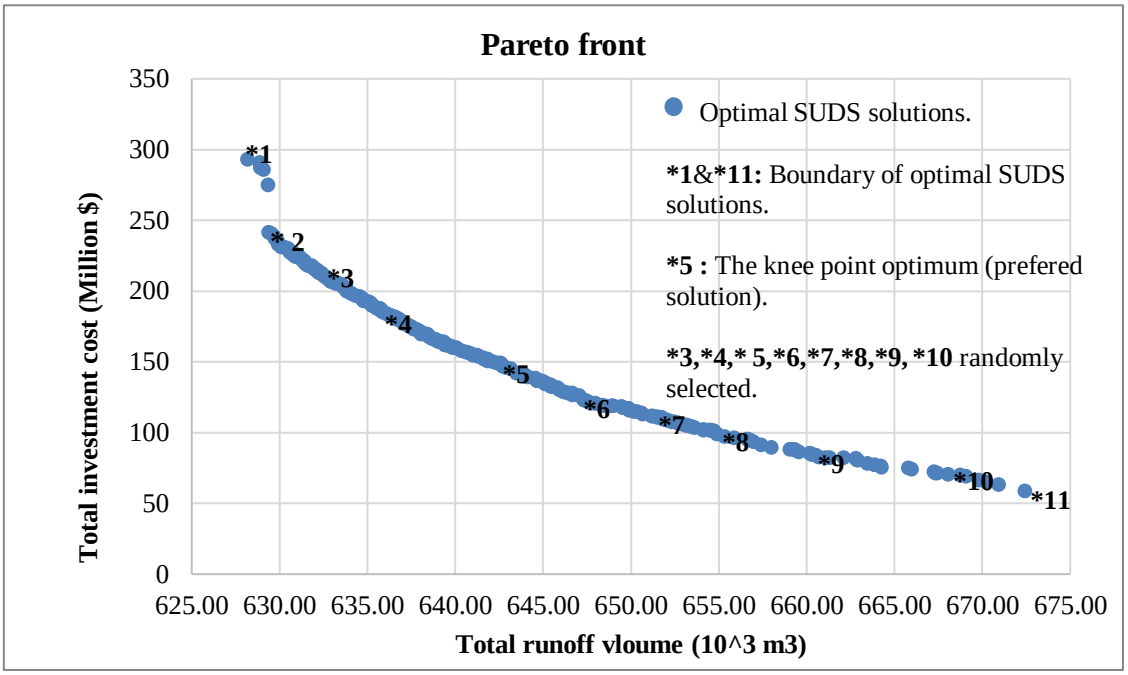


Figure D-9 Pareto-optimal front of SUDS solutions for scenario 14: 6-hour, 100-year rainfall + 30%CC & SUDS option 2.

Table D-5 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 14 (6-hour 100-year rainfall + 30%CC and SUDS option 2).

ID of SUDS solution	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	293	628160	19.8
*2	223	631180	19.4
*3	188	635530	18.8
*4	162	639380	18.3
*5	14	643460	17.8
*6	134	645130	17.6
*7	116	649880	17.0
*8	104	653490	16.5
*9	90	657980	16.0
*10	75	665760	15.0
*11	59	672420	14.1

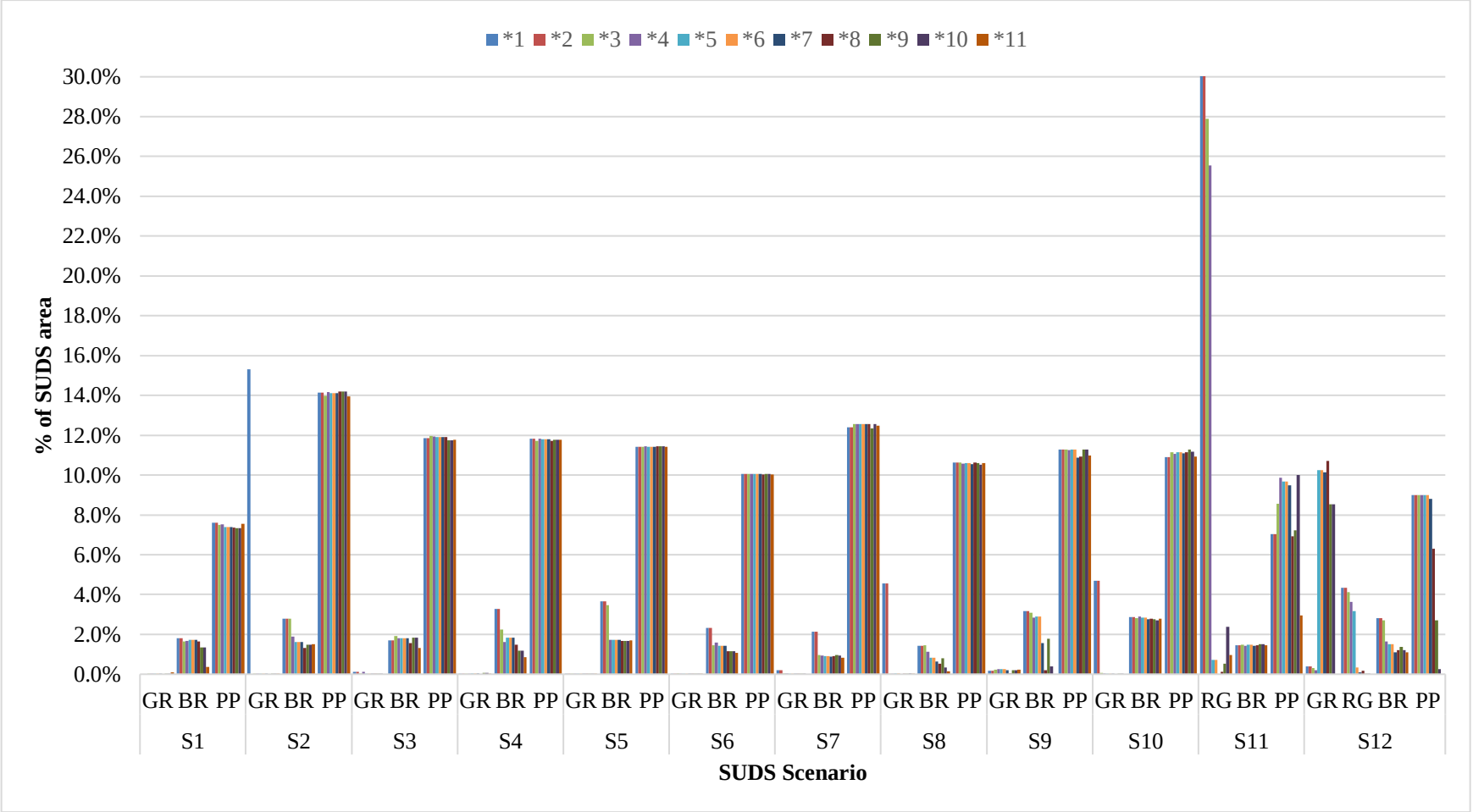


Figure D-10 SUDS percentage coverage in each sub-catchment for scenario 14's selected optimal solutions.

D-4-6 Scenario 17: 6-hour 100-year+ 45%CC rainfall and SUDS option 2*

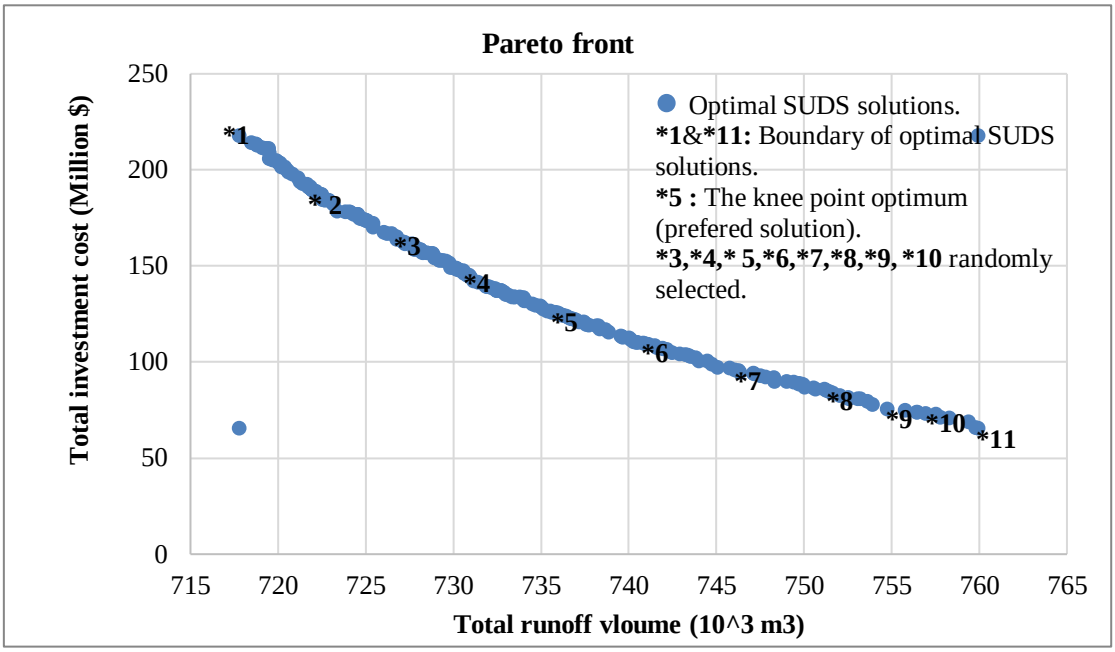


Figure D-11 Pareto-optimal front of SUDS solutions for scenario 17: 6-hour, 100-year rainfall + 45%CC & SUDS option 2.

Table D-6 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 17 (6-hour 100-year rainfall + 45%CC and SUDS option 2).

ID of SUDS scenario	Total Cost$	Total Volume (m3)	% of Reduction
*1	218	759960	12.2
*2	188	722280	16.6
*3	164	726790	16.1
*4	149	730180	15.7
*5	127	735350	15.1
*6	111	740310	14.5
*7	97	745790	13.9
*8	85	750670	13.3
*9	76	754750	12.8
*10	74	756440	12.7
*11	66	759960	12.2

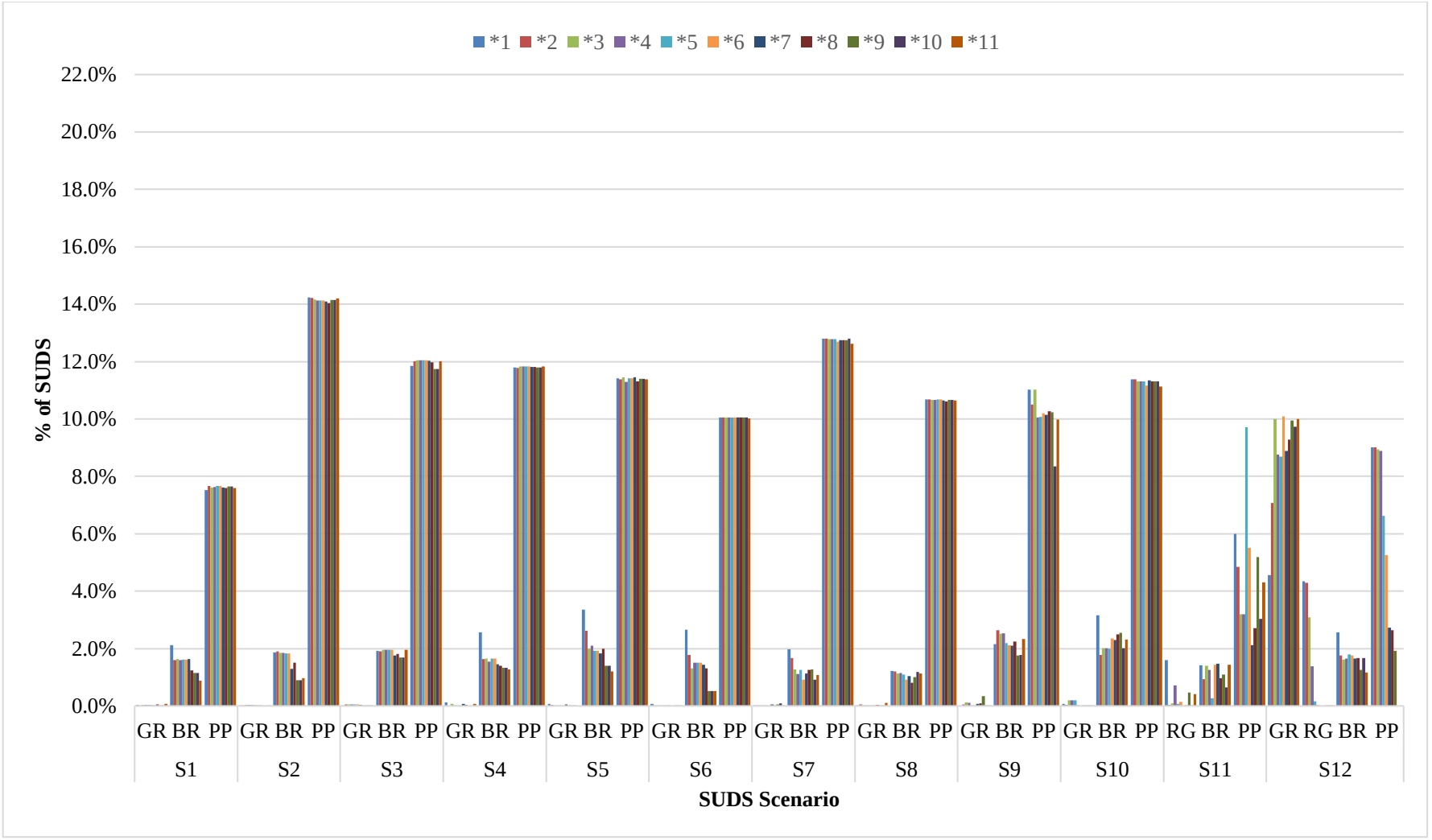


Figure D-12 SUDS percentage coverage in each sub-catchment for scenario 17's selected optimal solutions.

D-4-7 Scenario 3: 6-hour 2-year rainfall and SUDS option 3

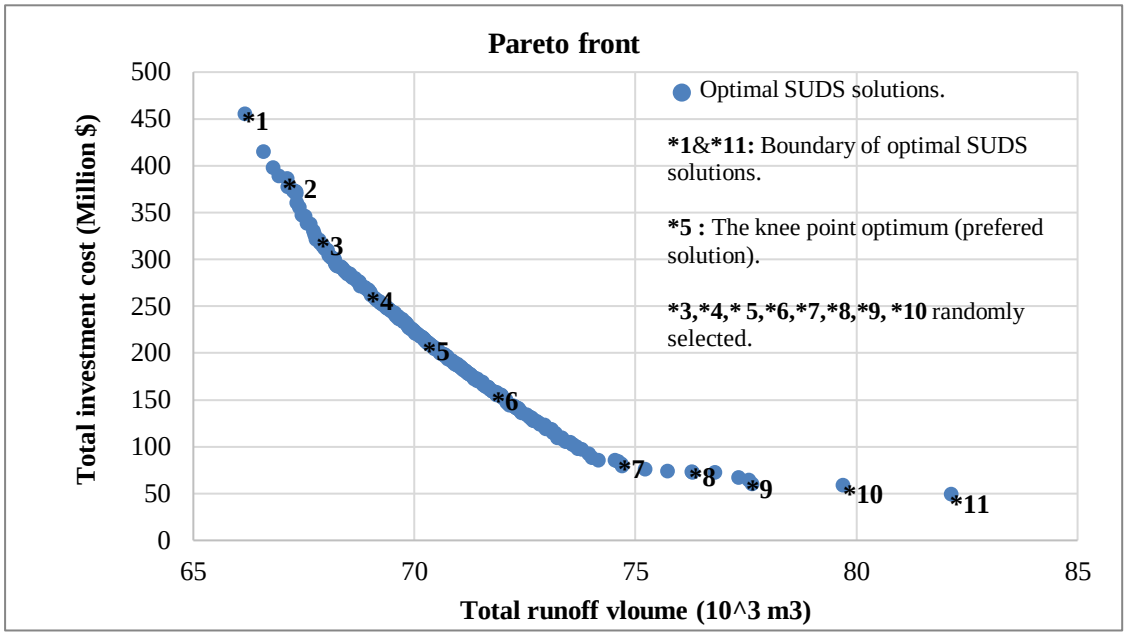


Figure D- 13 Pareto-optimal front of SUDS solutions for scenario 3: 6-hour, 2-year rainfall event & SUDS option 3.

Table D-7 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 3 (6-hour 2-year rainfall and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	456	66160	28
*2	389	66940	27.2
*3	322	67780	26.3
*4	262	69020	25.0
*5	192	7086	23.3
*6	165	71610	22.2
*7	85	74540	19.0
*8	73	76280	17.1
*9	67	77330	15.9
*10	59	79690	13.4
*11	49	82140	10.7

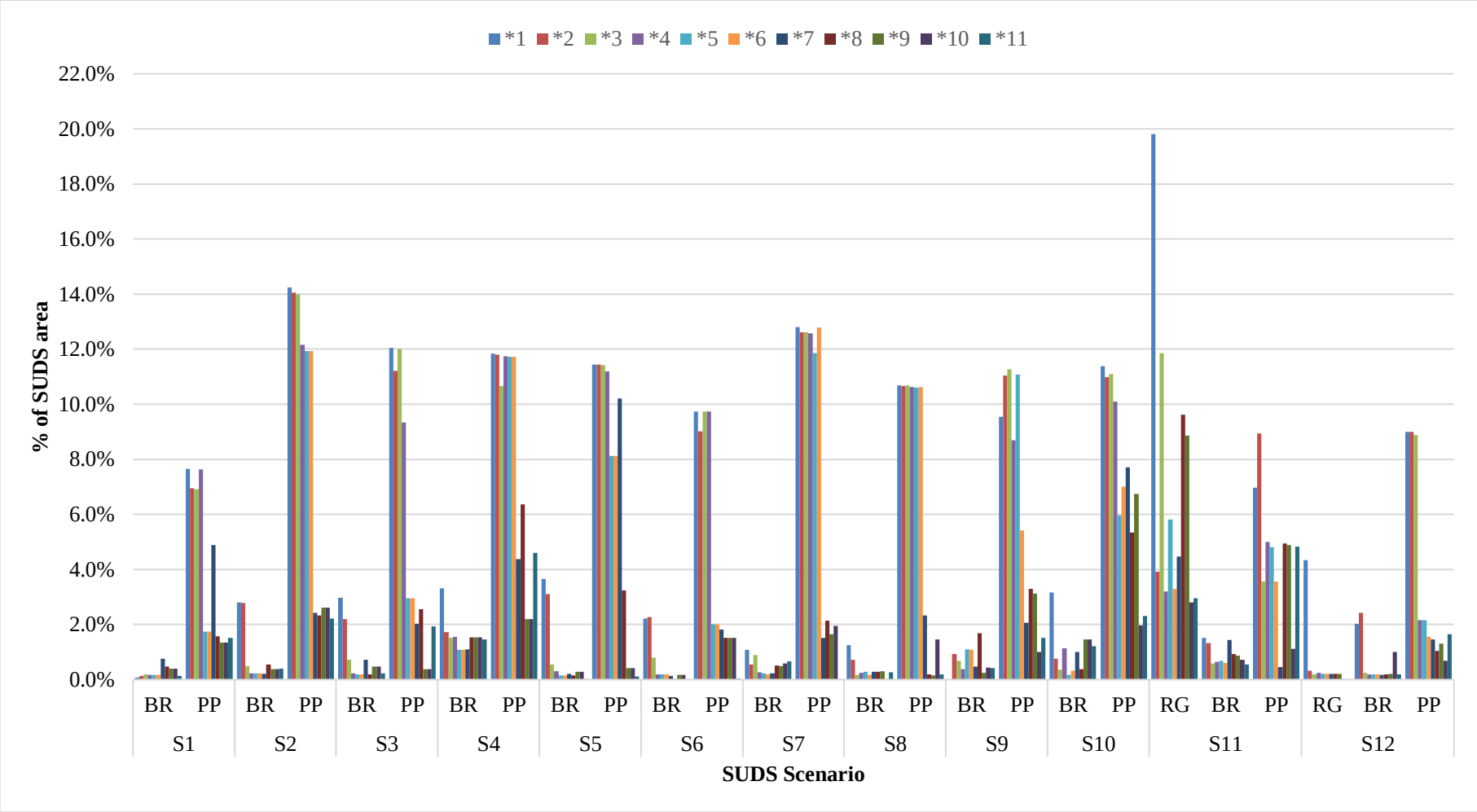


Figure D-14 SUDS percentage coverage in each sub-catchment for scenario 3's selected optimal solutions.

D-4-8 Scenario 6: 6-hour 10-year rainfall and SUDS option 3

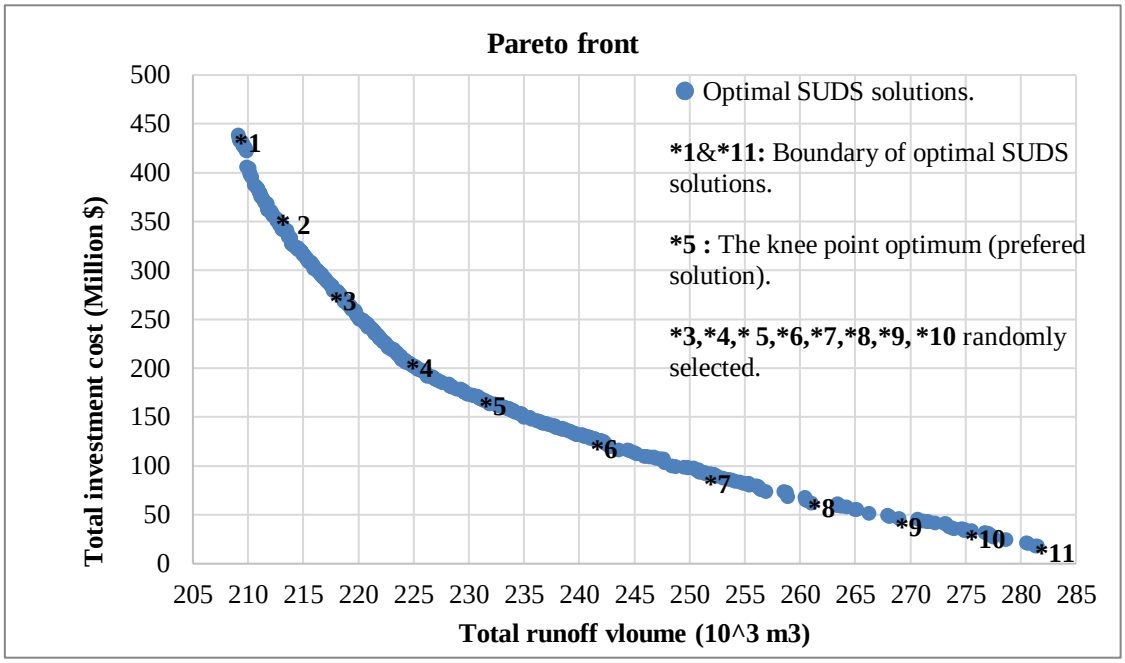


Figure D-15 Pareto-optimal front of SUDS solutions for scenario 6: 6-hour, 10-year rainfall event & SUDS option 3.

Table D-8 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 6 (6-hour 10-year rainfall and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	439	209070	27
*2	357	212230	26
*3	289	217110	24
*4	209	223900	22
*5	164	231800	19
*6	130	240470	16
*7	94	250810	12
*8	65.	260500	9
*9	49	267930	6
*10	34	274880	4
*11	18	281470	1

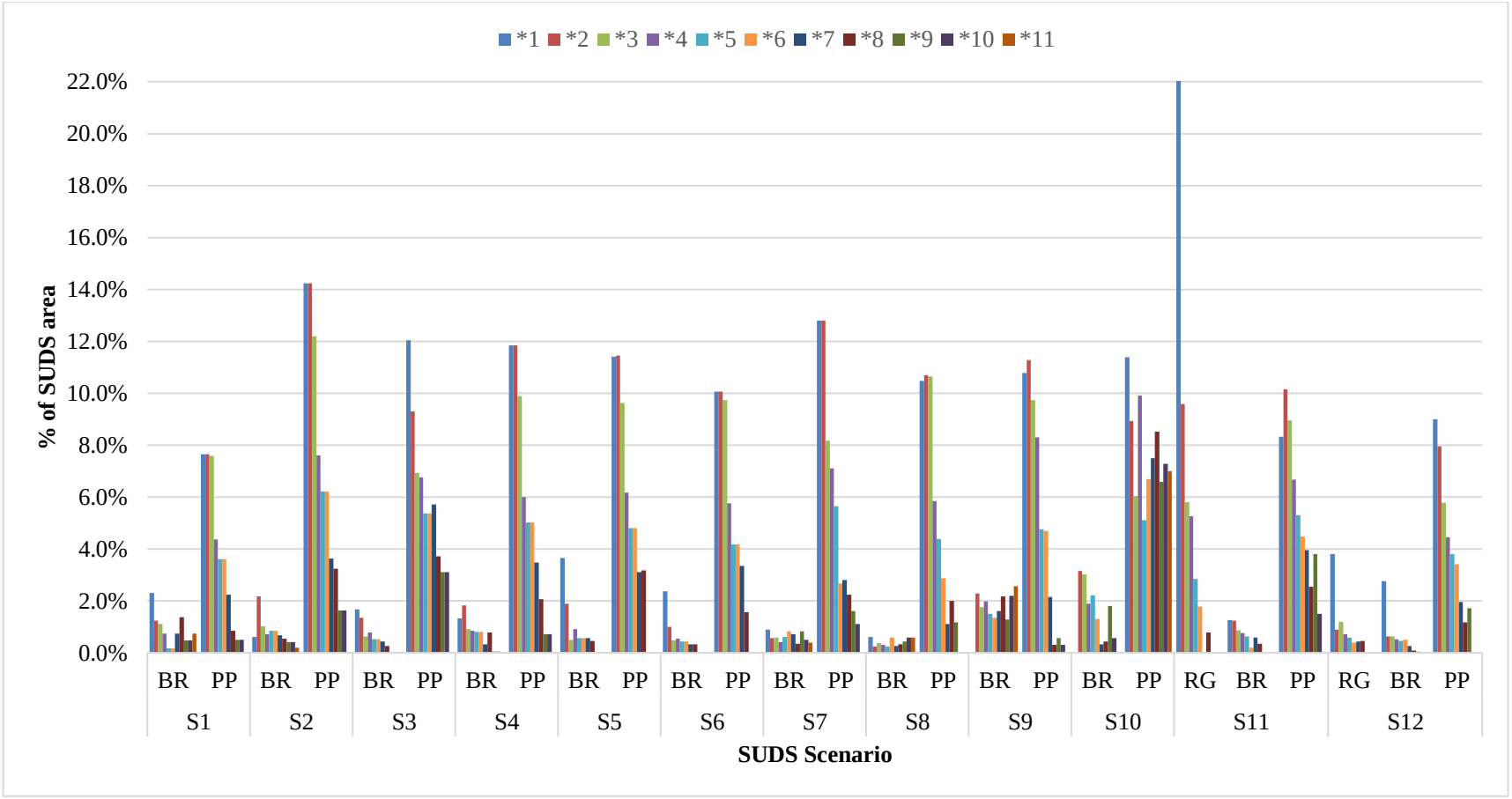


Figure D-16 SUDS percentage coverage in each sub-catchment for scenario 6's selected optimal solutions.

D-4-9 Scenario 9: 6-hour 25-year rainfall and SUDS option 3

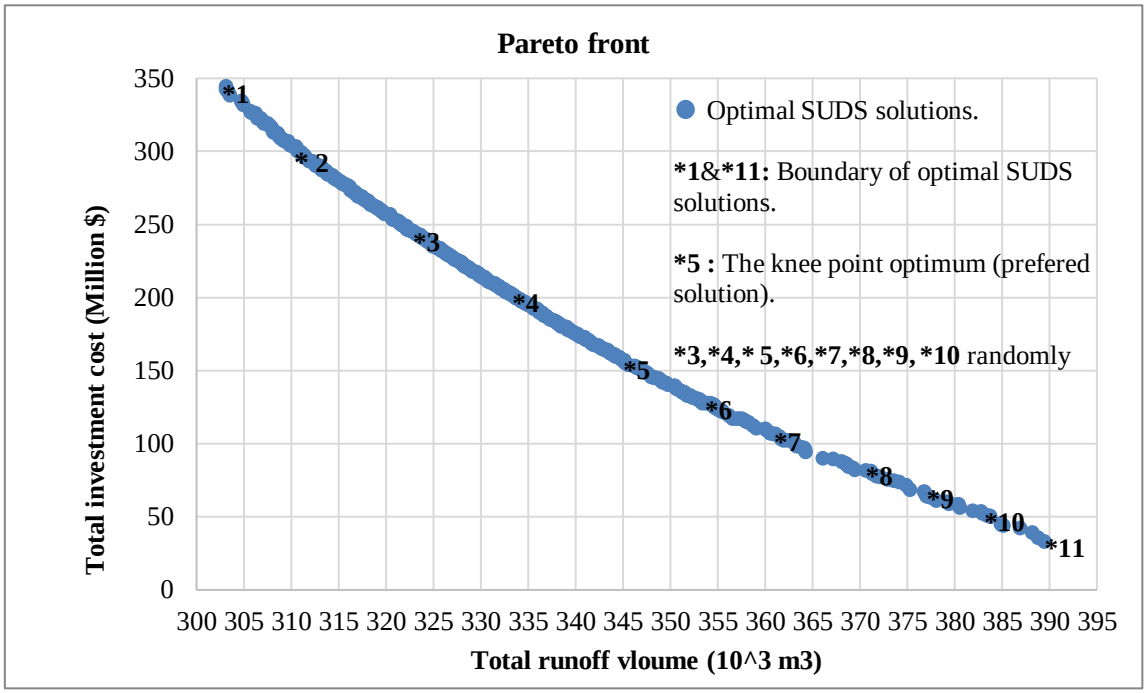


Figure D-17 Pareto-optimal front of SUDS solutions for scenario 9: 6-hour, 25-year rainfall event & SUDS option 3.

Table D-9 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 9 (6-hour 25-year rainfall and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	345	303120	25
*2	304	310500	23
*3	247	322320	20
*4	206	332460	17
*5	168	341980	15
*6	130	353210	12
*7	110	360140	10
*8	82	369480	8
*9	68	375320	7
*10	54	381950	5
*11	33	389480	3

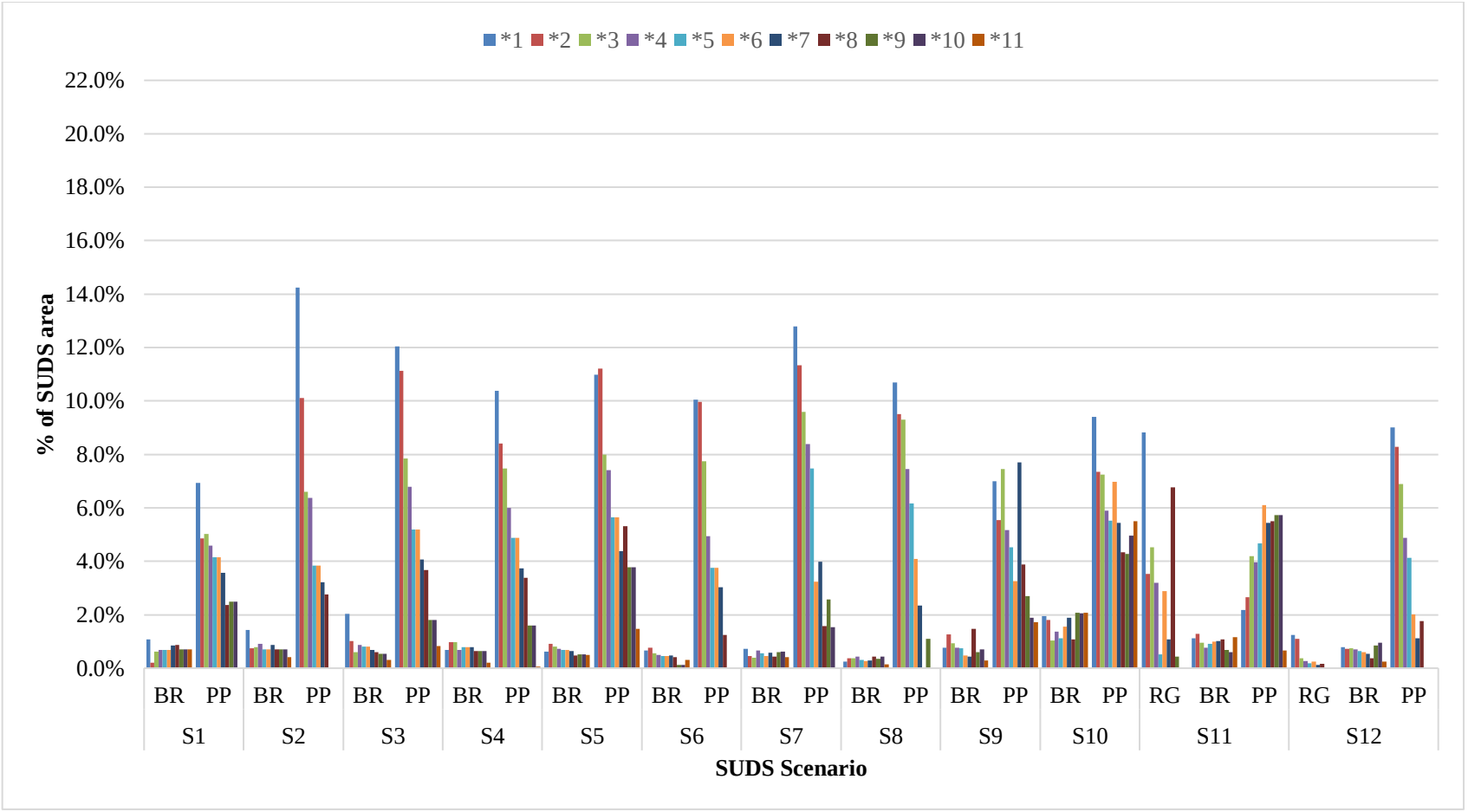


Figure D-18 SUDS percentage coverage in each sub-catchment for scenario 9's selected optimal solutions.

D-4-10 Scenario 12: 6-hour 100-year rainfall and SUDS option 3

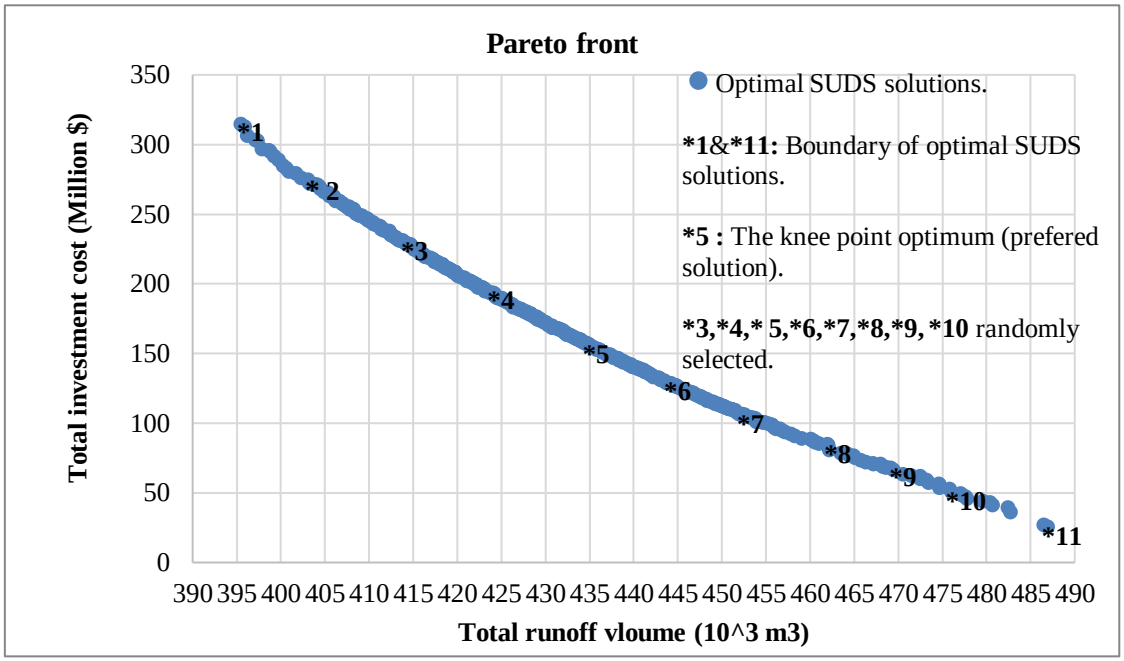


Figure D- 19 Pareto-optimal front of SUDS solutions for scenario 12: 6-hour, 100-year rainfall event & SUDS option 3.

Table D-10 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 12 (6-hour 100-year rainfall and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	315	395000	34
*2	273	403000	33
*3	230	414000	31
*4	191	424000	29
*5	153	436000	27
*6	127	444000	26
*7	101	454000	24
*8	85	461000	23
*9	69	468000	22
*10	54	475000	21
*11	25	487000	19

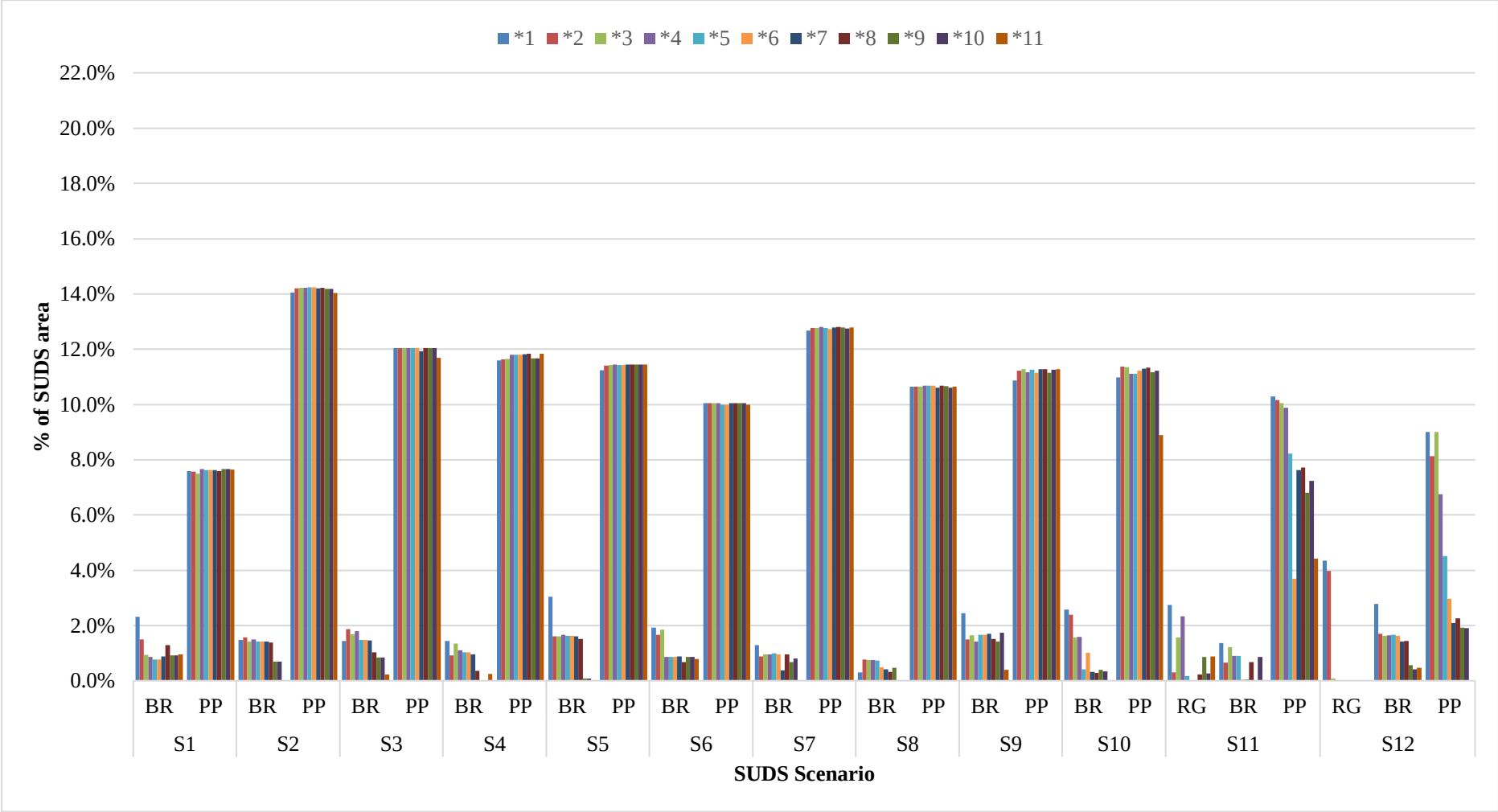


Figure D-20 SUDS percentage coverage in each sub-catchment for scenario 12's selected optimal solutions.

D-4-11 Scenario 15: 6-hour 100-year+ 30%CC rainfall and SUDS option 3*

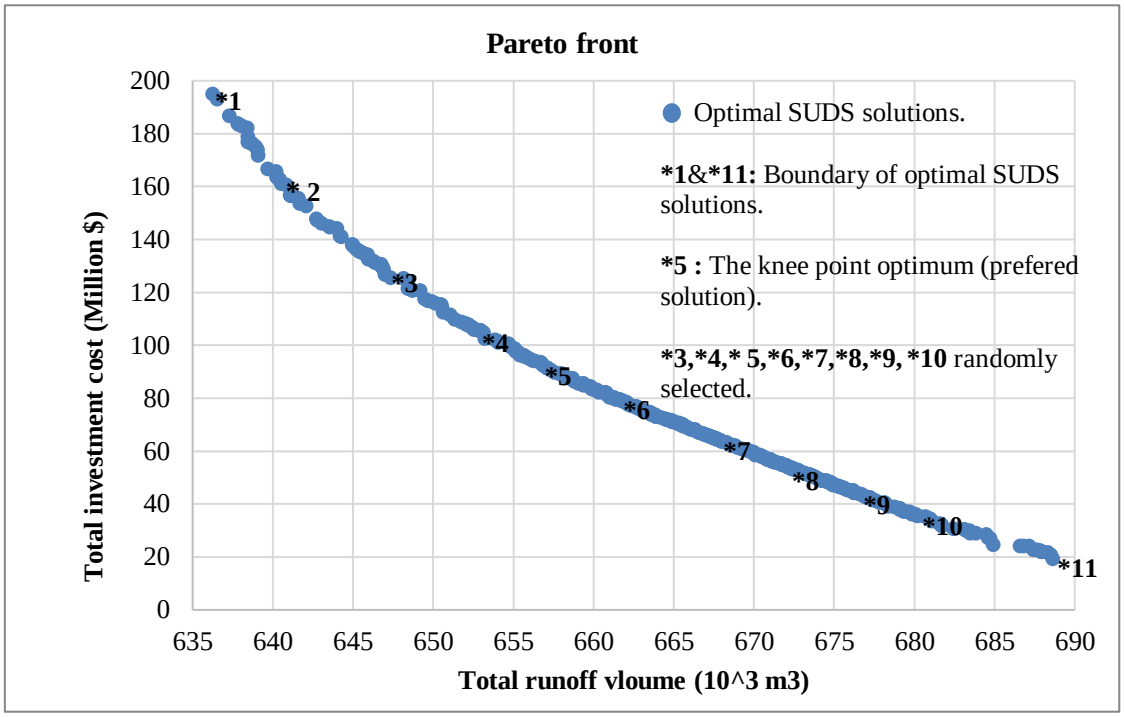


Figure D-21 Pareto-optimal front of SUDS solutions for scenario 15: 6-hour, 100-year rainfall 30%CC & SUDS option 3.

Table D-11 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 15 (6-hour 100-year rainfall 30%CC and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction
*1	195	636230	9
*2	161	640520	9
*3	127	646990	8
*4	106	652530	7
*5	89	657550	6
*6	79	661330	6
*7	65	667380	5
*8	54	672200	4
*9	44	676190	4
*10	36	680080	3
*11	19	688610	2

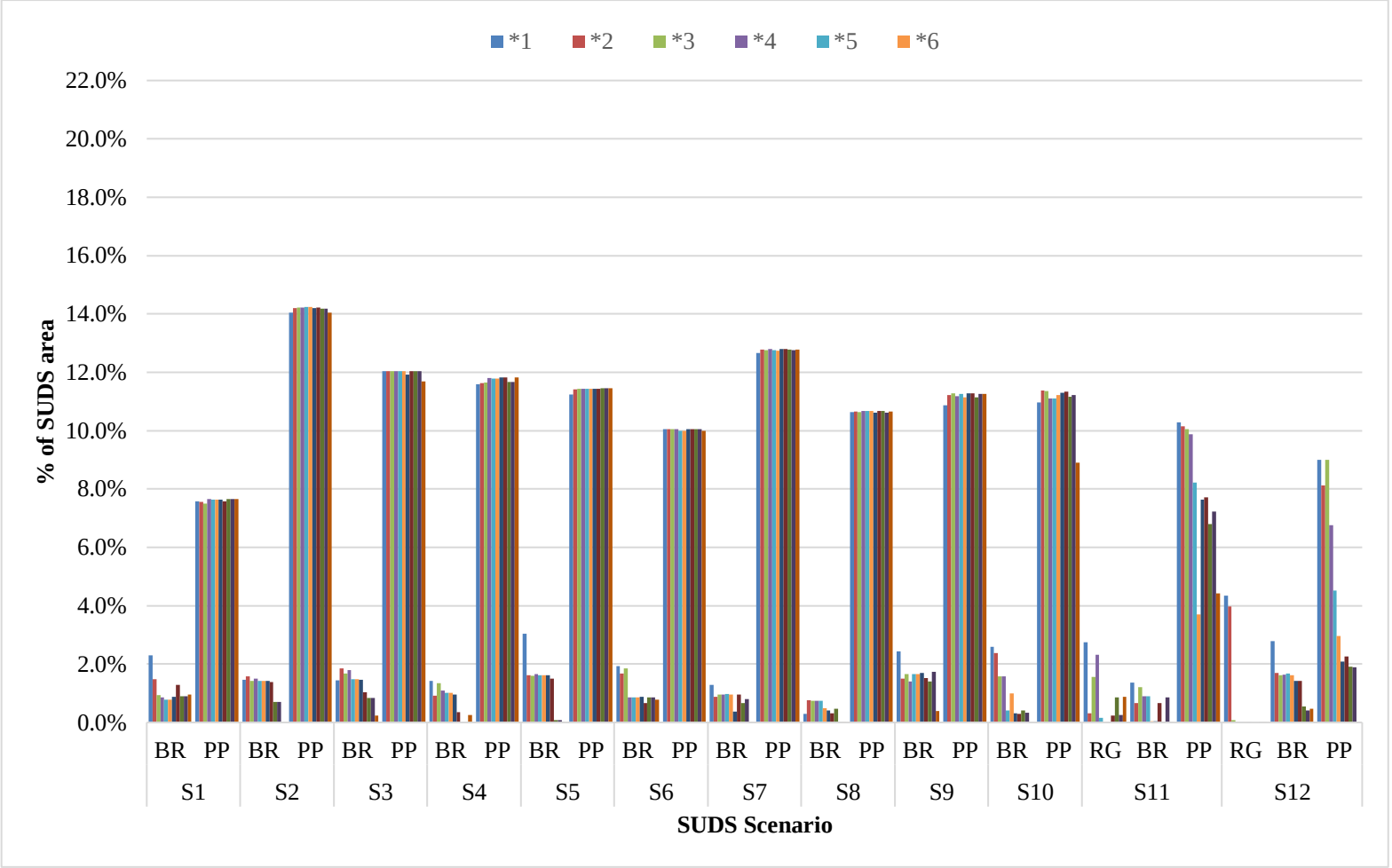


Figure D-22 SUDS percentage coverage in each sub-catchment for scenario 15's selected optimal solutions.

D-4-12 Scenario 18: 6-hour 100-year+ 45%CC rainfall and SUDS option 3*

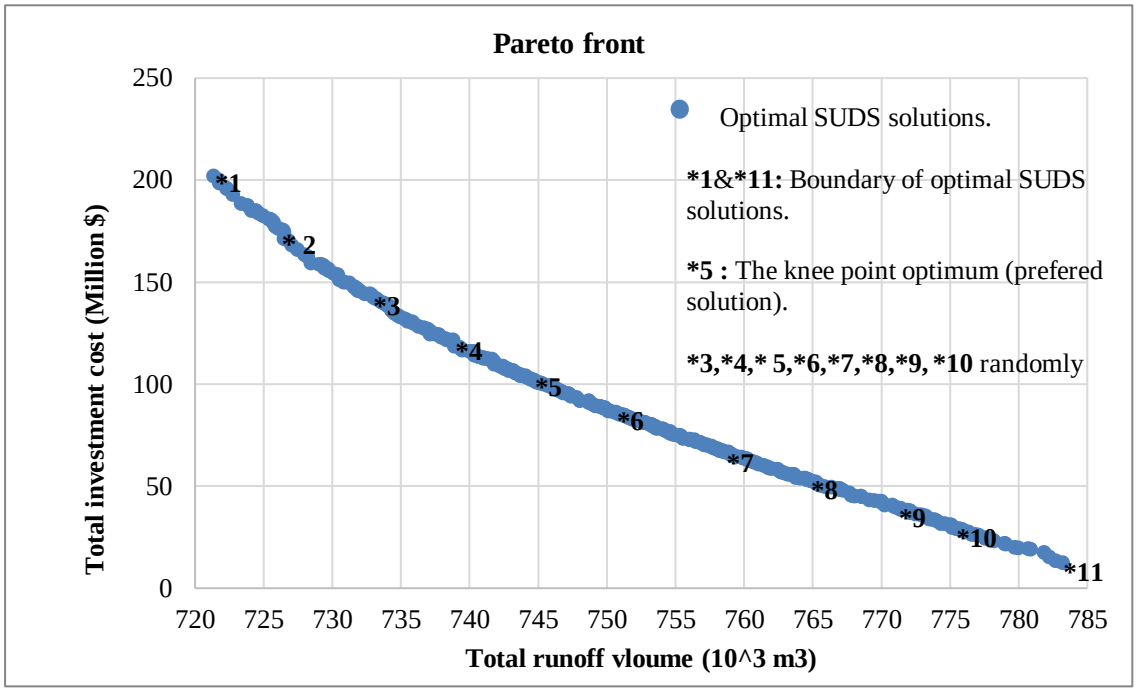


Figure D-23 Pareto-optimal front of SUDS solutions for scenario 18: 6-hour, 100-year rainfall + 45%CC* & SUDS option 3.

Table D-12 The total cost, total runoff volume, and % of volume reduction, for selected optimum solutions obtained for Scenario 18 (6-hour 100-year rainfall + 45%CC* and SUDS option 3).

ID of SUDS solutions	Total cost (Million $)	Total Volume (m3)	% of Reduction	ID of SUDS solutions
*1	202	721000	18	*1
*2	176	726000	17	*2
*3	143	733000	17	*3
*4	119	739000	16	*4
*5	101	745000	15	*5
*6	87	750000	15	*6
*7	67	758000	14	*7
*8	54	764000	13	*8
*9	40	770000	12	*9
*10	29	775000	12	*10
*11	12	783000	11	*11

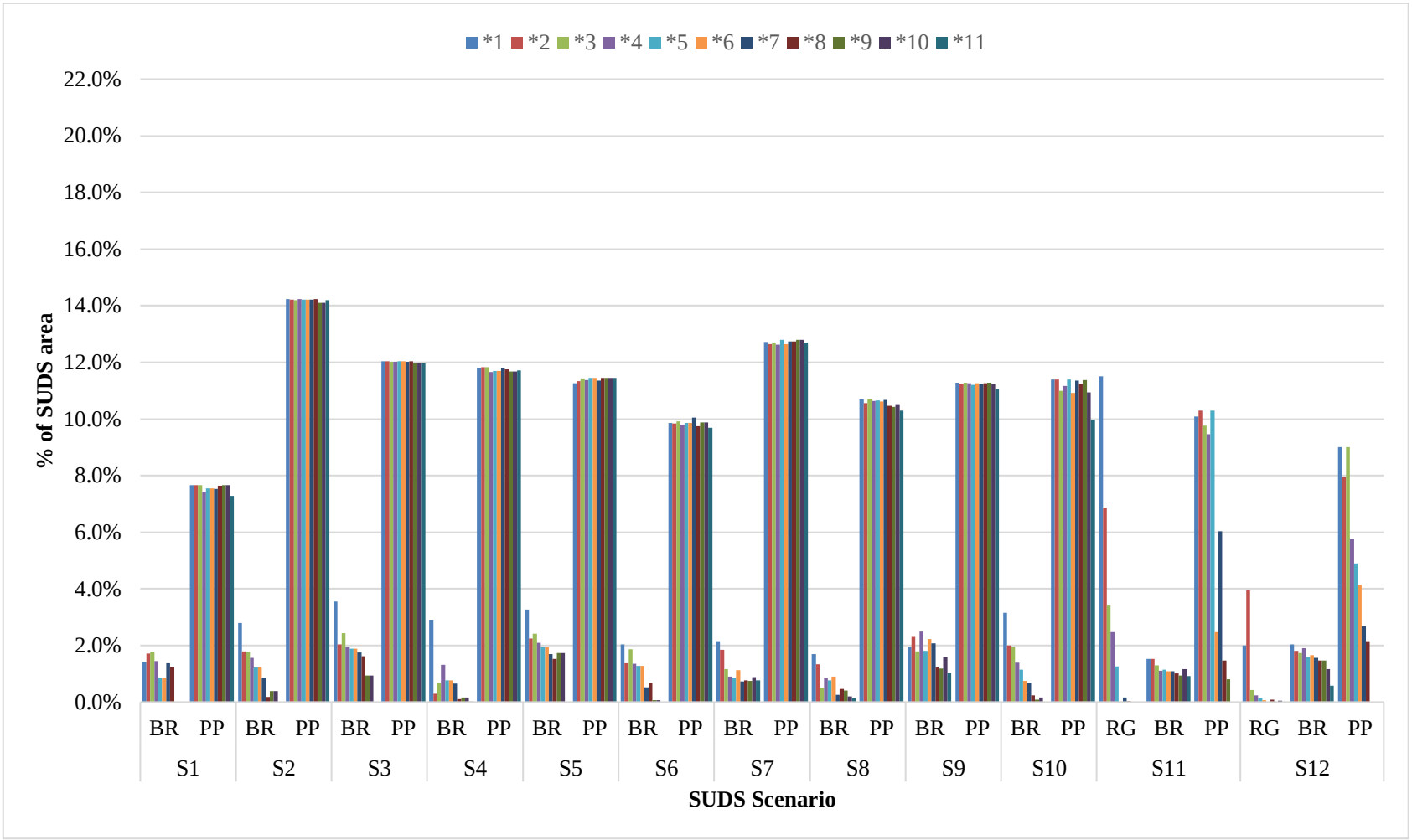


Figure D-24 SUDS percentage coverage in each sub-catchment for scenario 18's selected optimal solutions.