# Developing a Dynamical System Model for an Urban Aquifer –Wadi System

By

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# ABSTRACT

Urban waste water production increases day by day and its safe treatment and disposal need efficient procedures. In many areas, such effluents are discharged to open water bodies such as lakes, rivers and sea coastal areas. Since there are no perennial streams in arid and semi-arid regions the disposal of treated outfalls is often to dry wadis. However developing an understanding of complex urban drainage / urban aquifer / urban wadi systems, where processes act at different space and time scales, is not easy especially where as often not much data is exists.

Dynamical systems approaches have been used for many years in complex feedback systems like commercial companies to help understand how they work so that managers can manage better. So in this work the use of dynamical system modelling is investigated to see if this approach can help develop at least in semi-quantitative way an understanding good enough to aid managers of urban water systems where wadis are involved.

The approach taken was to develop a flow and then a solute transport model for the urban system of Riyadh City - Wadi Hanifah in the Kingdom of Saudi Arabia. The softwares used was ‘Stella’, and a representation of two aquifers, two soil systems, the sewerage system, the water supply system, the non-urban catchments and the urban drainage system was set up and run using daily meteorological data for about 20 years. The model was compared with limited field data on water levels, flows, flooding, and water quality and modified until results were consistent with field data. Model was then investigated by looking at effects of changing a wide range of hydrogeological and other parameter values, including pipe leakage rates, rainfall, and water supply rate.

In the Riyadh model system it was found that the whole system was interconnected in practice but that it was resilient to some stresses much more than to others stresses. It is concluded that dynamical system models allow complex systems to be represented quite easily and are good as a tool for thinking through and highlighting possible water management problems. However they are far less good than specialised models to represent specific parts of the system (e.g. groundwater flow), have numerical dispersion worries, and are difficult to calibrate properly because of their “lumping”. They are best thought of as a useful preliminary tool for developing conceptual models before more sophisticated models are developed and applied.

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# DEDICATION

*This thesis is dedicated*

*To my mother*

*to soul of my father who has travelled without saying Good-bye*

**الإهداء**

إلى الوالدة الغالية حفظها الله

إلى روح أبي الطاهرة تغمده الله بواسع رحمته

# TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION ........................................ 1

1.1 Introduction 1

1.2 Background 3

1.3 Aims and Objectives of Study ........................................................................9

1.4 Available data 10

1.4.1 Geological and Topography and Infrastructure Data ........................................ 10

1.4.2 Hydrogeological Data ........................................................................ 10

1.4.3 Climatic Data ........................................................................ 11

1.4.4 Thesis Structure ........................................................................ 12

CHAPTER 2: RIYADH SETTING ...................................... 14

2.1 Introduction 14

2.2 Geographical Location of Riyadh........................................................................15

2.3 Wadi Hanifah 16

2.4 Topography 19

2.5 Geology of study area ........................................................................19

2.5.1 Geological Setting of Riyadh........................................................................ 19

2.5.2 Jubaila Formation ........................................................................ 25

2.5.3 Arab Formation........................................................................ 26

2.5.4 Hith Formation........................................................................ 26

2.5.5 Alluvium ........................................................................ 27

2.6 Overview of Previous Work on the Hydrogeology of the Study Area...............................27

2.6.1 Groundwater in the Arabian Shelf Sediments................. ..............................................27

2.6.2 Surface water in Wadi Hanifah........................................................................ 29

2.6.3 Riyadh Aquifer .......... 31
2.6.4 Jubaila Aquifer .......... 32
**2.7 Climate of Riyadh .......... 33**
2.7.1 Introduction .......... 33
2.7.2 Climatic Conditions in Saudi Arabia .......... 33
2.7.3 Climatic pattern over the study area .......... 35
2.7.4 Rainfall .......... 36
2.7.5 Temperature .......... 37
2.7.6 Relative Humidity, Sunshine Duration and Wind Speed .......... 38
2.7.7 Evapotranspiration .......... 39
**2.8 Water in Riyadh .......... 41**
2.8.1 Introduction .......... 41
2.8.2 Water Supply .......... 42
2.8.3 Sewerage System .......... 45
2.8.4 Subsurface Network .......... 46
2.8.5 Surface Water .......... 47
2.8.6 Groundwater .......... 48
**2.9 Water Chemistry .......... 49**
2.9.1 Introduction .......... 49
2.9.2 Water chemistry interpretation .......... 50
2.9.3 Conclusion .......... 58
**2.10 Initial Conceptual Model of the Riyadh System .......... 59**
**CHAPTER 3: STELLA MODELLING .......... 62**
**3.1 Background .......... 62**

3.2 Application of SD in Ecosystem and Groundwater Modelling ..........................................63

3.3 Choice of a SD Modelling Approach / Stella in the Current Project..................................68

3.4 Stella Software ..........................................................................................................70

3.4.1 Choice of SD Software Package ........................................................................ 70

3.4.2 Basic Components of Stella ................................................................................ 71

3.4.3 Time Steps .......................................................................................................... 75

CHAPTER 4: FLOW MODEL .......................................... 78

4.1 Introduction 78

4.2 The Water System in Riyadh.......................................................................................79

4.3 Notes on the Methods of Estimating Some of the Flows ................................................81

4.3.1 Estimating Some of the Surface Water Flows Used in the Model ....................... 81

4.3.2 Estimating Runoff Using the Curve Number Method .......................................... 83

4.4 Model System…………………………………………………………… ................. 85

4.4.1 Introduction ………………………………….……… …………………….85

4.4.2 Groundwater balance equations for the Riyadh Aquifer ...................................... 86

4.4.3 Groundwater balance equations for the Jubaila Aquifer in the Wadi Hanifah area 88

4.4.4 Sewerage system .................................................................................................. 90

4.4.5 Soil Water balance equations in the city............................................................. 91

4.4.6 Soil Water balance in Wadi Hanifah ................................................................... 93

4.4.7 Surface water balance .......................................................................................... 96

4.4.8 Runoff and evapotranspiration estimation........................................................... 98

4.5 Running the Model .......................................................................................................99

4.6 Model Calibration ........................................................................................................100

4.6.1 Introduction........................................................................................................ 100

4.6.2 Comparison of model results and field data ........................................................ 102

4.6.3 Examination of the model output........................................................................ 108

**4.7 Conclusions 115**

**CHAPTER 5: SOLUTE TRANSPORT MODEL ................... 117**

**5.1 Introduction 117**

**5.2 Development of the Solute Transport Model ............................................................ 119**

**5.3 Representation of Reactions in the Solute Transport Model ........................................ 121**

**5.4 Sulfate Transport Model Set Up ................................................................................... 124**

5.4.1 Choice of Solute to Model ..................................................................................... 124

5.4.2 Development of Sulfate Model.............................................................................. 125

**5.5 Model Calibration .......................................................................................................... 127**

5.5.1 Approach................................................................................................................ 127

5.5.2 Comparison with concentration data ................................................................... 128

**5.6 Results.............................................................................................................................. 129**

**5.7 Conclusions ......................................................................................................................137**

**CHAPTER 6: : MODEL APPLICATIONS .......................... 139**

**6.1 Introduction 139**

6.1.1 Purpose of chapter .................................................................................................. 139

6.1.2 Hydrogeological implications of the model........................................................ 139

6.1.3 Sustainability ........................................................................................................... 140

6.1.4 Structure of chapter.................................................................................................. 142

**6.2 Model Scenarios ............................................................................................................. 143**

**6.3 Water Balances ................................................................................................................ 143**

**6.4 Hydrogeological implications Scenarios ......................................................................... 152**

6.4.1 Scenario 1: Hydraulic conductivity of Jubaila Formation .......................................... 152

6.4.2 Scenario 2: Hydraulic conductivity of Upper part Arab Formation .................... 156

**6.5 Sustainability scenarios ........................................................................................ 159**

6.5.1 Scenario 3: Rainfall change ................................................................................ 159

6.5.2 Scenario 4: Water Supply change ...................................................................... 161

6.5.3 Scenario 5: Leakages in Domestic Water networks .......................................... 162

6.5.4 Scenario 6: Leakage of Sewage Networks ........................................................ 167

**6.6 Discussion… 170**

6.6.1 Introduction.......................................................................................................... 170

6.6.2 Hydrogeology ..................................................................................................... 170

6.6.3 Sustainability ...................................................................................................... 171

**CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS ........................................... 177**

**7.1 Introduction. 177**

**7.2 Objectives 1 and 2: Developing an SD model of the flow of water and solutes between the Riyadh aquifer and wadi systems ........................................................................ 178**

**7.3 Objective 3: Developing an understanding of the hydrogeology of Riyadh including the nature of the links between the city and wadi water systems ........................................... 179**

**7.4 Objective 4: Consideration of possible management policies ....................................... 180**

**7.5 Objective 5: The use of SD modelling ........................................................................... 180**

**7.6 Achievement of Aim ...................................................................................................... 181**

**7.7 Recommendations .......................................................................................................... 183**

**REFERENCES**

**Appendice**

**Electronic appendices (CD)**

# LIST OF FIGURES


FIGURE 2-1 RIYADH LOCATION (WIKIMEDIA.ORG, 2007) ........ 16

FIGURE 2-2 WADI HANIFAH LOCATION( ADA, 1990 ) ........ 17

FIGURE 2-3 URBAN PART OF WADI HANIFAH (AL-JADH'D,2009) ........ 18

FIGURE 2-4 RIYADH TOPOGRAPHY (ADA, 2010) ........ 20

FIGURE 2-5 EAST-WEST CROSS SECTION OF GEOLOGICAL FORMATIONS IN CENTRAL SAUDI ARABIA (POWERS, 1968) ........ 23

FIGURE 2-6 GEOLOGICAL MAP OF RIYADH AREA (SAMHOURI, 2010). ........ 24

FIGURE 2-7 CROSS SECTION OF WADI HANIFAH ........ 25

FIGURE 2-8 AIR MASS MOVEMENT OVER THE ARABIAN PENINSULA ........ 35

FIGURE 2-9 DAILY AND MONTHLY RAINFALL (1990-2012) OVER RIYADH CITY (PEM,2013) ........ 36

FIGURE 2-10 AVERAGE DAILY AIR TEMPERATURE (1990-2012) IN THE RIYADH WEATHER STATION (PEM, 2013) ........ 38

FIGURE 2-11 MONTHLY MEAN RELATIVE HUMIDITY IN RIYADH CITY( PEM,2013) ........ 39

FIGURE 2-12 DAILY POTENTIAL EVAPOTRANSPIRATION (JENSEN-HASIE) IN THE RIYADH WEATHER STATION (1990-2012) ........ 41

FIGURE 2-13 RIYADH CITY-WADI HANIFAH WATER SUPPLY MODEL SYSTEM ........ 42

FIGURE 2-14 RIYADH WATER TRANSMISSION SYSTEM MAP (ILF,2009) ........ 43

FIGURE 2-15 GRAVITY DRAINAGE NETWORK (A) HALF PERFORATED HORIZONTAL PIPE; ........ 47

FIGURE 2-16 WADI HANIFAH STREAM (ADA,2002) ........ 48

FIGURE 2-17 PIPER DIAGRAM FOR ALL WATER SAMPLES IN THE STUDY AREA ........ 53

FIGURE 2-18 INITIAL CONCEPTUAL MODEL FOR THE WADI HANIFAH-RIYADH AREA ........ 60

FIGURE 3-1 NEW PRODUCT ADOPTION MODEL SHOW DYNAMIC STOCK AND FLOW DIAGRAM (FORRESTER,1971) ........ 63

FIGURE 3-2 BASIC COMPONENTS OF STELLA (STELLA V 10.0.6 , ISEE SYSTEMS,2014) ........ 72

FIGURE 3-3 DIAGRAM OF EXAMPLE OF STELLA MODEL(DARCY LAW FLOW) (STELLA V 10.0.6, ISEE SYSTEMS,2014) ........ 76

FIGURE 3-4 TIME STEPS TOOLS (STELLA , V 10.0.6, ISEE SYSTEMS, 2014) ........ 77

FIGURE 4-1 RIYADH CITY-WADI HANIFAH WATER SUPPLY MODEL SYSTEM ........ 80

FIGURE 4-2 INITIAL CONCEPTUAL MODEL OF THE RIYADH SYSTEM (CHAPTER 2) ........ 80

Figure 4-3 The flow system implied by Figure 4-2 ........................................................ 82

Figure 4-4 schematic diagram of horizontal drains (Al-Othman, 2011)........................................ 83

Figure 4-5 Cross section of groundwater stocks in Riyadh City ........................................ 88

Figure 4-6 Cross section of groundwater stocks in Wadi Hanifah ........................................ 90

Figure 4-7 Location of wells. Wells with hydrograph data are indicated using yellow (wadi) and blue (city) circles.(ADA,2002)........................................ 104

Figure 4-8 Daily groundwater level fluctuations in Wadi Hanifah........................................ 105

Figure 4-9 Daily groundwater level fluctuations in Riyadh City ........................................ 105

Figure 4-10 Image from wadi Hanifah catchment to east of the wadi ........................................ 107

Figure 4-11 The groundwater thickness in Wadi Hanifah and Riyadh City (m) ........................................ 109

Figure 4-12 Groundwater balance components in Riyadh City ($m^3$) ........................................ 110

Figure 4-13 Above - Wadi Hanifah groundwater balance components ($m^3$/d and $m^3$ for Groundwater_Wadi). Below – irrigation abstraction rates ($m^3$/d)........................................ 111

Figure 4-14 Above - flow rates for soil water system in Riyadh City ($m^3$/d) and the soil water volume ($m^3$). Below – treated sewage flow ($m^3$/d) ........................................ 113

Figure 4-15 Soil water flows in the urban areas of Wadi Hanifah (flooding events, blue arrows) ($m^3$/d) and the volume of water in the wadi sediments ($m^3$) ........................................ 114

Figure 4-16 Soil and surface water volumes in non-urban areas of Wadi Hanifah ($m^3$), precipitation on catchment ($m^3$) and evapotranspiration ($m^3$) ........................................ 115

Figure 5-1 Solute precipitation stock........................................ 122

Figure 5-2 $SO_4$ concentrations in the various waters and the values from the final model at the end of the model period (red lines) ........................................ 129

Figure 5-3 Simulated $SO_4$ concentrations (g/$m^3$)........................................ 130

Figure 5-4 Comparison between the mass of $SO_4$ (Surface_water_Wadi_1) and volume of water in the surface water course in the wadi ($m^3$ for water volumes, g for mass of sulfate) ........................................ 131

Figure 5-5 Effect of rainfall and evapotranspiration on concentration of the........................................ 132

Figure 5-6 Comparison between the mass of $SO_4$ (Surface_water_Wadi_1) and volume of water in the surface water course in the wadi ($m^3$ for water volumes, g for mass of sulfate) ........................................ 134

Figure 5-7 Effect of rainfall and evaporation on concentration of the surface water ........................................ 135

Figure 5-8 An example of the sensitivity of solute model to initial $SO_4$ concentrations ....................136

Figure 5-9 Comparison $SO_4$ GW wadi & $SO_4$ Soil water between standard & example sensitivity test models....137

Figure 6-1 City Soil water balance ($m^3$/day) for 31-12-2012 ....................146

Figure 6-2 Wadi Soil water balance ($m^3$/day) for 31-12-2012 ....................149

Figure 6-3 Wadi Surface water balance ($m^3$/day) for 31-12-2012 ....................151

Figure 6-4 A summary of the main water flows from model at end of run. Red indicates non-natural flows. Number is flow in thousands of cubic metres per day....................152

Figure 6-5 The changes of water stocks under scenario 1 (volumes in cubic metres) ....................153

Figure 6-6 Sulphate concentrations (mg/l) in waters in scenario 1 ....................154

Figure 6-7 The changes of water stocks under scenario 2....................157

Figure 6-8 Sulphate concentration in waters in scenario 2 ....................158

Figure 6-9 The changes of water stocks under scenario 3. Volumes in cubic metres. Actual means the standard model (0% change) ....................160

Figure 6-10 Various variations of sulphate concentration in scenario 3....................161

Figure 6-11 Sulphate concentrations (mg/l) in scenario 4 plotted for various % change in water supply....................163

Figure 6-12 Sulfate concentrations (mg/l) in scenario 4 plotted for various stocks ....................164

Figure 6-13 Sulfate concentration (mg/l) in scenario 5 divided according to leakage ....................165

Figure 6-14 Sulfate concentration (mg/l) in waters in scenario 5 divided according to stock ....................166

Figure 6-15 Sulphate concentration (mg/l) in scenario 6 divided according to leakage rate....................168

Figure 6-16 Sulphate concentration (mg/l) in waters in scenario 6 divided according to stock. Standard model leakage averages 37% ....................169

# LIST OF TABLES

TABLE 2-1 MESOZOIC STRATIGRAPHY OF CENTRAL SAUDI ARABIA ....................................... 22

TABLE 2-2 SOURCE OF WATER SUPPLY IN RIYADH CITY (CDSI, 2010) ................................. 44

TABLE 2-3 TYPE OF SEWAGE DISPOSAL IN RIYADH CITY (CDSI, 2010) ................................. 45

TABLE 2-4 CHEMICAL ANALYSES OF GROUNDWATER, SOIL WATER AND SURFACE WATER ..... 51

TABLE 2-5 CHEMICAL ANALYSIS OF RAIN WATER OVER RIYADH CITY (11–16 MARCH 1994) (ALABDULAÄLY& KHAN ,2000) ......................................................................... 52

TABLE 4-1 MANNING ROUGHNESS COEFFICIENT VALUES (CHOW, 1959) ................................ 84

TABLE 5-1 COMPARISON SO4 CONCENTRATIONS BETWEEN STANDARD & TEST MODELS ..... 136

TABLE 6-1 WATER BALANCE BUDGET FOR CITY SOIL ON 31-12-2012................................... 145

TABLE 6-2 ESTIMATED WATER BALANCE FOR THE WADI SOIL FOR 31-12-2012 .................... 148

TABLE 6-3 ESTIMATED WATER BALANCE FOR WADI SURFACE WATERS ON 31-12-2012........ 150

# **Symbols List**

| Symbols | Explanation |
|---|---|
| A | cross sectional area |
| AET | Actual evapotranspiration |
| CN | Curve number |
| $ET_{JH}$ | Potential evaporation (Jensen-Hasie,1963) |
| $I_a$ | initial abstraction |
| K | hydraulic conductivity |
| n | Manning's coefficient |
| P | Rainfall |
| PET | Potential evapotranspiration |
| $Q_D$ | discharge rate |
| $Q_R$ | Runoff |
| R | hydraulic radius |
| $S_R$ | Potential maximum retention after runoff |
| $S_w$ | Slope of water surface |
| $T_a$ | The average air temperature |
| V | mean of flow velocity |

# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

The problem of water constitutes a permanent challenge for the countries of the Middle East, in general, and the Kingdom of Saudi Arabia (KSA) in particular, where the annual rainfall averages are less than 100 mm at many places (Almazroui, 2011). Apart from climate change impacts, industrialization and population growth in the Kingdom put extra pressure on water resources, which should be properly managed according to reduction of wastage, conservation of the existing resources and groundwater augmentation by natural or artificial recharges (MOEP, 2010). For this purpose, on the one hand, the number of groundwater recharge dams must be increased in the Kingdom and also in the future groundwater recharge possibilities from the urban water discharge must be planned properly from now on. In the future, the following three factors are expected to play significant role in water resources management within the Kingdom to cope with the steadily increasing demand on water (MOEP, 2010).

(a) There is a tendency for socio-economic growth transformation of agricultural lands to urban areas. This implies that the urbanization will increase by time, and accordingly, urban water discharges will also increase,

(b) Strong competition is expected between demands for urban water (drinking and domestic uses) and irrigation leading to either over-pumping of available aquifers or desalinization water volume increment.

(c) Major water projects are planned to increase aquifer storage capabilities in order to cope with increasing demand.

In arid regions, aquifers are the key reservoirs for domestic, agricultural and industrial supplies. On the one hand, the scarcity of rainfall and consequent weak groundwater recharge makes these reservoirs more precious than ever under the pressure of population growth. Additional requirements of agricultural productions and local industrial activities, not only exert pressure on the limited groundwater resources, but also after the discharge of wastewater or sewage network leakage increase the possibility of groundwater pollution.

It is, therefore, necessary to conserve precious groundwater reservoirs. Most water used in urban areas is discharged, but if it could be re-used, water resources could be increased significantly.

In many cities in the Kingdom of Saudi Arabia (KSA), urban water is discharged to urban wadi systems, where it either runs off or infiltrates into the wadi deposits and flows away through the subsurface water system. In these wadis, the discharge water is increased by natural runoff, which may dilute it, and may flow out of the city to non-urban areas, where it could be used for irrigation. In addition, irrigation may be used from wells in the wadi deposits within the urban area. If this works well, urban waste water can be re-used, but what is not known is if it is sustainable or how it could be managed. For example, is discharged urban waste water contaminating aquifers around urban areas? Is irrigation use of urban aquifer groundwater added to by waste discharges causing unsustainable increase in concentrations in groundwater systems? How should such wadi / urban discharge systems be managed to ensure sustainability? These are all important questions for KSA and for other arid zone countries.

## 1.2 Background

Groundwater is a major source of water supply in the KSA. It shares about 40% of total water supply in the Kingdom (CDSI, 2011). Groundwater resources are cheap to develop compared to other sources of supply in the country, and therefore, exploitation of this resource increased rapidly after introduction of groundwater based irrigation systems for crop production in the early eighties (MAW 1988). Groundwater plays an important role in the tremendous growth of the agriculture in the country. It helped the desert country to become self-sufficient and to even become an exporter of food as well as to develop its socio-economy. However, ever increasing exploitation of groundwater to meet the growing demand of water for irrigation has put huge pressure on limited groundwater resources in the country.

Groundwater in the KSA occurs mainly in two aquifer types: the shallow alluvial and the deep rock reservoirs. The deep rock aquifers are sedimentary in origin, usually sandstone and limestone, extending over thousands of square kilometres. Groundwater in the Kingdom is mostly abstracted from these large deep aquifer systems. This fossil groundwater, recharged some 20 000 years ago (Burden, 1982; Lloyd & Farag, 1978) has a thickness of hundreds of metres at depths of usually between 150 and 1 500 m (MAW, 1984). The natural recharge capability of these aquifers is very poor (MAW, 1984). Only a small amount of annual recharge occurs in these aquifers through upland and foothill zones, where the rocks have surface outcrops. On the other hand, the shallow aquifers are generally unconfined, small in area and have water tables that respond rapidly to local precipitations (FAO 2009, Abdurrahman, 2000a).

Climate types in Saudi Arabia vary between arid and semi-arid. Rainfall is very scarce and erratic in most parts of the country. The average annual rainfall ranges from 25 mm to 150 mm (MAW 1988). The average annual potential evaporation ranges from 2,500 mm to about 4,500 mm. Consequently, annual groundwater recharge is very less. Only a small fraction of seasonal surface runoff infiltrates through the alluvial sediments and sedimentary layers in the valleys and recharges groundwater, while most of it is lost within evaporation. It has been estimated that the natural recharge to deep aquifers is approximately $1.28 \times 10^9$ $m^3$/year (MOP, 1985), while approximately $394 \times 10^6$ $m^3$/year flows out from Saudi Arabia across its national borders. On the other hand, groundwater withdrawal for irrigation is about $17.5 \times 10^9$ $m^3$ in 2004 (MOEP,2010). Negligible recharge compared to huge withdrawal has caused declination of groundwater level in all the major aquifers in the country (MAW, 1984). The shallow aquifers are also being used at a much faster rate than these could be replenished and consequently are also dying out very fast.

Considering huge environmental impacts, Saudi government restricted groundwater withdrawal for irrigation in 2002. Even the shallow aquifers used for water tapping in city areas were suspended to counter the falling water levels (FAO, 1998). This has reduced groundwater withdrawal for irrigation in recent years. However, it did not improve the situation of declining groundwater level significantly. Therefore, a number of attempts has been planned to reduce irrigation demand by introducing water saving techniques and enhance groundwater recharge in order to improve the situation.

Artificial recharge has been taken as one of the major strategies to achieve sustainability in groundwater resources in Saudi Arabia. Approximately 275 dams have been built to improve groundwater recharges in the country. The dams are able to control groundwater recharge approximately 993 x $10^6$ $m^3$/year (MOEP, 2010). However, the recharge is still a fraction of total withdrawal of groundwater. Available surface water is also very limited for mass groundwater recharge. To overcome this complex situation, the Saudi government has planned to use treated wastewater as a major source for groundwater recharge.

Urban areas of Saudi Arabia produce huge amounts of wastewater. In 2010, about 2.43 x $10^9$ $m^3$ of municipal wastewater was generated every year in the Kingdom (MOWE, 2009). The amount of urban wastewater is increasing in Saudi Arabia with the increase of urban populations, their economic ability and changes in life-styles. It is expected that urban population of the country will reach about 32 million in 2020 or about 80% of the total population of the country, and therefore, more wastewater will be generated from urban areas of Saudi Arabia. Treated wastewater will also increase continuously as more treatment plants are constructed and as more parts of different cities are connected to sewage networks. It is anticipated that the amounts of wastewater will increase from about 30% of domestic water supply to almost 70% by 2025 (MOWE, 2011). The government has a national policy to reuse the treated wastewater and has made significant progress toward this goal. The country has targeted to reuse over 65% of wastewater in 2020 and 100% in 2025.

Treated wastewater can be a very important source, which can be utilized for many purposes in the KSA. However, the amounts actually used are very small, Saudi

Arabia using only a fraction of treated wastewater in agriculture and industry. A major portion of treated wastewater, totalling over 8 x $10^8$ $m^3$ /year is discharged to water bodies (e.g., Arabian Gulf or Red Sea) without any economic benefit. Rather, it often causes environmental pollution and hazard to marine ecosystem. Groundwater recharge using wastewater can be an economic way to supply this water for irrigation purpose. It can also be used for sustainable management of this precious resource in the context of climate change. Climate models predicted that the Middle East region by the middle of the 21st century will have a relatively small and insignificant change in precipitation, but a relatively large temperature increase in the range of 1 to 1.5 °C (Almazroui et al., 2013; IPCC, 2013). This will severely affect surface water resources and increase water demand in domestic, agricultural and industrial sectors. Estimates suggest that it would increase a 15% in demand for irrigation water from the agricultural sector. As groundwater is less affected by climate variability or extremes weather events, storing water in aquifers can be a good option to adapt with climate change impacts on water resources of Saudi Arabia. Therefore, it can be expected that wastewater reuse for groundwater recharge will, if environmental pollution can be kept at acceptable levels, able to meet the growing demand for fresh water; and help the country to adapt to the adverse effects of climate change.

Recharge to groundwater by using reclaimed water is an important method to reduce groundwater depletion, especially in semi-arid and arid areas. The reuse of treated wastewater for groundwater recharge has been found successful to counteract water scarcity and reduce pollution of surface waters in many regions of the world.

Kingdom of Saudi Arabia has also experimented groundwater recharge using treated wastewater. A portion of treated water is discharged into wadi, which contributes to groundwater recharging. For example, a part of treated wastewater from Riyadh city is now discharged into Wadi Hanifah, which contributes to groundwater recharge. It is expected that the recharged water will flow downward through subsurface due to gravity. It will be more purified through natural filtration process of soil after travelling from the area of infiltration to the area of abstraction. It has been reported that it is more economical and convenient to transfer huge amount of treated water to irrigation land distributed over a large area compared to transferring it by pipeline (Missimer et al., 2014).

Therefore, it is very essential to determine the amount of treatment required for recharging groundwater in a particular geological setup. Different effluent qualities are expected in wastewater due to different methods of treatment for producing reclaimed wastewater. Effluent must conform to reuse standards appropriate to its application. In some geological setups, it is required to give priority to remove organic compound and in some cases removal of heavy metals (Li et al., 2014). The health issues need to be given the prime consideration in defining pretreatment requirements.

There is a need of management policies based on scientific information in order to achieve success in groundwater recharge using treated wastewater without any environmental or health impacts. Detailed research in this regard is essential in order to conceptualize and simulate the system as well as to assess the benefits, problems and successes of such projects. One way of conceptualization of a dynamic system is to build a computer simulation model. The models can be used to test theories and to simulate complex reality, whilst discovering their implications and contradictions.

However, simulation of groundwater system recharged with treated wastewater is very intricate as it depends on may interrelated factors, such as, multiple water sources, water demand, rainfall, evapotranspiration, treated wastewater discharge rates, soil composition, geological structures and hydraulic properties, topography/relative elevations, natural recharge, irrigation demand, sewer leakage, water pipeline leakage, effluents in treated wastewater, and pollution transportation and attenuation, and subsequently the interactions with socio-economics including government policies and relative cost driven decision making. System Dynamics (SD) offers a novel way of modelling complex systems and analysing their dynamic behaviour.

A SD modelling approach can consider a system in a holistic way in order to solve complex problems of the system by modelling the causal structure originated from the problematic behaviour of the system, such as: feedback loops, cause-effect interrelationships, nonlinearity and delays (Sterman 2000). Therefore, SD is considered as an effective tool for conceptualizing, visualizing and communicating the future evolution of complex systems. SD can be used to create quantitative and qualitative models that take the interrelationships of physical process such as: water infiltration, interaction with soil, groundwater movement, pollution transportation, groundwater withdrawal etc. with behavioural process, such as decision rules, policies, perceptions, etc. of a system. This allows SD to assess systemic impacts of different processes or policies in a time-compressed mode (Sterman 1994). Various software tools like Stella, Powersim, Vensim, Dynamo, etc. are widely used for developing of

SD simulation programs. These programs require graphical objects to develop the system structure and its underlying mathematical functions, which allow the models simulation to be quickly and easily developed (Zhang et al. 2008).

Though relatively rarely used in hydrogeology, it is suggested that application of the SD approach to simulate a groundwater system recharged by treated wastewater will help to understand the dynamics of this complex system in order to provide a basis of understanding for eventually formulating the necessary regulatory policies to try to achieve sustainability

## 1.3 Aims and Objectives of Study

The aim of the study is to determine whether system dynamics modelling is likely to be a useful way to determine whether urban waste water discharge to urban wadis is sustainable from a water quality point of view, and how it should be managed.

The way this will be attempted will be to examine in detail an important example –the Riyadh-Wadi Hanifah area on the Arabian Peninsula in the central provinces of the KSA. A systems dynamics modelling method will be trialled, attempting to determine by example if this approach would be useful elsewhere.

The objectives of the research are therefore to:

1) develop a model for movement of water between the city and the wadi including all the water sources that feed the city;

2) develop a model of solute transfers using the model of water movement as a basis, by linking the mass concentration of solute with volumes of water as follows;

3) use the model, by the process of developing it and also by use of sensitivity analysis, to understand the nature of the links between the city and wadi water systems;

4) use the developed model to determine what effects management policies might have on water quality and quantity;

5) determine by experience in applying the SD approach to Riyadh what its advantages and disadvantages are in this sort of application.

## 1.4 Available data

### 1.4.1 Geological and Topography and Infrastructure Data

Aerial photographs are available at scales of 1: 100,000 and 1: 50,000. They are used for defining the physiography of the study area. The use of the maps in different aspects of the study is discussed in other sections of this thesis.

Many geological studies and maps cover the study area. Vaslet et. al. (1991) reported explanatory notes to the geological map of the ‘Riyadh Quadrangle’.

Some data are available on infrastructure, for example sewer types and coverage.

### 1.4.2 Hydrogeological Data

The Riyadh City-Wadi Hanifah area has attracted many research studies. The Riyadh Development Authority (ADA) has undertaken several studies on groundwater and surface water in the City of Riyadh and Wadi Hanifah.

These studies provide hydrogeological data from observation wells in the City and Wadi Hanifah, and they also present data for water chemistry and the main solute concentrations in the groundwater in the city and the wadi as well as the surface water in Wadi Hanifah.

Limited groundwater abstraction data for irrigation are available. Wadi surface water hydrographs are not available, but there are a few spot measurements.

There has also been a range of previous studies on various aspects of the geology, geophysics and hydrogeology of the study, and these provide generally data about aquifer parameters and quality of water for specific limited regions of the city.

Generally, data on water levels and hydrological parameters are either missing or for uncertain aquifers or only available for limited periods of time. This lack of data forms one of the main difficulties faced in the research study, but it is a difficulty that is likely to be shared in most investigations of urban aquifer – wadi systems in many countries.

### 1.4.3 Climatic Data

The weather data are from the King Khalid Airport Meteorological Station in Riyadh. The data include all meteorological elements for the period from 1990 to 2012. Available daily data are for various factors including precipitation, relative humidity, air temperature, pressure, wind speed and direction.

The weather data enable calculation of the volume of rain water falling on the city and on the wadi as well as in calculating the amount of evapotranspiration in the study area. The availability of the measurements is discussed in detail in Chapter 2.

### 1.4.4 Thesis Structure

The thesis is divided into two main parts, first being the development of the SD model for the water movement and solute movement in the City-wadi system. The second part is the exploration of the model. The thesis contains seven chapters, which are described briefly as follows.

Chapter one: INTRODUCTION

It includes introduction, background of the study, aim and objectives of research and the availability of data.

Chapter two: RIYADH SETTING

This chapter contains general data about Riyadh City and wadi Hanifah, such as location, topography, geological and hydrogeological data for the study area and all available weather data.

Chapter Three: STELLA MODELLING

Chapter 3 is an introduction to systems dynamics modelling and the software code used in the rest of the research, ‘Stella’. The Chapter starts with a definition of System dynamics (SD) modelling, and then discusses previous applications of SD in ecosystem and groundwater modelling. The Stella program is then described. Finally, the reasons for choosing SD modelling and the Stella code are presented.

Chapter Four: WATER FLOW MODEL

This chapter explains all the sources of water in the city and the wadi, building an initial conceptual model. Then the development of the water movement model, the quantitative representation of the conceptual model, is described.

Chapter Five: SOLUTE MODEL

This chapter describes the development of the solute model using the flow model simulation as the basis.

Chapter Six: MODEL APPLICATIONS

Chapter 6 uses the model to investigate the inferred flow and solute movement in the city-wadi system. It the investigates various hydrogeological and sustainability scenarios in order to explore possible management options.

Chapter Seven: CONCLUSIONS AND RECOMMENDATIONS

In Chapter 7, the conclusions reached during the study are presented as they relate to Riyadh, to arid area urban aquifer – wadi systems in general, and to the usefulness of the SD modelling approach. Future recommendations are then presented concerning the water management in this example arid area urban - wadi) system.

# CHAPTER 2: RIYADH SETTING

## 2.1 Introduction

Riyadh, the capital of Saudi Arabia is located in the centre of the Arabian Peninsula. It is the largest city of Saudi Arabia and covers an area of 1300 $km^2$ and homes approximately 5.7 million people including expatriates (Region, 2005). About 24.9% of total population of Saudi Arabia lives in Riyadh (CDSI, 2011). It is also home to the largest share of the Saudi population (23.3%) (Salam et al., 2014).

The city was founded during the Pre-Islamic era and was known as Hajr until the $16^{th}$ century (Cybriwsky, 2013). The city is located in the central Arabia and it has been dating since the $3^{rd}$ century AD. Hajr served as the capital of the province of Al-Yamamah during the Middle age. It was made the capital of the first Saudi State in 1774. It was kept as the capital during the establishment of modern Kingdom of Saudi Arabia in September 1932. Administratively, Riyadh is divided into fifteen branch municipalities and each branch municipality contains several districts. The total number of districts in Riyadh is over 130. Riyadh Municipality, headed by the mayor, and Riyadh Development Authority, chaired by the governor of Riyadh, manage the city (Kechichian, 2001).

As a capital of modern Saudi Arabia, the city has grown from a small isolated town into a vast and sprawling city. The city was developed in grid squares and the main roads connect the inner areas. The population of the city has also grown rapidly following the line of development (Nadeem, 2012).

However, the growth of population in the city is not only due to natural reasons but also due to continuous migration of Saudis from other parts of the Kingdom. The average population growth rate of Riyadh city is annually 8.1% in contrast to 3.6% growth of the overall population of the country (Ashwan et al., 2012). It has been reported that Riyadh's population has increased by 120% in last 10 years, which is one of the highest in the world (Mulligan & Crampton, 2005). It is expected that the city will be the first mega city of the region with a population of 11.1 million by 2020 (Roberts, 2010). It has also been projected that the city will home 33% to 36% of total population of the country and thus, one of the highest ratios of capital to national population in the world (Struyk, 2005).

## 2.2 Geographical Location of Riyadh

Riyadh is located in the centre of the Arabian Peninsula, situated on a large sedimentary plateau (Qhtani & Al Fassam, 2011). Geographically, it is located between 24°30' and 25°N latitude and between 46°30' and 47°E longitude, and lies about 600 metres above the mean sea level (Loni et al., 2013). In the map of Saudi Arabia, Riyadh is located slightly to the east of the centre and this is located in the middle of the Tuwaig escarpment. Due to its strategic location, Riyadh is considered as the connecting link among all parts of the Arabian Peninsula (Powers et al., 1966). It is also considered as the political, economic and cultural hub in the Middle East region.


Figure 2-1 Riyadh location (Wikimedia.org, 2007)

## 2.3 Wadi Hanifah

Wadi Hanifah is situated on the west side of Riyadh, extending from northwest to southeast (Figure 2-2). The City of Riyadh is located at the juncture of Wadi Ḥanifah and Wadi Batha. However, most of the city is located in Wadi Hanifah, which is a well-known wadi within the Arabian Peninsula. The catchment area of Wadi Hanifah is about 4400 $km^2$ (Fnais, 2011). The total length of Wadi Hanifah is 120 km extending from Tuwaiq Escarpment in the north to the open desert in the south, passing through the western edges of Riyadh in its middle part. A series of about forty smaller tributaries, known as sha'ibs, carry water into Wadi Hanifah. The lengths of these tributaries are up to about 25 kilometres. Most of these tributaries are located along the western side of the valley. The valley immediately around the wadi river is gorge-like, with a flat alluvium-filled floor in which the river runs (Figure 2-3). The depth of the wadi 'gorge' ranges between 10 and 100 metres, and its width ranges from 100 to 1000 metres approximately (Al-Sayari & Zötl, 2012). The banks and valley stream beds are mainly consist of alluvial deposits that have medium to large grain size, with silts.

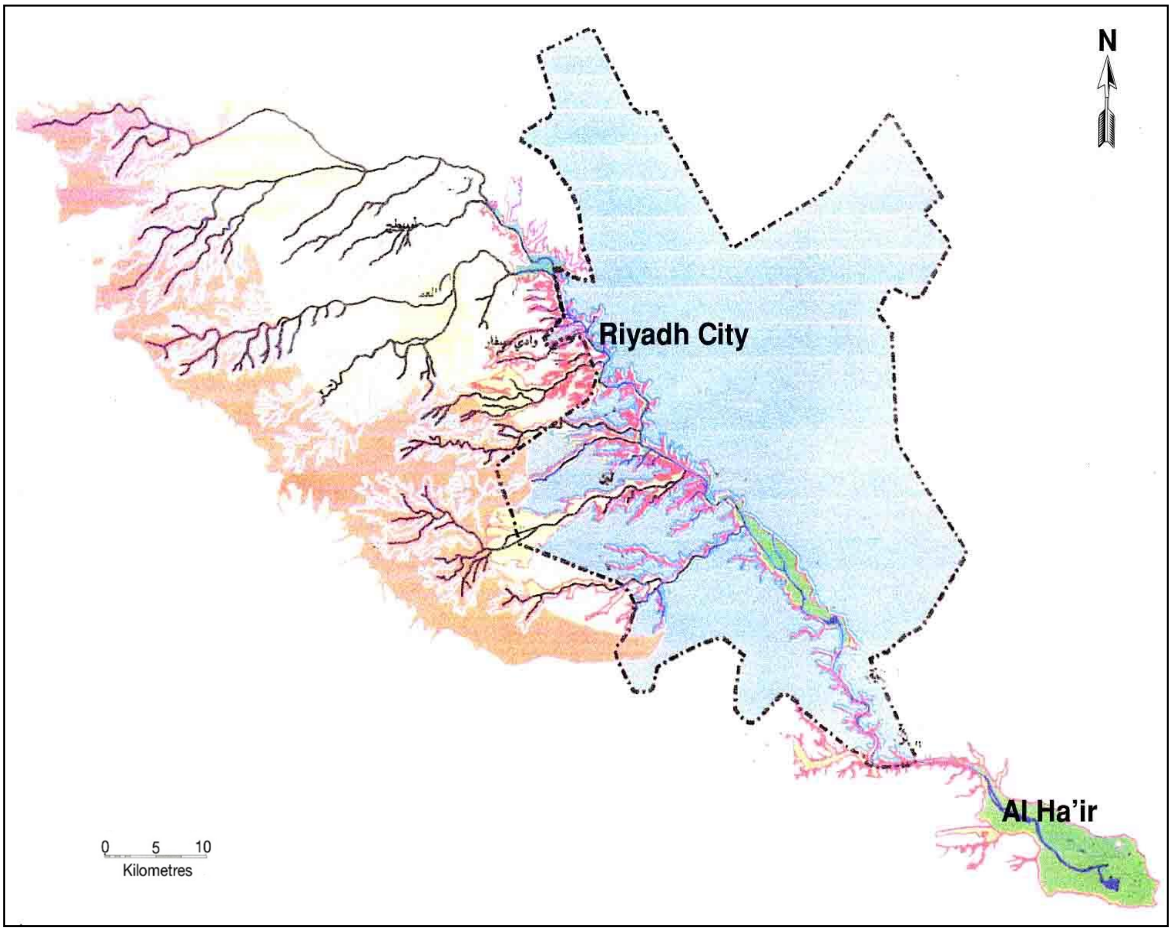



Figure 2-2 Wadi Hanifah location( ADA, 1990 )

Wadi Hanifah is used as the water body into which treated and untreated urban water generated in the city of Riyadh is discharged (Spalding & Exner, 1993; Subyani, 2004). Therefore, from the middle point of the wadi (near Riyadh city), there is a perennial flow of water resulting from the daily discharge of 650,000 cubic metres of treated and untreated water, rising to one million cubic metres per day in total flow (Al-Othman, 2008). This permanent flow of water has caused formation of swamps in the Wadi which is a unique phenomenon in such an arid environment.

Please click link to view image in public domain.

Figure 2-3 Urban part of Wadi Hanifah (Al-Jadh'd,2009)

Wadi Ḥanifah is very important for the water management of Riyadh city. It used to be a main source of water but now it is being used to dispose the city's wastewater. It is considered that it will play a key role in future to supply significant amount of quality water for recycling (Şen et al. 2010).

## 2.4 Topography

Riyadh city is located above 600m above the mean sea level. The topography of Riyadh is reasonably flat. However, the Tuwaiq Mountains form a series of steep cliffs and escarpments that are more than 500 m high to the west, southwest and south of the city. The escarpment is frequently divided into different cuestas due to the more resistant strata.

On the other hand, the topography of Wadi Hanifah varies widely (Fnais, 2011). The west part of the wadi catchment slopes towards the east following the slope of the outcrop of Jubaila limestone. In the east, the topography is altered due to variations in geology (Fnais, 2011). The Westerly resistant limestone is replaced by softer limestone that results in a landscape that consists of small conical hills in a slightly wave-like land. The resistant limestone outcrops which form a line of steep hills extending to the north-west and south-east with elevations varying from 685 m in the north to 620 m in the southeast. The basin in the north and the south consists of steep hills that is cut by narrow channels that are filled with scree.

## 2.5 Geology of study area

### 2.5.1 Geological Setting of Riyadh

The geology of Saudi Arabia can be classified into two broad groups namely, Arabian shield and Arabian shelf. 40% of the country is underlain by the Arabian shield, which consists of igneous and metamorphic rocks dated to the Precambrian age (Powers et al., 1966). The remaining 60% of the country is covered by a set of Arabian Shelf sedimentary strata. The Arabian shield is present from the west coast of KSA to about 500 km towards the east.

The rock is exposed in the west, northwest and southwest. On the other hand, the sedimentary rocks Arabian Shelf formed during Cambrian to Quaternary ages cover the north and east parts of the country (Al-Sayari & Zotl, 2012).

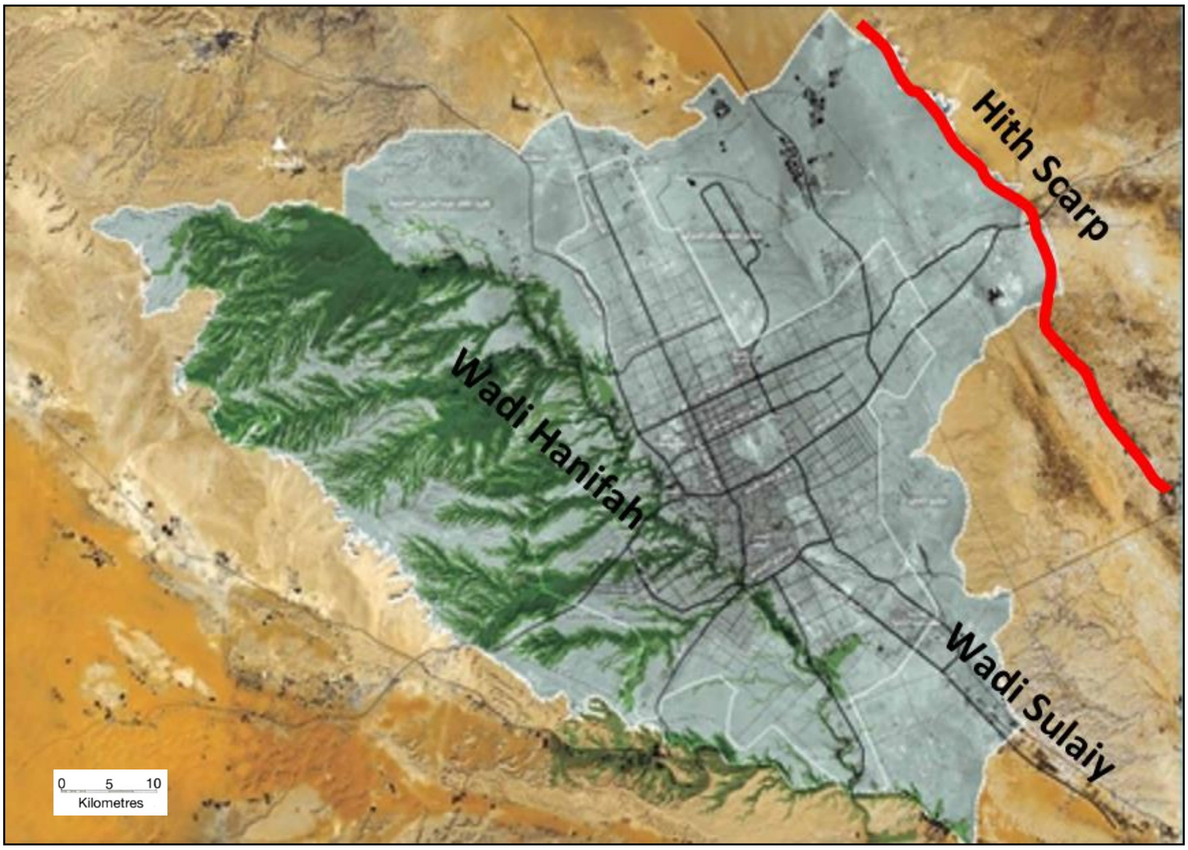



Figure 2-4 Riyadh Topography (ADA, 2010)

The igneous and metamorphic rocks (Arabian shield) (Brown & Jackson, 1960) of the Shield form a topography that has dome-shape and they are often covered by superficial deposits of alluvial sands and gravels (Al-Refeai & Al-Ghamdy, 1994; Edgell, 2006). On the other hand, the sedimentary rocks have a gentle dip (approximately $1^{o}$) to the east, towards the Arabian Gulf, and also to the south. The sedimentary rocks of Arabian Shelf are mostly composed of limestone, sandstones, shale and silts, and often covered by (unconsolidated) aeolian deposits. Sometimes it is covered by thick layers of alluvium and soils (Al-Refeai & Al-Ghamdy, 1994).

The city of Riyadh is located over sedimentary formations of the Arabian Shelf known as the Najd sedimentary formations (Al-Aswad, 1997; Alsharhan & Kendall, 1986).

The stratigraphic sequence of the Riyadh area is shown in Table 2-1, and a general cross section through central Saudi Arabia is shown in Figure 2-5. At the surface, the older rocks appear in the west, with gradually younger rocks to the east, all of which have wide outcrop. Alluvium occurs in the wadis and covers the rock in the city.

The rocks dip in a northeast direction at an angle of approximately one degree (Sharief et al. 1991).

The Jubaila Formation consists of massive limestone in the upper part and fractured limestone in the lower part. The Arab Formation overlies the Jubaila Formation, with lithologies ranging from aphanitic to coarse calcarenitic limestone. The lower part consists of a sequence of alternating pale yellow aphanitic and calcarenite limestones. The middle part of the Formation consists of highly fractured and solution-collapse brecciated limestone and bedded limestone.

Table 2-1 Mesozoic stratigraphy of central Saudi Arabia
(Powers et al., 1966)

<table>
<tr><th colspan="3">Age</th><th>Formation</th><th>Thickness<br>(Type of reference section)</th></tr>
<tr><td>CAINOZOIC</td><td colspan="2">QUARTERNARY</td><td>Surficial Deposits</td><td></td></tr>
<tr><td rowspan="6">MESOZOIC</td><td>CRETACEOUS</td><td>Berriasian</td><td>Sulaiy<br>(Limestone)</td><td>170 m</td></tr>
<tr><td rowspan="5">JURASSIC</td><td rowspan="2">Tithonian</td><td>Hith<br>(Anhydrite)</td><td>90 m</td></tr>
<tr><td>Arab<br>(Limestone)</td><td>124 m</td></tr>
<tr><td rowspan="2">Kimmeridgian</td><td>Jubaila<br>(Limestone)</td><td>±118 m</td></tr>
<tr><td>Hanifah<br>(Limestone)</td><td>113m</td></tr>
<tr><td>Oxfordian</td><td>Tuwaiq Mountain<br>(Limestone)</td><td>203 m</td></tr>
</table>

The upper part consists of fine grained pale yellow aphanitic limestone with calcarenite interbedding. The Quaternary superficial deposits include the alluvium forming the base of Wadi Hanifah and its tributary wadis comprising gravels, silts and clays. They also include the alluvial deposits along the Wadi Sulaiy catchment to the east of Riyadh (Hussein and Loni, 2011) (Figure 2-4).

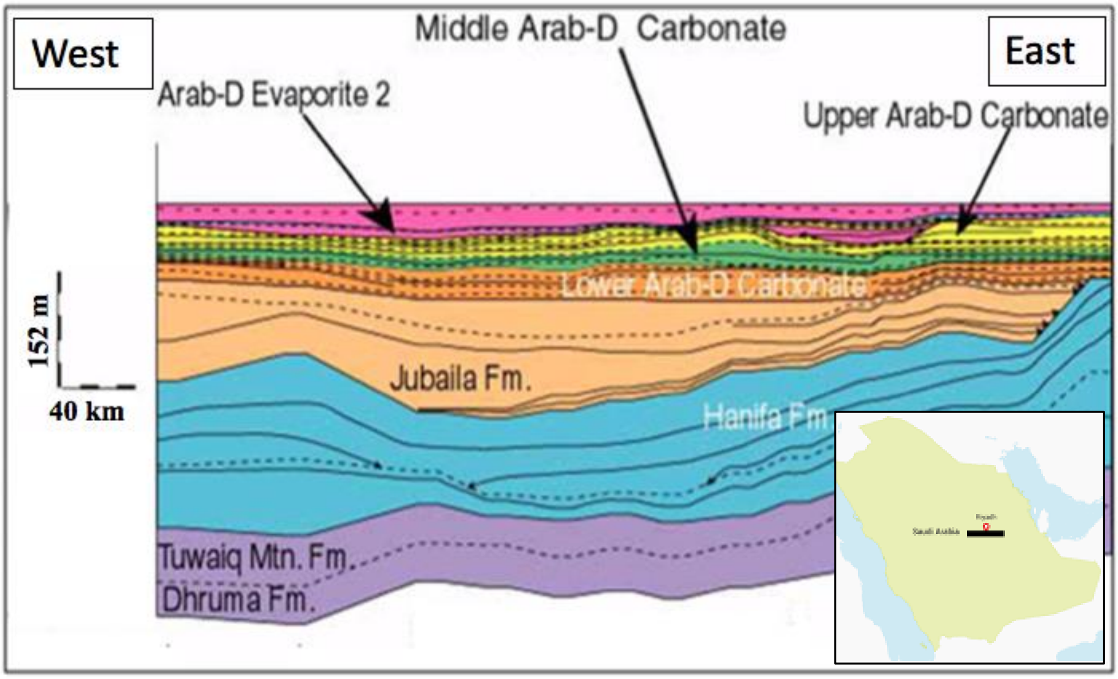



Figure 2-5 East-west cross Section of geological formations in central Saudi Arabia (Powers, 1968)

The distribution of the formations listed in Table 2-1 in the Riyadh area is indicated in Figure 2-6, and Figure 2-7 shows a west-east geological cross-section through Wadi Hanifah and the city.

The geology around Riyadh and its significance from hydrogeological points of view are discussed in more detail in the following subsections.

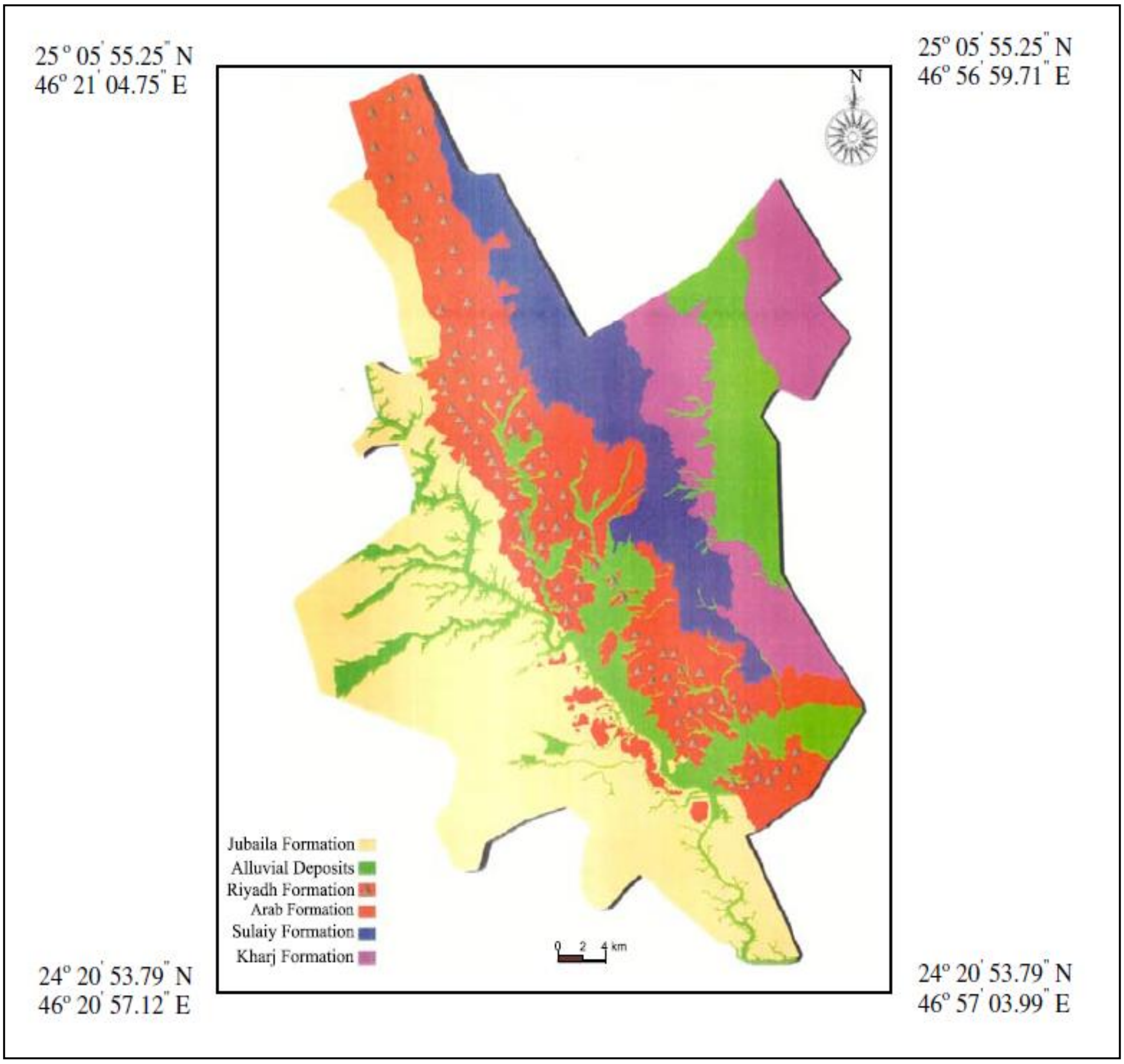



Figure 2-6 Geological map of Riyadh area (Samhouri, 2010).

Age order of formations is (oldest to youngest): Jubaila, Arab, Sulaiy, and Kharj. Alluvium lies unconformably over several of the older formations.

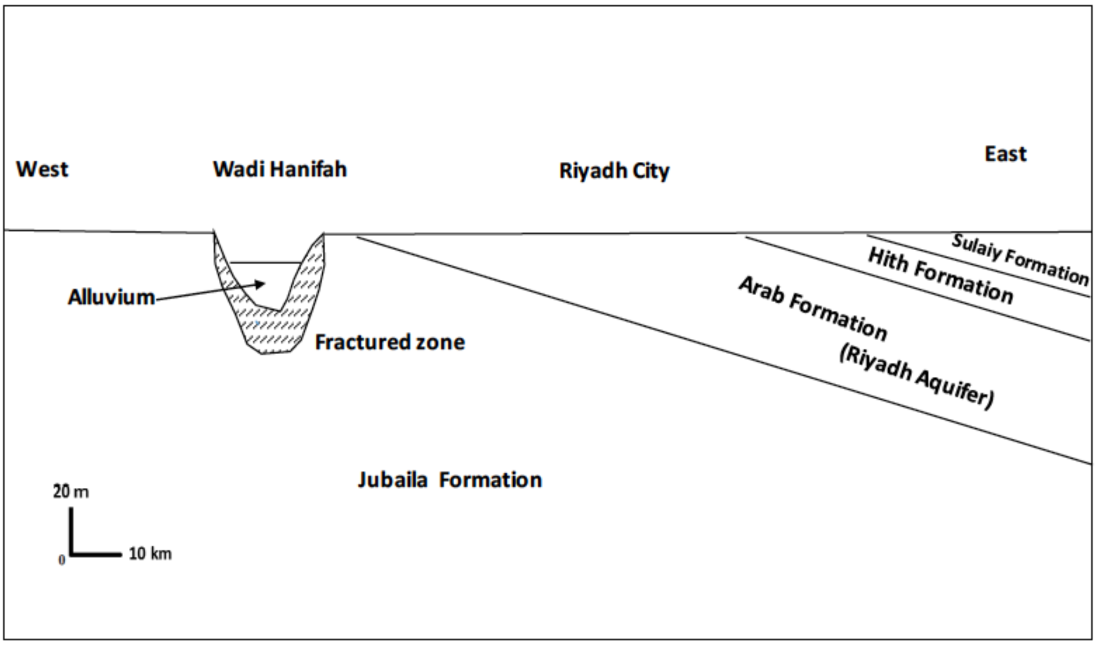



Figure 2-7 Cross section of Wadi Hanifah

### 2.5.2 Jubaila Formation

The Jubaila Formation is the oldest unit of relevance to the hydrogeology, being underlain by the lower low permeability part of the Hanifah Formation (Table 2-1). Outcrop of the Jubaila Formation lies west of Riyadh city (Figure 2-6) and the Formation dips to the northeast.

It is composed of compact limestone with some inter-bedded calcarenite and several beds of dolomite (Shadfan & Mashhady, 1985; Memesh et al., 2008). The rocks of Jubaila Formation are cracked by the effect of erosion on outcrops (Basyoni,2011). The Jubaila Formation, like the underlying Tuwaiq Mountain and Hanifah Formations, is basically a shallow water carbonate unit. The Jubaila Formation has an average thickness of approximately 120 metres. However, the thickness varies widely from place to place. In the east of Riyadh, the Jubaila limestone is overlain by the gypsiferous limestone of the

Arab Formation. This formation has played an important role in water supply and in the development of Riyadh city.

### 2.5.3 Arab Formation

The Arab Formation, extending from northwest to southeast, overlies the Jubaila Formation on the east of Riyadh city (Figure 2-6)(Memesh et al., 2008). This formation is composed of limestone, mainly calcarenite with some aphantic facies. The thickness of the Arab Formation is about 125 metres. The outcrop of the Arab Formation is of the order of 20,000 square kilometres in area, and therefore, it has a significant ability to store groundwater on a regional scale (MAW,1984). However, like the Jubaila Formation, the thickness of Arab Formation also varies widely. The thickness of this formation is comparatively very thin at Riyadh. Therefore, the Arab Formation limestone underneath Riyadh is not a significant water resource locally, in spite of its more weathered and fractured condition. The Riyadh aquifer is the middle part of the Arab Formation and is composed of sandstone with subordinate shale (Powers et al. 1986).

### 2.5.4 Hith Formation

The Hith Formation, which is mainly a massive anhydrite, can be found about 30 kilometres southeast of Riyadh overlying the Arab Formation, and gently dips eastward (Alsharhan & Kendall, 1994). The maximum thickness of this formation reaches up to 90m. The outcrop of this formation forms an escarpment east of the city. The edge of the limestone is marked by scarp, that has fracturing and collapse structures due to the dissolution of anhydrite, it might also forms a hydraulic barrier (Figure 2-4). Groundwater flows generally from south- west to north-east. However the flow is redirected to the south and sometimes to the south-east once it reaches the Hith Escarpment (Fnais, 2011).

### 2.5.5 Alluvium

Alluvium is widely found in valley streams around and inside the city of Riyadh (Konyuhov & Maleki, 2006). The alluviums can be classified into two broad classes: the first one is composed of clay mixed with layers of silt and gravel in the Wadi Hanifah, Alsen and Batha valleys, while the other type of alluvium is composed of silty sand and sandy clay mixed with gravel layers in Sulaiy wadi (Figure 2-4). The alluvium results from active processes occurring in present-day wadis. However, inactive deposits are found in older channels and perched terraces in large wadis (Hotzl et. al., 1978).

Alluvium has a roughly uniform thickness locally between 15 and 20 metres in Riyadh city and wadi Hanifah. The Quaternary superficial deposits include the alluvium (comprising gravels, silts and clays) forming the base of Wadi Hanifah and wadi Sulaiy catchment area and its tributary wadis around Riyadh City (Hussein and Loni, 2011).

## 2.6 Overview of Previous Work on the Hydrogeology of the Study Area

### 2.6.1 Groundwater in the Arabian Shelf Sediments

The Arabian Shelf is composed of a sequence of sedimentary layers lying on the Arabian shield rocks and dipping gently away from the shield and into a number of deep basins (Sharaf & Hussein, 1996; Al-Rashed & Sherif, 2000; Abderrahman, 2005). The sequence is formed of continental and marine sedimentary rocks, due to successive transgression and regression cycles of the gulf waters (Lerner, 2002). Groundwater in Saudi Arabia is found in thick, high yield aquifers within these sedimentary rocks in the north, east, and south of the Arabian Shield. The groundwater in these sedimentary basins is ‘fossil’ groundwater (Burden, 1982; Lloyd and Farag, 1978), formed at different ages when climates were different and therefore there were different recharge mechanisms. Groundwater in these aquifers is often confined and lies within thick sand and limestone units hundreds of metres thick at depths varying from 150 to 1,500 m. The hydrogeological characteristics of these aquifers vary very widely. The current natural recharge of these aquifers is negligible.

According to their time of formation, the aquifers in Arabian plate can be divided into four groups: (1) Precambrian-Palaeozoic aquifers, which include the Huqf, Haima, Saq, Tabuk, Wajid, Haushi and Khuff aquifers; (2) Triassic-Jurassic aquifers, which include Minjur, Dhruma, and Hanifah aquifers; (3) Cretaceous aquifers, which include Thammam (Sulaiy-Yamama, Buwaib), Wasia-Biyadh, Aruma and Simsima aquifers; and (4) Tertiary-Quaternary aquifers, which include Umm er Radhuma, Dammam, Rus and Neogene aquifers. However, the principal aquifers are the Saq, Wajid, Qassim, Minjur, Dhurma, Wasia and Bayad, Umm er Radhuma, Dammam and Neogene aquifers. The groundwater in the country is mainly abstracted from these principal aquifers.

The study area formations in general are massive limestone, the groundwater occurring in fractured zones adjacent to wadi valleys and in karstic limestone layers, the size of caves ranging from decimetres to few metres (Al-Bassam et al., 2000). Consequently, the lower sedimentary sequence of the Jubaila Formation is an aquifer as is the middle part of Arab Formation (Riyadh Aquifer) due to the presence of secondary porosity (Alrehaili and Hussein, 2011; ADA, 1990).

The water quality in these latter aquifers varies greatly from place to place. Near the populated areas, it can be highly contaminated due to seepage of polluted water. The availability of groundwater in these aquifers is limited and the quality is also sometimes not suitable for water supply (ADA,2002). Therefore, they are not currently used as sources of water supply to the City of Riyadh.

### 2.6.2 Surface water in Wadi Hanifah

Wadi Hanifah was a dry bed which used to flow during rainfall only (ADA,2002). The permanent flow started in the early 1980s when dry weather flows from the Riyadh storm water network (connected to Wadi Hanifah) exceeded the natural capacity of absorption in the alluvium. Water currently flows in the southern section of the Wadi due to the city drained groundwater, the storm network discharge of Riyadh and also wastewater treatment plant effluent. Permanent flow in the wadi has also caused rise of the groundwater level in the catchment (ADA,2002).

The rainfall over Wadi Hanifah catchment is very irregular. It is averages at 6 to 8 events of rainfall per year, which usually occur during the months from December to April. However, the duration of rainfall events are short and the intensities are relatively high, and therefore, enough to produce surface runoff. It has been estimated that a fifty year storm of ten minute duration would yield a 100 mm/hr rainfall intensity. Assuming a storm of the same frequency with 2-hour duration would yield only 15 mm/hr in Riyadh

(Salih & Ghanem,2002). The mean annual rainfall in the basin is 84.5 mm/a with a very high standard deviation of 40 mm/a (Salih & Ghanem,2002). It has been estimated that about 15 million $m^3$ of rainfall lands on the Wadi Hanifah catchment on average every year (Hussein and Zaidi ,2012).

The volume of water that flows into Wadi Hanifah varies based on the annual rainfall. Alhamid and Matin (2000) estimated that cross sections within Riyadh city could carry up to a quantity of 125 $m^3$/s discharge, without causing spills form overbank. During heavy rainfall events, discharge exceeds the natural capacity of channel and causes floods. Dramatic changes in wadi landuse with the urban development of Riyadh city have increased the severity and frequency of floods in the wadi. Nowadays floods become an every year phenomenon during high rainfall events, which often cause damage to property and economy (Loo et al., 2014). Quality of water in the wadi is also very low as it is used as the natural drain of the city. It has been reported that many water quality parameters, particularly the contents of faecal coliforms, hydrocarbons, nitrogen, nitrate and sulphate are higher than permissible level of household use (ADA,2002).

The absence of regular historical of runoff measurements results in difficulties in deriving relationship between runoff in Wadi Hanifah and rainfall in the basin. Furthermore, the discharge pattern in the wadi became more complicated after connecting it with the Riyadh storm water network. The upper section of Wadi Hanifah, which is located north of Riyadh, has runoff that recharges neighbouring aquifers, while downstream of the city boundary perennial flow is created. It has been estimated that base flow in the Wade varying between 50,000 and 500,000 $m^3$/day over a distance downstream of Riyadh. Below Wadi Hanifah there are weathered and fractured bed rocks where groundwater is also stored and this is replenishable groundwater; however it is not connected to the deep formation aquifers, which have either fossil water or partially recharged from outcrop areas.

### 2.6.3 Riyadh Aquifer

Groundwater plays an important role in water supply of Riyadh city. Before building of desalination water supply, groundwater was used as a major source of water supply in Riyadh. Groundwater in Riyadh is abstracted from two horizons, shallow aquifers, that is used for irrigation and industrial uses, and deep aquifers, which is mainly used for potable water.

Riyadh city is situated on the plateaus formed by the limestones of the upper Jurassic Jubaila and Arab Formations. The underlying thick sequence of sedimentary rocks of the Arabian Shelf contains number of large and deep confined aquifers (Burdon, 1982; Hotzl & Zotl, 1984; Al-Rashed & Sherif, 2000) such as Jilh, Minjur, Jubaila, Biyadh and Wasia. Among them the Minjur and Wasia-Biyadh aquifer system is the largest aquifer system. As mentioned before these are deep and 'fossil' waters with negligible groundwater recharge from the outcrop areas. (Hotzl & Zotl, 1984)

The Riyadh Aquifer is in the middle part of the Arab Formation due to the presence of secondary porosity (Alrehaili and Hussein, 2011). In past , groundwater from this aquifer is mixed with desalinated seawater to reduce salinity before it is supplied to Riyadh city, but due to contamination was stopped in early 1980s (ADA,2002).

The parameters of Riyadh Aquifer within the city are: the Hydraulic conductivity is 100±30 m/day and the storage coefficient ranges between $1\times10^{-4}$ and $1\times10^{-2}$ and the thickness is around 120 metres (Mowafy et al., 1996).

### 2.6.4 Jubaila Aquifer

The city of Riyadh lies on the edge of the Jubaila Limestone outcrop and the Arab Formation (Figure 2-6). The Jubaila Limestone is composed of 55 plateaus that extend to the west of Riyadh where Wadi Hanifah has cut a deep bed. In the east of Riyadh, the Jubaila Limestone is overlain by limestone of the Arab Formation (Okla, 1986; Alsharhan & Magara, 1994; Al-Othman & Ahmed, 2012). The groundwater in the Riyadh area is abstracted from shallow aquifers (Al-Othman & Ahmed, 2012) of both the Arab and Jubaila Formations. However, a major portion of groundwater from shallow groundwater sources comes from the Jubaila Formation.

The Jubaila aquifer is classified as a secondary aquifer. According to its yield capacity, it is considered as a moderate aquifer (Burdon, 1982). Groundwater in Jubaila Limestone occurs in secondary pore spaces that was a result of faulting, fractures and solution cavities. Two tributaries of Wadi Hanifah, namely, Wadi Alaysin and Wadi Batha, are formed over the Jubaila Formation (Pollastro, 2003). Tributaries have also made shallow beds partly cut into the Arab Formation. Due to the existence of fractures and solution cavities the Jubaila Limestone is highly permeable locations and therefore, can act as a good source of groundwater supply. Particularly, high quantities of groundwater can be abstracted from the areas where the cavities are connected to wadis. The transmissivity of Jubaila aquifer is in a range between 150 and 105 $m^2$/day and the thickness is 116 metres. Confined storage coefficient values average $1.3\times10^{-4}$ (Italconsult, 1969; Parsons Basil Consultant, 1969; GDC, 1979). Depth to groundwater in the Jubaila aquifer around the city of Riyadh varies from 19 to 210 m (Hussein,2011). Groundwater in Jubaila Formation flows towards Wadi Hanifah in the northern part of city and towards the southeast and south directions in the southern parts of the city. The average hydraulic gradient of groundwater in Jubaila Formation is about 0.005 (Alrehaili & Hussein, 2012).

The groundwater in this Formation is now heavily contaminated (Alrehaili & Tahir Hussein, 2012). So, groundwater pumped from this part of Wadi Hanifah is contaminated and is not suitable for domestic uses. However, Alhamid et al. (2007) reported that the groundwater quality in the wadi is much better in comparing with surface water.

## 2.7 Climate of Riyadh

### 2.7.1 Introduction

Riyadh experiences a continental climate that include hot, long and dry summers and cool, short and moist winters (Iqbal & Al-Homoud, 2007; El-Mubarak et al., 2014; Tsiouri et al., 2014). Due to its location in the interior part of the Arabian peninsula, the climate of Riyadh is less influenced by the Mediterranean (Qureshi & Khan, 1994; Lelieveld et al., 2012) and the Arabian Gulf climate (Sen, 2013). The climate of city is predominantly influenced by sub-tropical high pressures (Subyani, 1999) and occasional depressions (Edgell, 2006; Shahin, 2007).

### 2.7.2 Climatic Conditions in Saudi Arabia

The climatic pattern over the study area is influenced by air masses that affect rainfall distribution over the study area. Various air masses influences and rainfall patterns over Saudi Arabia have been studied and mapped by several researchers (Sen, 1983 ; Alyamani and Sen, 1993, Maclaren, 1979).

Different air masses which have an influence on the Kingdom's climate are illustrated in Figure 2-8 which shows that there are three major air masses carrying moisture flowing into Saudi Arabia: (i) maritime tropical air masses from the south and southeast, originating from the Arabian Sea and Indian Ocean; (ii) continental tropical air masses coming from the Atlantic Ocean that passes to the middle and northern parts of the African continent; and (iii) maritime polar air masses derived from the eastern Mediterranean Sea. The maritime tropical air masses bring moisture during the autumn, but in early winter the maritime polar air masses increasingly disturb these monsoonal air masses and displace them at lower altitudes. These maritime depressions result in the tropical continental air masses being limited to warm air packets and extreme weather conditions occur, which are associated with the passage of a very warm air packet.

Both the continental tropical air masses and the maritime polar air masses are moved toward the east and prevail during the winter season. During this season, the western region, particularly the coastal area is characterized by its relatively low rate of rainfall (Sen, 1983), whereas, due to topographic effects, the highlands receive considerably more rainfall . In spring, the effect of the Mediterranean air movement diminishes, the southern originating monsoon taking its place, penetrating into the southern part of Saudi Arabia.

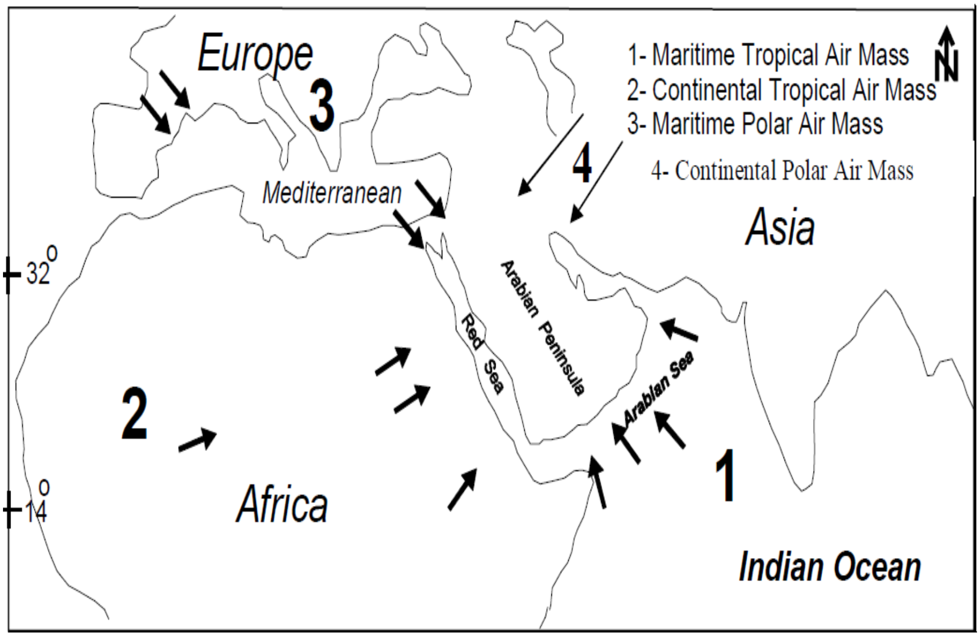



Figure 2-8 Air mass movement over the Arabian Peninsula
(Sen, 1983)

During summer the cyclonic flow sweeps along the Mediterranean Sea from the west toward the east and continues moving over the northern and central regions of the country preventing the maritime air masses of the southwesterly monsoon from penetrating into the north regions of Saudi Arabia. Due to this, the summer season will be rather dry in the area considered (Sen, 1983).

### 2.7.3 Climatic pattern over the study area

The micro-climate of the study area is typically arid and can be considered amongst the driest in the Arabian Peninsula, with an average annual rainfall around 100mm. Rainfall is very low, unpredictable as well as highly irregular from year to year. Generally, most rainfall occurs locally and it is usually happen as a violent strong storms that have short duration. Over the area, the seasonality of the rainfall is strong. It reflects the high percentage of rain which occurs in winter and spring.

### 2.7.4 Rainfall

As indicated above, rainfall is very low, unpredictable as well as highly irregular from year to year (Figure 2-9). Rainfall mostly occurs locally as short and violent storms. Over the area the seasonality of the rainfall is strong.

The mean annual rainfall in the city is 100 mm. However, like other parts of the country, precipitation in Riyadh exhibits spatial and temporal variability (Almazroui, 2011; Almazroui et al., 2012). The mean annual rainfall in Riyadh city is found to vary from 85.1 mm in the south to 111.6 mm in the north (Al-Saleh, 1997; Wheater et al., 1999). Rainfall in the city mostly occurs during the rainy season which extends from October to May. However, on average, the city receives rainfall (>0.1 mm) only in 17 days in a year(Al-Saleh, 1997 ) The highest rainfall is found to occur in October and the lowest in June. The rainfall is also found to vary widely from year-to-year. The coefficient of variation of annual rainfall is about 46% (Al-Saleh, 1997).

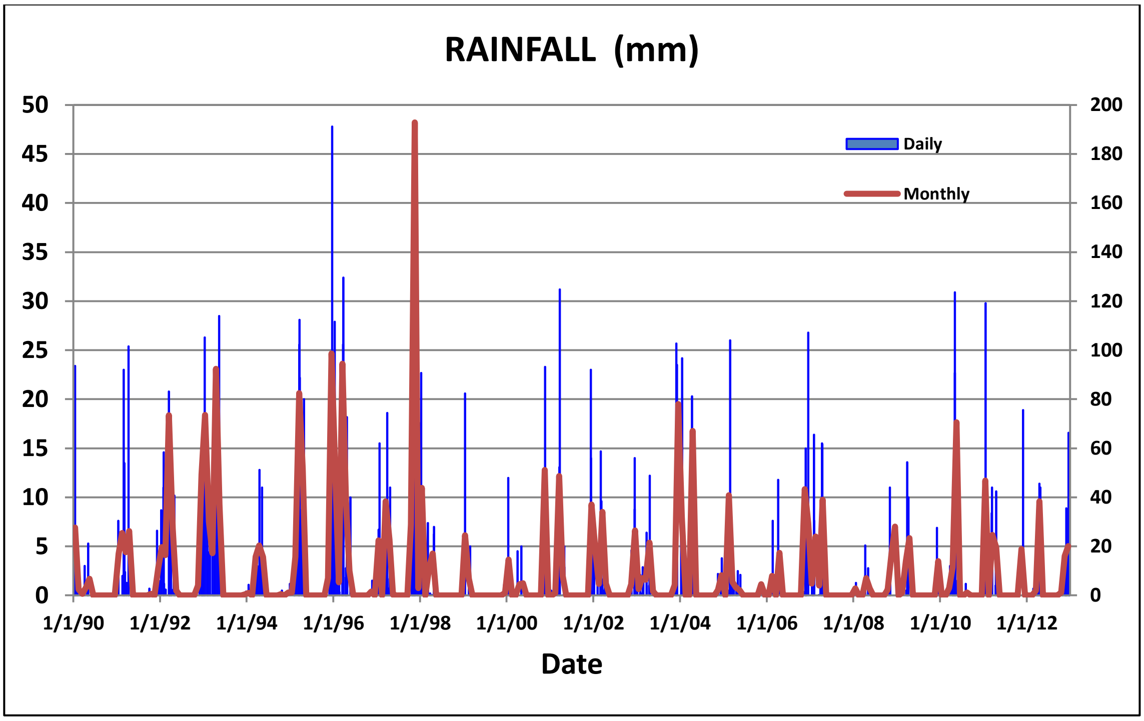



Figure 2-9 Daily and Monthly Rainfall (1990-2012) over Riyadh City (PEM,2013)

The most common forms of precipitation in the city are moderate rain, thunderstorms, and light rain (Shepherd, 2006). However, storm rainfall have high-intensity and the most common from moderate , thunderstorms and light rain but that the most rain comes in violent thunderstorms. Rainfall storms, most of the time, occurs locally and it is common to have a violent thunderstorms of short duration. It has been reported that approximately 50% of all rain is an intensive storm that excess of 20mm/hour, and about 20% to 30% of storms has intensities over 40mm/hour (Al-Saleh, 1997).

### 2.7.5 Temperature

The average annual temperature of Riyadh city is 24.7°C (Donat et al., 2014). The minimum temperature in the city varies from 8ºC in January to about 28ºC in August. On the other hand, the maximum temperature varies from 19ºC in January to 48ºC in August. The minimum temperature rarely goes below 3°C and the maximum temperature rarely goes above 45°C. However, freezing temperatures can be experienced sometimes during winter nights.

The mean diurnal temperature range (DTR) in the city varies between 15.2°C during the winter month of January and 19.2°C in the summer month of July (Chowdhury & Al-Zahrani, 2013). The variability of mean annual temperature of the city is only 2.5%, which indicates a remarkably high degree of intrinsic stability in the thermal regime of the city.

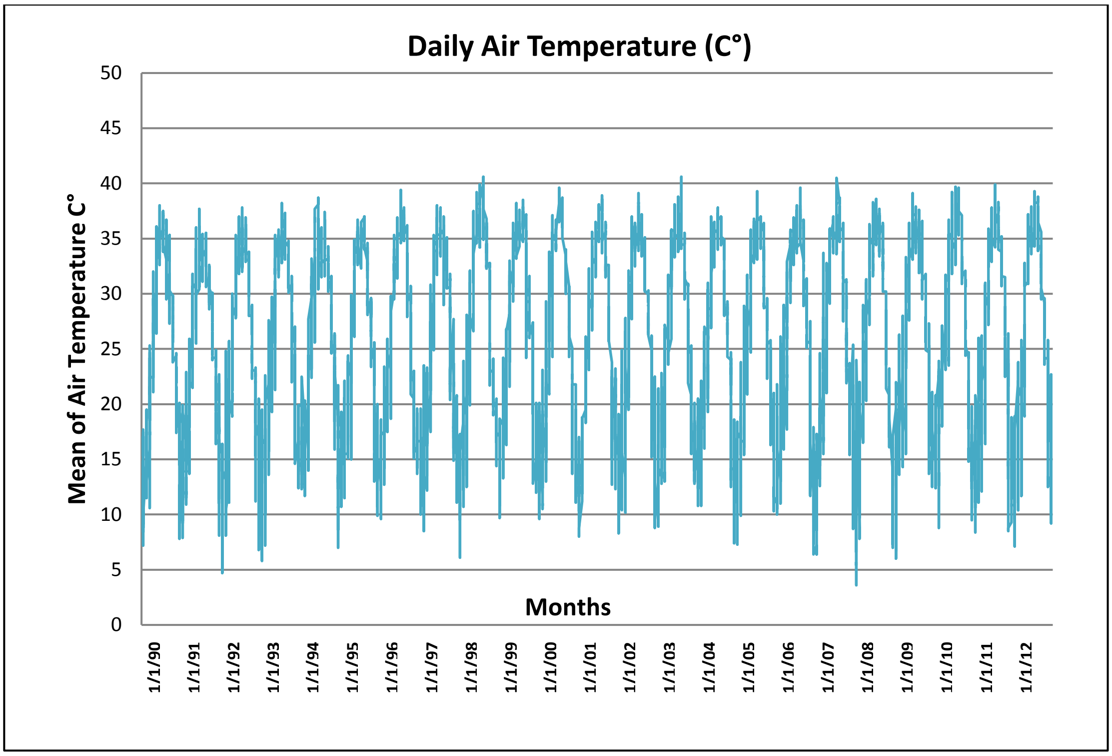



Figure 2-10 Average daily air temperature (1990-2012) in the Riyadh weather station (PEM, 2013)

### 2.7.6 Relative Humidity, Sunshine Duration and Wind Speed

The relative humidity of the city varies between 14% in dry summer and 70% in wet winter, with an annual mean of approximately 36% (Alnaizy & Simonet, 2012)(Figure2-11).

The sunshine duration varies between 6.5 hours in December and 10.1 hours during June (Qureshi & Khan, 1994). The lowest mean wind speed is 4.16 km/h in December and the highest is 6.12 km/h in July (PEM,2013).

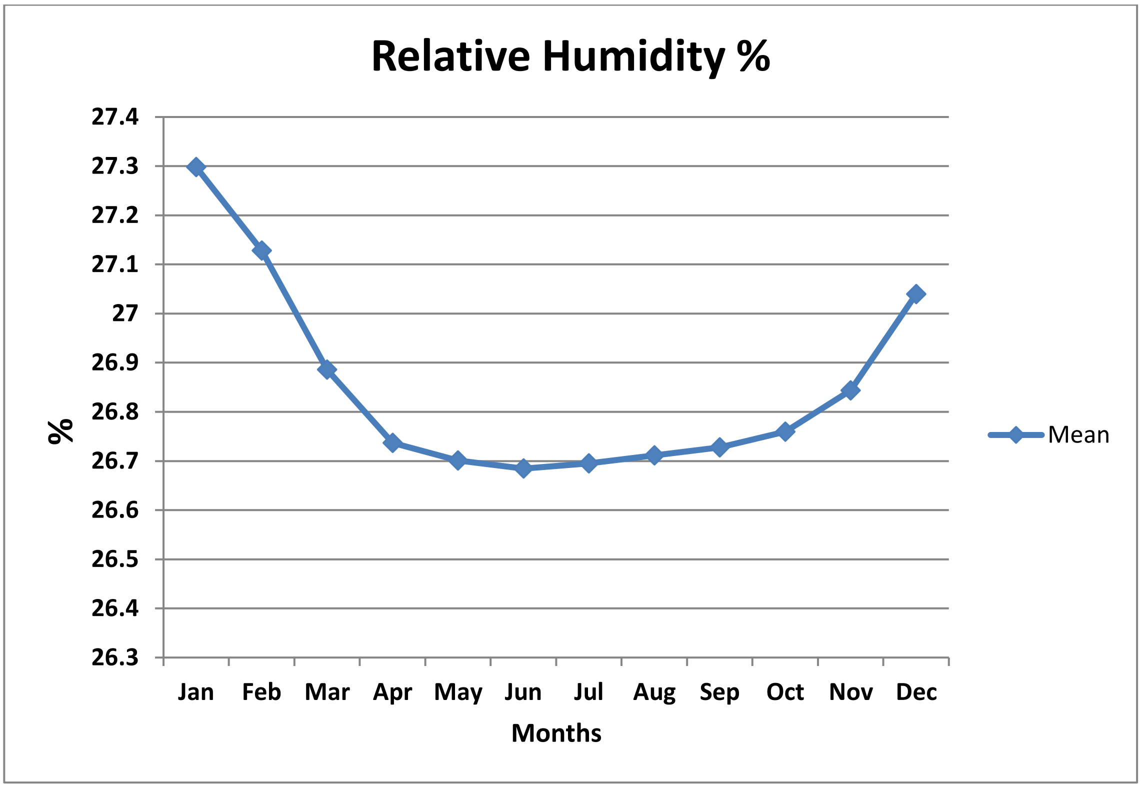



Figure 2-11 Monthly mean relative humidity in Riyadh city( PEM,2013)

### 2.7.7 Evapotranspiration

Riyadh has dry climate that leads to high evaporation and evapotranspiration. The average annual potential evaporation in the city is approximately 3429 mm, and the monthly average is recorded at 286 mm. The minimum evaporation of about 100 mm is estimated in December and the maximum of 287 mm in July (First Climate Change Report of KSA, 2005).

Figure 2-12 shows the potential evapotranspiration for Riyadh calculated using the Jensen-Hasie method. This method (Jensen–Haise, 1963) is one method to calculate potential evapotranspiration by using climate data.

Salih and Sendil (1984) proposed an empirical relationship for estimating a better local potential evapotranspiration value based on estimating potential evapotranspiration (PET) using the Jensen-Hasie method.

Jensen-Hasie (1963) potential evaporation, $ET_{JH}$ in mm/day, is calculated as follows:

$$ET_{JH} = (0.025T_a + 0.08)\frac{R_s}{28.6} \qquad \textbf{( 2.1)}$$

where $R_s$ is the incoming short wave radiation in W/m$^2$ and $T_a$ is the average air temperature at 2m height above ground surface in $^oC$.

Salih and Sendil (1984) compared several methods for estimating potential evapotranspiration ($ET_0$) in the Kingdom of Saudi Arabia and though their method has similar assumptions and limitations as for other methods including Hargreaves, Penman and modified Penman methodologies, it has the advantage that it has been developed specifically for Saudi Arabia. Their equation for potential evapotranspiration ($ET_0$) is:

$$(ET_0)\ (mm/day) = 1.16\ (ET_{JH}) - 0.37 \qquad (mm/day) \qquad \textbf{( 2.2)}$$

where : ($ET_{JH}$) is mean daily potential evapotranspiration estimated by Jensen-Hasie method. This equation has been recommended for predicting evapotranspiration in irrigation areas, from Salih and Sendil (1984) estimates, for regions similar the study area. Salih and Sendil (1984) have recommended this equation to estimate the potential evapotranspiration under extremely arid conditions, after examining results obtained from measured evapotranspiration and by comparing and evaluating five selected empirical estimation methods using climatic data collected from four observation stations within central region of Saudi Arabia. This empirical relationship has been used in the current study. Potential evapotranspiration (PET) includes the amount of evaporation and transpiration from the soil and plant surfaces provided that there is a continuous supply of water for these two phenomena to take place. In case of insufficient water supply, the plants cannot take enough plant water, and therefore, the actual evapotranspiration (AET) from soil surface and plants is less than PET. AET is estimated in the model by multiplying the PET by factor. This is discussed in Section 4.4.8.

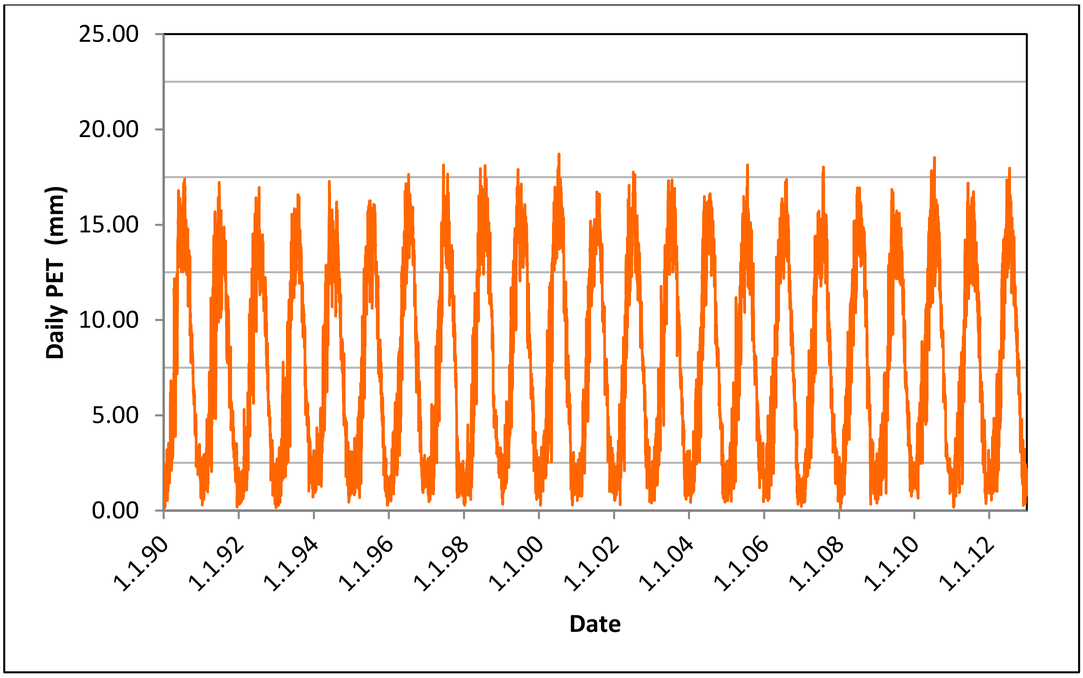



Figure 2-12 Daily potential evapotranspiration (Jensen-Hasie) in the Riyadh Weather Station (1990-2012)

## 2.8 Water in Riyadh

### 2.8.1 Introduction

It is needed to describe the water system of Riyadh as this will be taken into account in the model.

The water system in the Riyadh-Wadi Hanifah area is complex. Figure 2-13 shows a flow diagram for water flow dynamics, including water supply system, groundwater recharge, water demand, hydrological and sewage components. In the following subsections further details of the water supply, sewerage system, urban drainage system and the surface water runoff are described in turn.

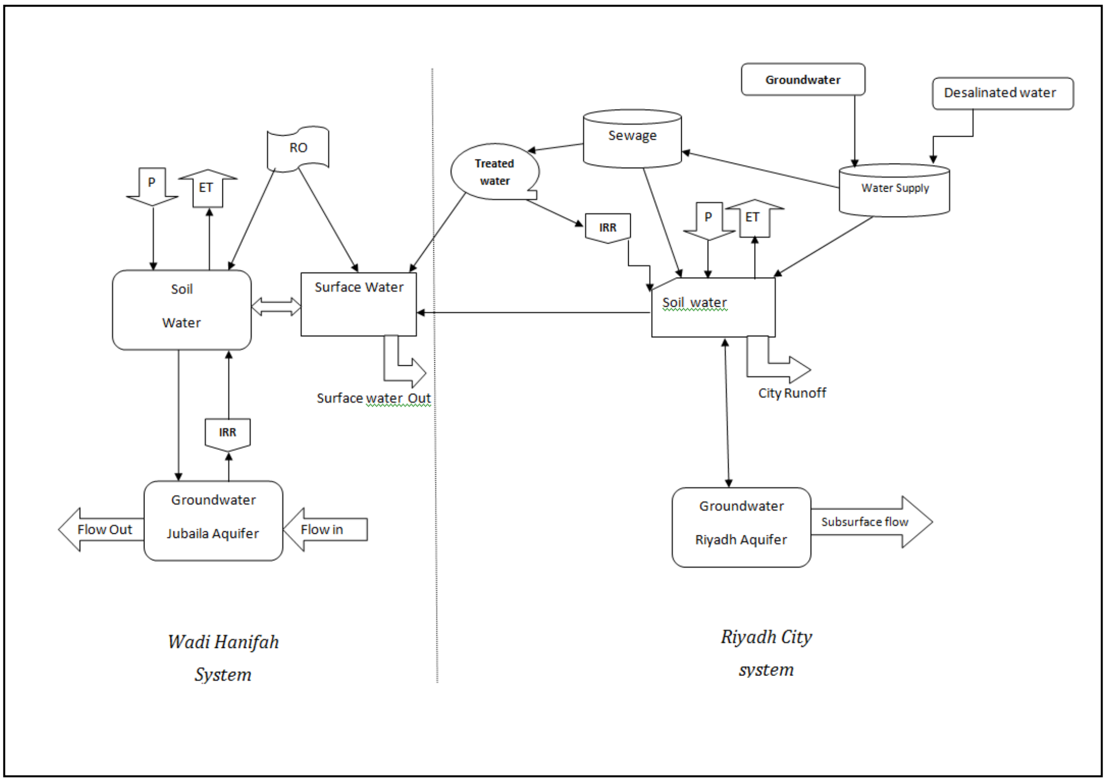



Figure 2-13 Riyadh City-Wadi Hanifah water supply model system

## 2.8.2 Water Supply

Riyadh city gets its supply water from two main resources: first desalinated water from Eastern Coastal areas; and secondly groundwater from deep aquifers. The desalinated water is transported by a pipeline system at a rate of about 1.2 million m3/day (ILF, 2009).

The Saline Water Conversion Corporation (SWCC) treats sea water in several desalination plants using the Multi Stage Flush System (Abderrahman, 2006), and transported via several independent pipeline systems over 1000 km through the desert to Riyadh City (Figure 2-14), where it is stored in reservoirs and fed into the distribution system. The desalinated water is transported via a 1.8 metre diameter pipe system (SWCC, 2013).


Figure 2-14 Riyadh Water Transmission System Map (ILF,2009)

Groundwater comprises about 1/3 of total water supply, and is pumped from aquifers at Minjur, Wasia, Nesah, Nemar and Al-Hair 110 km to the southeast (Al-Othman, 2011). Within the city, the networks of water supply leak to soil around 30% of total domestic water supply (Al Zahrani, 2009).

The groundwater pumped to Riyadh city comes from four water supply projects near city. About 80,000 cubic metres per day is pumped from two fields of deep wells tapping the Minjur Aquifer 60 km north of city. The Bowaib Water Project consists of 18 wells and the second, the Salboukh well field, includes cooling towers, a filtration plant, a desalination plant and precipitation tanks.

The third well field gets groundwater from the Wasei Aquifer situated 110 km east of Riyadh. It comprises 62 wells, with a capacity of 200,000 cubic metres per day. The well field includes storage tanks, pipelines, pumping stations, filtration plant and a plant for generating electricity.

In 2005 new deep wells fields were constructed to pump water from the Umm Er Radhumah aquifer 218 km to the east of city. These supply around 340,000 cubic metres per day (Abderrahman, 2006).

In addition to the public water supply network, there are also other sources of water for the city, including catchment tanks and wells (Table 2-2). In totals, these supply only about 3% of the population.

Table 2-2 Source of Water Supply in Riyadh city (CDSI, 2010)

| Riyadh City | Source of Water Supply | | | | Total ($m^3$/day) |
|---|---|---|---|---|---|
| | Public Network ($m^3$/day) | Catchment Tank ($m^3$/day) | Well ($m^3$/day) | Other ($m^3$/day) | |
| Housing Units | 824011 | 29679 | 3369 | 787 | 857846 |
| Persons | 4846155 | 146645 | 12085 | 3001 | 5007886 |

### 2.8.3 Sewerage System

Table 2-3 lists the types of sewage disposal in Riyadh. Sewerage networks cover 72% of city area, serving around 621947 out of 857846 housing units (CDSI, 2010), septic tanks being used in the new residential areas to discharge wastewaters. The sewers leak at a rate of about 35% (Elhadj; 2004 ), and most of the water in septic tanks infiltrates into the ground.

Table 2-3 Type of Sewage Disposal in Riyadh city (CDSI, 2010)

| Riyadh City | Type of Sewage Disposal | | | | Total ($m^3$/day) |
|---|---|---|---|---|---|
| | Public sewage ($m^3$/day) | Ditch ($m^3$/day) | Private Sewage ($m^3$/day) | Other ($m^3$/day) | |
| Housing Units | 621947 | 227155 | 6047 | 2697 | 857846 |
| Persons | 3615630 | 1353521 | 30559 | 8176 | 5007886 |

The city sewerage networks and thousands of tank trucks transfer the sewage water to the five centralized sewage treatment plants in Riyadh. The capacities of these range between 3000 $m^3$/day and 200,000 $m^3$/day and the total daily capacity of plants is 634,000 cubic metres/d (Abderrahman, 2006). There are also 77 decentralized treatment plants and these have a total capacity of 178,000 $m^3$/day (MWE, 2006b). In addition an extension to the Northern Riyadh Wastewater Treatment Plant provides another 100,000 $m^3$/day capacity. The total daily capacity of plants is around 912,000 cubic metres. In the future, there are plans to expand the treatment plants to 1,200,000 $m^3$/day, and replace three existing treatment plants. The proposed sewage treatment plants are tertiary treatment, each plants has an average capacity of 400,000 $m^3$/day with an peak capacity of 640,000 $m^3$/day.

The treated water is discharged to Wadi Hanifah, about 170,000–200,000 $m^3$/day being used for landscaping and agricultural irrigation in city, and 15,000–20,000 $m^3$/day being used by industries (Al-Jasser, 2010).

### 2.8.4 Subsurface Network

A gravity drainage network was built to discharge leakage from domestic networks in the city to Wadi Hanifah for lowering the water level in the soil under the city. This network was designed and built at 5 metres depth below ground surface. It has been constructed at locations where the groundwater reached near to ground surface. ArRiyadh development Authority (ADA) has built 23 major drainage projects covering a distance of 217 km to lower and keep the water level to a safe level, that is, below the foundation level (Al-Othman,2011).

The network was designed as horizontal drains collecting water under the gravity action. Also, the drains were designed to collect storm water generated due to infrequent precipitation events. Figure 2-15 shows the elements of the network. The horizontal pipes receive percolated water by gravity action, with perforation of the top half of drains. The surface wells contacted with the upper end of vertical shaft at specified locations and linked with the existing network of horizontal drainage pipes. There are inlets at ground surface to collect storm water and flush the horizontal drainage system.

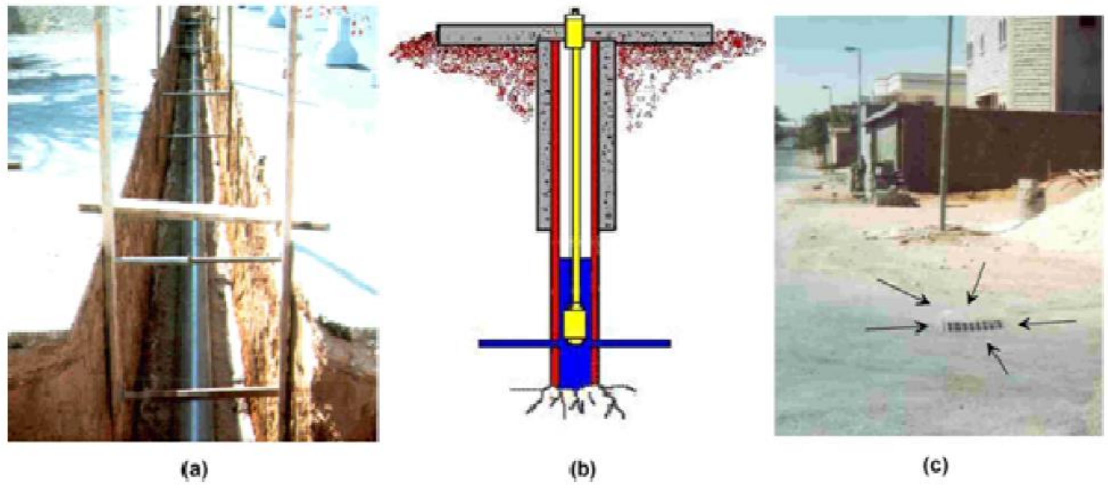



Figure 2-15 Gravity drainage network (a) half perforated horizontal pipe; (b) vertical shaft; (c) surface inlet.(Al-Othman;2011)

The accumulated water from horizontal pipe flows through gravity as open channel flow and is collected at two pumping stations and discharged to Wadi-Hanifah through two giant open channels.

### 2.8.5 Surface Water

The catchment area of wadi Hanifah covers an area about 4400 $km^2$. There were no permanent surface water flows in main channel of wadi Hanifah under natural conditions, and no known reports of springs or seepages, but there are anecdotal reports of springs downstream of wadi Hanifah in the 1960s (ADA,2002).

Since the early 1980s, there has been permanent dry weather flow in the lower parts of the wadi assumed to be resulting from urban discharges of sewage water, agricultural water, seepage losses and leakage from water supply systems. The main source of surface water probably comes from treated wastewater discharges from wastewater treatment plants Riyadh.

During the mid-1990's, volumes of water adding to surface water flow in wadi come from the rising groundwater management network (ADA, 2002). One million cubic metres per day of surface water flows along the main drainage channel known as the "Wadi Hanifah Stream"(Al-Othman, 2008) (Figure 2-16).


Figure 2-16 Wadi Hanifah Stream (ADA,2002)

Flood flows occurs every few years during high rainfall events, these being natural phenomena of the wadi system and can be dangerous and can cause damage. On the other hand, flood water can be advantageous in resulting in recharge and in transporting silt to fields (ADA, 1990).

### 2.8.6 Groundwater

There are insufficient water level data from Riyadh to construct any piezometric level maps. So this section can only be qualitative.

The groundwater level data that do exist suggest that there is water in the urban reach of wadi Hanifah and it is assumed it flows down hydraulic gradient towards the southeast. Below the wadi below the upper low permeability little fractured upper part of the Jubaila Formation there is groundwater probably flowing towards the south. The upper part of the Jubalia Formation has low permeability or very low permeability (ADA;2002) and the amount of recharge from the wadi sediments through these low permeability units is uncertain but the deep wells have water levels below the water level in the wadi sediments. The wadi surface waters are perennial because of waste water discharge, and it is assumed that the wadi sediments also receive much water through waste water discharge too. They will also receive water from the catchment to the west from runoff, shallow subsurface flow and tributaries flow but no data on this.

The soils under the city get recharge from all the leakaging from the urban pipes and also rain. As this soil develops on a topographic slope to the south and east the flow is assumed to go to the south and east. At depth below the city there is the Riyadh Aquifer(Arab Formation). This starts in the city so flow is only to the south and east. All this assumptions will be put together in Section 2.10 but first the chemistry will be looked at to get if any more information on sources of water and flows can be determined.

## 2.9 Water Chemistry

### 2.9.1 Introduction

Chemical analysis data for groundwater in the study area are presented in Table 2-4. These data include analyses for four different types of water: 1) surface water, 2) city groundwater (Riyadh aquifer), 3) wadi soil water (i.e. the groundwater in the wadi sediments), and 4) wadi groundwater (Jubaila aquifer). The data are few. The different waters are presented in a Piper diagram in Figure 2-15 which indicates the waters are similar in chemistry with the possible exception of the city groundwater. The samples are collected from a set of pumped, monitoring, shallow wells mainly within the Wadi Hanifah the Quaternary deposits.

### 2.9.2 Water chemistry interpretation

#### *2.9.2.1 Precipitation water data*

The chemical analysis of rain water over Riyadh city are reported by Alabdulaäly and Khan (2000). The twenty-three samples of rainwater were collected in March and April 1994. The results (Table 2-5) show the rain water is slightly alkaline with a mean pH value of 7.6 and a TDS of 154 mg/l. The average concentrations of the major ions Ca, Na, $SO_4$ , Cl and $NO_3$ are 51, 6.0, 33, 17 and 4.3 mg/l. These values are all rather high compared with analyses from many parts of the world, and may include dry deposition as well as wet deposition. However, they are also much lower concentration than groundwaters. Calculations using phreeqc (Parkhurst et al., 2011) indicate that simple evapotranspiration of these rain fall waters will not produce the same chemistry as the groundwaters indicating dissolution is also important.

Table 2-4 Chemical analyses of groundwater, soil water and surface water
(ADA;1990, 2005, 2008, 2009, 2010), (Hussein ,2012) Al-Othman (2008), (Al-Ghanim & Al-Akel ;2008), (Al-Arifi et al. ,2013) and (Loni et al. ,2013).

| **ID** | **Date** | **pH** | **E.C. (µS/cm)** | **TDS** | **$HCO_3$ mg/l** | **Ca mg/l** | **Cl mg/l** | **Mg mg/l** | **$NO_3$ mg/l** | **K mg/l** | **Na mg/l** | **$SO_4$ mg/l** | **Water Sources** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Dec-05 | 7.9 | 2674.3 | 1998.7 | 311.3 | 269 | 406 | 63 | 3.3 | 15 | 299 | 700 | Surface water |
| 2 | Dec-06 | 7.8 | | 3269.2 | | 1027 | 63 | 483 | 128 | | | 117 | |
| 3 | May-08 | 7.9 | | | 250 | 355 | 400 | 102 | 90 | 20 | 450 | 900 | |
| 4 | Dec-06 | | 3960 | | 228 | 464 | 407 | 120 | | 17 | 254 | 1276 | City Groundwater (Riyadh aquifer) |
| 5 | Jun-11 | | | | | 437 | 580 | 120 | 140 | 18 | 310 | 1100 | |
| 6 | Mar-07 | | 3960 | | 247 | 154 | 285 | 64 | 63 | 7.2 | 162 | 337 | Wadi Soil water |
| 7 | Jun-08 | | | | 222 | 185 | 399 | 88 | 41 | 7.6 | 238 | 537 | |
| 8 | Sep-09 | | | | 252 | 172 | 347 | 98 | 90 | 8 | 215 | 534 | |
| 9 | Sep-10 | | | | 269 | 408 | 884 | 162 | 95 | 8 | 449 | 1038 | |
| 10 | Oct-90 | | | | 226 | 168 | 302 | 69 | 102 | 7.5 | 172 | 370 | Wadi Groundwater (Jubaila aquifer) |
| 11 | 2005 | 7.3 | 4759.1 | | 381 | 453 | 864 | 142 | 30 | 14 | 665 | 1262 | |
| 12 | Jun-08 | | | | 221 | 185 | 396 | 88 | 48 | 7.6 | 238 | 537 | |
| 13 | Sep-09 | | | | 322 | 327 | 675 | 129 | 2.6 | 9.6 | 317 | 737 | |
| 14 | Sep-10 | | | | 163 | 176 | 511 | 104 | 60 | 7.3 | 312 | 609 | |
| 15 | 2011 | 7.2 | 4001.37 | | 180 | 309 | 1193 | 173 | 18 | 9.0 | 680 | 1057 | |
| 16 | Dec-12 | | | | 299 | 230 | 490 | 87 | | 7.8 | 260 | 494.4 | |

Table 2-5 Chemical analysis of rain water over Riyadh city (11–16 March 1994) (Alabdulaäly& Khan ,2000)

| Location | | Cond. | Parameter (mg $L^{-1}$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number | pH | (ms/cm) | TDS | Alkalinity | Hardness | Ca | Mg | Na | K | $NO_3$ | Cl | $SO_4$ | F |
| 1 | 7.42 | 0.25 | 136 | 46 | 114 | 43.0 | 1.46 | 9.62 | 1.25 | 3.40 | 23.70 | 27.96 | 0 |
| 3 | 7.57 | 0.30 | 146 | 70 | 126 | 46.4 | 2.40 | 6.44 | 3.88 | 0.25 | 17.13 | 26.70 | 0.05 |
| 4 | 7.54 | 0.21 | 118 | 70 | 104 | 39.2 | 1.58 | 5.68 | 1.04 | 0.38 | 10.73 | 18.73 | 0 |
| 5 | 7.78 | 0.29 | 140 | 104 | 135 | 52.1 | 1.12 | 3.12 | 0.65 | 1.90 | 6.80 | 17.43 | 0 |
| 8 | 7.53 | 0.17 | 86 | 54 | 75 | 28.8 | 0.77 | 2.55 | 0.67 | 1.55 | 4.39 | 15.49 | 0 |
| 10 | 7.71 | 0.23 | 136 | 76 | 121 | 44.0 | 2.60 | 7.24 | 1.21 | 0.47 | 13.82 | 22.88 | 0 |
| 11 | 7.04 | 0.27 | 156 | 80 | 141 | 53.0 | 1.90 | 4.32 | 1.00 | 12.78 | 8.68 | 30.95 | 0.15 |
| 12 | 7.38 | 0.26 | 152 | 64 | 134 | 49.6 | 2.43 | 7.62 | 1.34 | 1.84 | 18.05 | 29.87 | 0.12 |
| 13 | 6.94 | 0.48 | 282 | 26 | 229 | 87.0 | 2.86 | 11.46 | 2.15 | 16.91 | 54.10 | 90.40 | 2.13 |
| 14 | 7.49 | 0.35 | 172 | 74 | 192 | 60.0 | 2.15 | 4.64 | 1.80 | 0.22 | 7.69 | 53.77 | 0.34 |
| 15 | 7.14 | 0.29 | 168 | 76 | 140 | 53.0 | 2.00 | 3.05 | 1.08 | 7.18 | 26.22 | 27.71 | 0.03 |
| Average | 7.41 | 0.28 | 153.8 | 67.3 | 137.4 | 50.56 | 1.93 | 5.98 | 1.46 | 4.26 | 17.39 | 32.9 | 0.26 |
| SD | 0.286 | 0.081 | 48.72 | 20.17 | 41.67 | 14.68 | 0.647 | 2.845 | 0.916 | 5.679 | 14.05 | 21.65 | 0.63 |
| Median | 7.49 | 0.27 | 146 | 70 | 134 | 49.6 | 2.0 | 5.68 | 1.21 | 1.84 | 13.82 | 27.71 | 0.032 |
| CV% | — | 2.89 | 31.7 | 30.0 | 30.3 | 29.0 | 33.5 | 47.6 | 62.7 | 133.3 | 60.8 | 65.6 | 242.3 |

SD = standard deviation, CV = coefficient of variation

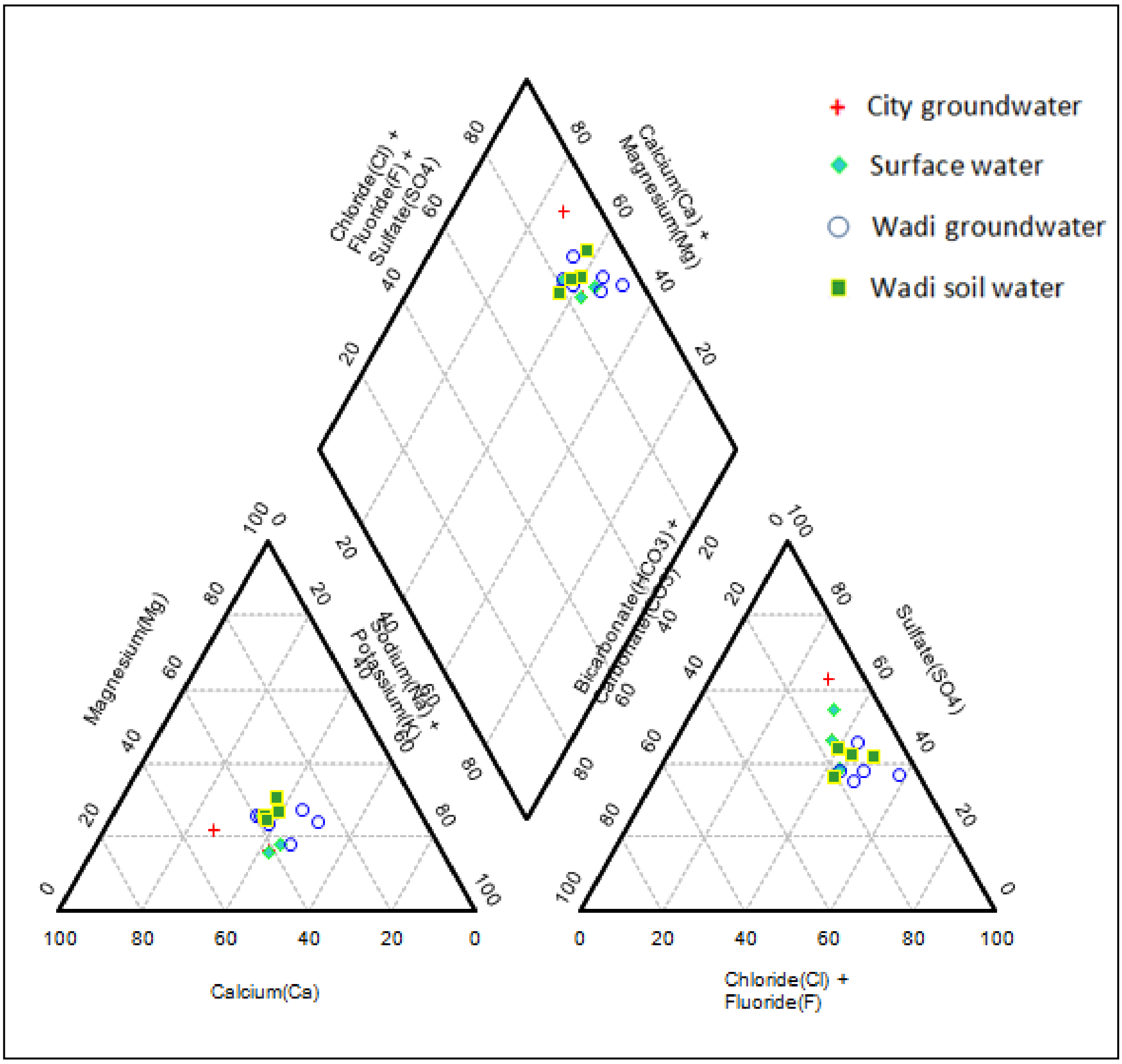



Figure 2-17 Piper diagram for all water samples in the study area

#### ***2.9.2.2 Surface water data***

The surface water data, as can be seen in Table 2-2, shows that the three waters have very different concentrations and they are very variable in values. TDS value for sample 2 have much higher TDS value than samples 1 and 3. Sample 1 has low $NO_3$ concentration but the concentrations of Cl and $SO_4$ are relatively high. Sample 2 has a very high concentration of Ca and it is almost three times as much as Ca concentration in sample 1 and sample 3. Sample 3 has high concentration of Cl, $NO_3$ and $SO_4$. The concentration of $SO_4$ in two samples are high but one sample (2) is low, suggesting a range of concentrations can occur. Al-Othman (2008) has studied the surface drainage water from 31 locations exists along the stream of Wadi Hanifah and the general conclusion was that that the surface water is of mainly Na, Ca and $SO_4$ dominated water. The high value of salinity and TDS for surface water would have a negative effect on all water usage in the wadi Hanifah. Using surface water (stream water) for prolonged irrigation in wadi Hanifah was predicted on soil salinity and the sodium hazards (Al-Othman, 2008).

#### ***2.9.2.3 Wadi soil water***

The wadi soil water samples presented in Table 2-4 are collected from depths between 8 and 20 m, the shallowness of which would increase the likelihood of contamination and evaporation. It might also mean that representative concentrations for the whole thickness of wadi sediments represented in the model is not available. Cl and $SO_4$ concentrations are relatively high (up to 880 mg/l for Cl and over 1000 mg/l for $SO_4$). Pollution may be the cause but often even in non-urban wadis Cl and $SO_4$ can be high. High evaporation rates might too increase Cl and $SO_4$, and extreme evaporation may cause precipitation of salts that are then dissolved by the first flush of a new recharge event (e.g. Drever and Smith, 1978).

The three lowest Cl concentration samples have Na:Cl molar ratios close to 1:1. However, the highest concentration Cl has a lower Na molar concentration value than the Cl. This is most likely due to cationic exchange when with the more NaCl rich water invading part of the aquifer previously containing fresher, higher Ca/Na waters.

Cl: $SO_4$ ratio and Ca and Mg has a similar distribution to Na:Cl, and this may be due to the similar source. It can be noticed a high $NO_3$ concentration in almost all samples suggests contaminated waters, and $SO_4$ reduction is therefore unlikely too. The waters are well under-saturated with respect to gypsum according to calculations using phreeqc, except for one sample. $SO_4$ is therefore a conservative species other than where precipitation occurs. Ca is controlled more by $SO_4$ than $HCO_3$.

$NO_3$ concentrations indicate pollution as expected in this shallow system. There is one site with extreme $NO_3$ value so a probably local pollution source.

The wadi sediment groundwaters have concentrations similar to other wadi groundwaters in Saudi Arabia (Subyani,2005).

#### ***2.9.2.4 Wadi groundwater data (Jubaila Aquifer)***

The water samples for this aquifer were collected from wells with an average depth of 100m. The deep water might suggest the ion concentration in these samples are not related to shallow contaminated horizons. However, there is a good hydraulic connectivity with shallow aquifers which might be the source of high concentrations of $NO_3$, $SO_4$ and Cl. The concentrations of these waters are presented in Table 2-4 and great variation in concentrations between samples can be noted. There is no obvious overall trend with time. This suggests an active system so connections with recharge from wadi sediments or may be different waters in the system being mixed in different proportions depending on pumping conditions.

The range of Cl and TDS is similar to the Cl and TDS range in the wadi soil groundwater which may indicate similar source. The Piper diagram in Figure 2-17 indicates that the proportions of ions are similar too.

The Na/Cl molar ratios are close to 1 suggesting that the source might be NaCl. There appears to be possibly two groupings of waters one with higher Cl, gap being between about 700 mg/l and about 860 mg/l. This may relate to source or process or may be coincidence. The high Cl concentration corresponds to high $SO_4$ concentration, which might suggest that these anions come from the same source or are affected by the same process.

It could be Cl and $SO_4$ come from dissolution of evaporites in the rock, especially where it is overlain by the gypsiferous limestone of the Arab Formation (Section 2.5.2). May be variation in concentrations seen is mixing in well between the two waters – lower and higher Cl.

It can be noted also that Cl and $NO_3$ concentrations are inversely related. Cl and $SO_4$ may come from natural sources such as dissolution of anhydrite and gypsum (Hussein et al., 2012), while $NO_3$ comes from human activates like urban or fertilizer pollution.

However, all samples contain some $NO_3$ that could suggest that all samples are polluted due to human activates. This is an important observation as there is little source for $NO_3$ except through vertical movement from the wadi sediments above hence proving that this connection exists. The inverse relationship between Cl and $NO_3$ suggest that the higher Cl water is older (contains less pollution) or coming through a less polluting pathway.

The high $NO_3$ in most of the samples suggests contaminated waters, and therefore $SO_4$ reduction also is unlikely so $SO_4$ is likely to be a conservative species in the deep aquifer system too. The higher Cl is generally associated with higher Ca and Mg and also commonly higher $HCO_3$, and again this may be due to precipitation and redissolution of carbonates ($CaCO_3$ and $MgCO_3$ but not dolomite as it takes too long to precipitate) and Ca $SO_4$.

#### *2.9.2.5 <u>City groundwater data (Riyadh Aquifer)</u>*

The molar ratio of Na/Cl is approximately 1 which suggest that the source of Na and Cl is the same and no ion exchange took place .This waters, as can be seen in Table 2-4 and Figure 2-17, are rather different from the other waters. There are much more $SO_4$ and Ca than for the groundwater and wadi soil water. The presence of anhydrite deposits belonging to the Hith Formation (Section 2.5.4) is likely to be the source of high Ca and $SO_4$ concentrations in the Riyadh Aquifer. The water samples of the Riyadh Aquifer are collected from depths between 200 and 1100 m (Table 2-4) and they are all approximately saturated with respect to gypsum. The deep origin of water samples suggests that the samples are representative for the aquifer. Also, the presence of anhydrite and the saturation with respect to gypsum support the assumption that elevated Ca and $SO_4$ concentration are due to the anhydrite deposits. $NO_3$ concentration is much greater than the wadi soil water and groundwater. Therefore, the source is most likely to be from pollution. The high $NO_3$ in almost all samples suggests contaminated waters, and $SO_4$ reduction is unlikely again. K is also much higher than for the other waters which might be another indicator of pollution.

### 2.9.3 Conclusion

The aforementioned details conclude that there are a great range of water chemistries in all parts of the system time, and indicates dynamic nature of the system, or perhaps a very heterogeneous solute source distribution which is then mixed by pumping. Soil water and groundwater in wadi Hanifah area, are in general terms quite similar suggesting a connection and therefore the soil might feed deep groundwater. Certainly the deep groundwater has $NO_3$ in it that means that it probably came from the wadi as other routes of pollution are more difficult to imagine. However, city groundwater has much higher Ca, $SO_4$, $NO_3$, and K in relation to Cl than the other waters suggesting a different sources or mechanisms. But again it has $NO_3$ suggesting urban polluted waters recharge the deep aquifer.

All waters show natural (e.g. gypsum, halite, calcite and probably dolomite) and anthropogenic influences (i.e. $NO_3$ from urban sewage water) on groundwater quality. To some extent as one increases the other decreases may be reflecting older and more recently recharged waters. Even deep aquifer groundwater has $NO_3$, indicating the penetration of urban pollution (i.e. recently recharged waters) to depth. The high $NO_3$ in almost all samples suggests contaminated waters, and $SO_4$ reduction is unlikely so $SO_4$ is likely to be unreactive other than sometimes precipitating.

The surface waters are even more variable than the groundwaters. Ignoring one sample with a chemistry that is very different (high Ca and low $SO_4$) the other samples have a composition that is within the range of the groundwaters and a chemistry general similar (oxic, $NO_3$-containing). So looks like it is consistent that surface and groundwaters are all influenced by urban discharge water. Unfortunately no discharge water analyses are available.

In conclusion all waters are influenced by urban waste water even deep groundwaters but there may also be some effects of evaporation and evaporite dissolution. All waters sampled are contaminated and sulfate is likely to be unreacting except for precipitation.

## 2.10 Initial Conceptual Model of the Riyadh System

Figure 2-18 shows the initial conceptual model for the Riyadh- wadi area. The main features of the model are described below.

Wadi Hanifah sediments are present up to 20 m thick along the line of the valley. The valley has tributary valleys, some of which have some sediments in them. The rest of the catchment of the wadi to the west is weathered limestone of the Jubaila Formation that is expected to have a reasonable permeability to very shallow depths below which permeability is much lesser due to few fractures. However, around the wadi there is evidence that the Jubaila Formation is fractured and hence of slightly greater permeability. The wadi sediments receive recharge from the natural catchment to the west either through the tributary wadi alluvium or through the shallow weathered parts of the Jubaila Formation or through runoff in high intensity storms. Also recharge is possible from upstream sediments in the main wadi valley. The wadi sediments are also recharged through urban waste water discharge through the treatment works.

Some interaction between the wadi river and the sediments is expected too but direction is uncertain. Recharge also comes from irrigation from wells in the wadi sediment and also from the underlying Jubaila Aquifer (see below). Discharge is to downstream wadi sediments, to abstraction wells, to evapotranspiration, and to leakage through the low permeability upper Jubaila Formation limestones to the Jubaila Aquifer.

Below the fractured zone around the wadi sediments, the Jubaila Formation is of low permeability until its lower part and in the lower part it is higher permeability, more fracturing being present. This deep aquifer, the Jubaila Aquifer, receives water from the wadi sediments through the overlying little fractured upper part of the Jubaila Formation.

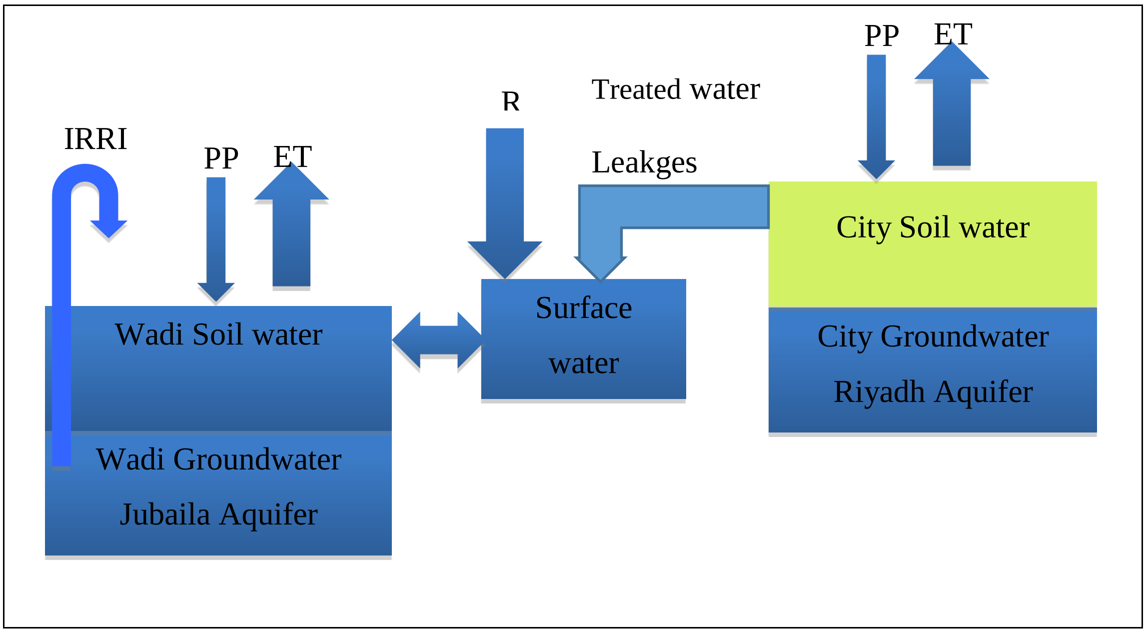



Figure 2-18 Initial conceptual model for the wadi Hanifah-Riyadh area

The river in the wadi only flows continuously from the point where it receives urban water discharge from drain systems and from the treated effluent discharge. There may be some flow from and to the wadi sediments. There is also flow from runoff during the most severe storms from the catchment to the west and from upflow. The catchment to the southwest is assumed to have a weathered zone near surface that is probably of greater permeability than the deeper limestone. However, no information on the depth or permeability of the weathered zone has been found. Discharge of the river occurs to downstream of the urban part of the wadi. At lowest flows there is some water retained in the wadi river by check dams across its channel. At rainfall times the whole of the wadi floor can flood. Evaporation occurs from the river surface.

Below the city area to east of the wadi Hanifah, there is a city soil zone that receives water from rainfall, water supply pipes leakage, and sewer leakage. When water levels are high enough, discharge occurs to the deep (5m) drainage networks in the city that discharge to the river in the wadi and also into sewers. It also occurs to city runoff that discharges to the east. Discharge also probably occurs to the deep Riyadh Aquifer below the city. The flow in the Riyadh Aquifer flows to the east away from the wadi Hanifah.

For most of the time the flows in the wadi river are maintained by urban discharges. Rainfall occasionally is sufficient to cause flooding, but probably main source of water in the system is the imported water from distance aquifers and from desalination plants as a result of leaking water pipes and sewers or discharges from treatment works. Evaporation is very big and removes much water but perhaps not much solute from the shallow system.

# CHAPTER 3: STELLA MODELLING

## 3.1 Background

System dynamics (SD) is an approach used to understand the nonlinear behaviour of complicated systems over time. The concept of SD was originated from the applications of engineering control system theory and the theory of information feedback systems. Forrester (1961) first proposed the idea of SD in 1956 to support corporate managers to increase their comprehension of industrial processes. In the late 1960s, scientists on other fields begun to use SD in their respective fields for policy analysis and design (Radzichi and Taylor, 2008). With time it has become a unique, powerful simulation modelling methodology, especially for studying dynamic characteristics of large complex systems. Nowadays, SD is widely used in policy and decision making analysis for complex physical, environmental, economic or social systems. Particularly, it is very popular tool used to identify the options or strategies to deal with multi-phase complex problems, and assessment of severity and timing of impacts in response to actions.

System dynamics assumes that the macro behaviour of a system is primarily determined by its internal micro structure or objects. Identification of relationships between different objects within a system, is the base of the method (Elshorbagy et al., 2005). Therefore, the core of SD system structure is composed of feedback loops that integrate the fundamental state constituents as rate, and information (Figure 3-1). All concepts in the system are considered by SD as continuous quantities, circular causality and interconnected in loops of information feedback. It can identify independent accumulations of entities in the system and their inflows and outflows, in addition to formulation of a behavioural model, which is capable to reproduce by itself (Forrester, 1961; Sterman, 2000; Simonovic, 2009).

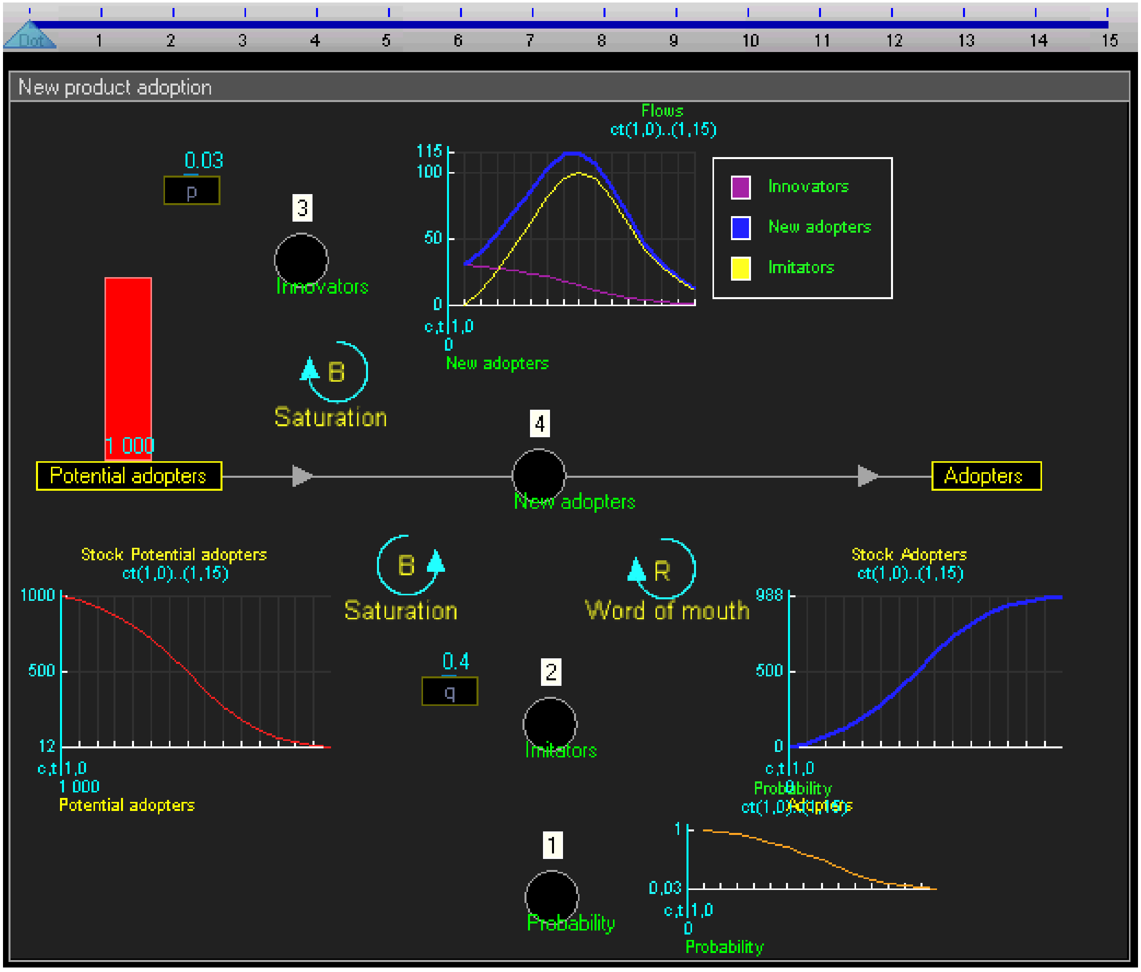



Figure 3-1 New product adoption model show dynamic stock and flow diagram (Forrester,1971)

## 3.2 Application of SD in Ecosystem and Groundwater Modelling

SD was initially developed for solving problems in industrial systems. In recent years, it has been widely applied to solve a wide range of dynamic problems arising in complex ecological, managerial, social, economic or any other systems described by information feedback, mutual interaction, interdependence, and circular causality. In ecosystem modelling, SD was first applied by Gutierrez and Fey (1980). They developed an ecological dynamic model using SD for the management of the environment systems and natural resources. In recent years, SD has been applied in several areas of ecology and water resources studies, including environmental sustainability (Xu et al., 2002; Yu et al., 2003), water resources policy planning (Winz et al., 2009; Ahmed and Simonovic, 2004), reservoir operation (Ahmad and Simonovic, 2000), urban dynamics (Forrester, 1969), and water resources management (Gastelum et al., 2009; Simonovic and Rajasekaram, 2004; Madani and Marino, 2009). Simonovic and Fahmy (1999) used SD in water resources policy analysis and planning for the Nile River basin for long-term. Guo et al. (2001) considered SD for environmental policy planning in China. SD model has been used as well by Leal Neto et al. (2006) for environmental controlling of Sepetiba Bay Watershed, Brazil. SD employed to develop a integrated water resources management (IWRM) model for Canada by Simonovic and Rajasekaram (2004). Moreover, overlapping in time with the present study, Qi and Chang (2011) adapted SD to estimate water demand in Manatee County of Florida. Furthermore, Karamouz et al. (2011) used SD to model water resources in Daranjir basin of Iran.

Application of SD in groundwater simulation and management has been reported by a number of authors. Tellam et al. (1996) used it in the context of groundwater flow in wetland systems and they found that it is clumsy in comparison with more traditional groundwater flow modelling codes, but it made the groundwater modelling more accessible for their ecologist colleagues, who were also using SD in their work. Abbott and Stanley (1999) employed SD to simulate groundwater recharge and the mechanisms of flow in a fractured aquifer in Vermont, USA by integrating field and laboratory data. They reported that iterative simulations of SD components can produce a very realistic representation of bedrock groundwater recharge and flow patterns from available knowledge. Ying (2008) considered SD to simulate the transportation of nitrate from septic lands to river through shallow groundwater bearing zones. Pruneda (2007) employed SD to develop an interactive tool to simulate the effects of surface water diversions replacement by groundwater on in-stream flows. He reported that SD can be used to model groundwater flow simulation by avoiding the use of complicated groundwater simulation models. Niazi et al. (2014) developed a comprehensive system dynamics model to simulate aquifer storage and recovery, and furthermore they concluded that SD is an effective tool to conserve groundwater resources and reduce groundwater depletion in arid and semi-arid regions. Roach and Tidwell (2009) developed a groundwater flow model with high-resolution, spatially distributed elements by extending the idea of multiple cells. They also implemented compartmental groundwater models within the context of spatial system dynamics for rapid scenario analysis. Their other conclusion is that SD is efficient in simulation groundwater dynamics simulation.

During the current research project, SD modelling has also been applied for water supply planning in the Han River basin, South Korea (Chung et al., 2011), in Hubei Province, China, also for sustainable utilization of national water resources (Dan and Wei-Shuai, 2012), in addition to the identification of the strategies to adapt climate change in Tuwei River basin of North-west China (Wang et al., 2013). Sustainable management of water resources in the Eastern Snake Plain aquifer in the western USA applied SD model (Ryu et al., 2012), for adaptation planning to increase irrigation demand in Baojixia irrigation district of China (Wang et al., 2014). It has also been used in planning of urban water reuse in the Great Lakes region of Michigan, USA (Nasiri et al., 2012) and also for modelling complex urban water systems of Tabriz city, Iran (Zarghami et al., 2012).

During the current project, Stella software has been widely used for hydrological and hydro-ecological studies in recent years. Ouyang et al. (2015) used Stella to estimate the dynamices of water and nitrogen rotation in a woody crop plantation, whereas Leitman and Kiker (2015) adapted the Stella to simulate river flows in a basin. Pallipparambil et al. (2015) considered the use of the same for modeling biomass production of the biofuel crop. Martínez-López et al. (2015) used it for strategies of the community response to hydrological pressures. On the other hand, Azanu et al. (2013) employed it to predict uptake and chemical processes in sewage-fed agriculture ecosystem. Ouyang et al. (2010b) estimated the atrazine runoff, leaching, adsorption, and degradation from an agricultural land. Zhang et al. (2015) employed it for estimating removal of nitrogen in wetlands. Mayo et al. (2014) studied the transformation of nitrogen in a pond that have coupled high rate and water hyacinth. Ouyang et al. (2013) estimated the emissions of carbon dioxide in soil from a short-rotation woody crop. Rivers et al. (2011) modelled the movement of phosphorus in a watershed, and Ouyang et al. (2010a) used the same model for estimation of water dynamics in a vertical-flow constructed wetland. There are many such exmaples available, where Stella has been successfully applied to simulate complex hydro-ecological problems. All the studies reported the efficacy of Stella in solving multiple complex problems.

Sun et al. (2012) simulated hydrological process of water and reported that Stella is an excellent tool for this purpose. Xuan et al. (2010) modelled subsurface wetlands flows using Stella and reported that it can address the complexity between plant nutrient uptake and medium sorption. Zheng et al. (2010) employed the Stella for ecological modelling by combining water balance equations, local soil and climate data and remarked that Stella ensures easy application in developing areas, and therefore, it is an efficient tool for ecological management. Assaf et al. (2009) developed a Stella based model using economic principles in addition to simple aquifer representation, and reported the efficacy of Stella. Ying (2008) used Stella to simulate transport of nitrate from septic lands to river through shallow groundwater bearing zones. Pruneda (2007) applied the Stella to simulate the effects of river discharge on groundwater recharge. Many studies reported that Stella can be used to simulate groundwater flow without any complicated groundwater simulation models like MODFLOW.

From the review of above studies, many of which were undertaken during the present study, it can be remarked that SD approach can be potentially used to solve the complex problems of ecology and hydrogeology. It allows decision makers to have better opportunity in understanding the problem more effectively and realistically. Therefore, it may be possible to use SD to aid in groundwater management systems and could therefore be a suitable choice for use in developing a model for complete Riyadh water flow and solute transport system. It seems that application of SD approaches has rarely been undertaken in urban water assessments, but could potentially be a convenient approach. Further discussion of the choice of SD is presented in Section 3.3.

## 3.3 Choice of a SD Modelling Approach / Stella in the Current Project

Usually, two or three dimensional groundwater models are used to simulate groundwater flow (Freeze and Chery, 1979). Numerous software packages have been developed in order to aid such modelling, such as, HYDRUS, MODFLOW, etc. These models are usually called single-purpose models, which mean that they simulate only one aspect at a time, for example, groundwater availability, economic exploitation, etc. (Bidwell and Good, 2007). In hydro-ecological studies, it is often required to simulate many different kinds of systems as the decisions are made not only based on the availability of water, but also based on many ecological parameters (Bond et al., 2002; Hale et al., 2015). Furthermore, it is often required to take decisions based on the physical and socio-economic impacts that water development and use have. Therefore, for simulation of multiple issues such as watershed, groundwater and surface flow jointly, it is required to link the catchment, groundwater and surface water models together to form an integrated modelling tool in order to provide a dynamic representation of the total hydrological system (Kassim, 2005). Each individual model is required to operate independently and then the integration is done through a series of data processing and transfer (Vache et al., 2015). This approach is considered to be a “passive” linkage and it is usually very complicated. Such integrated models usually take hours to run, and therefore, are very time consuming. Many of the conventional hydrological software packages that are used are bound to develop integrated tool that are difficult to understand and operate (Cline and Swain, 2002; Rao and Reddy, 2014). Furthermore, such passive integrated systems often fail to address many physical, environmental and socio-economic issues due to limited scope of conventional hydrological and hydrogeological modelling tools (Voinov et al., 2004). Therefore, the scope of application of such hybrid modelling systems in hydro-ecosystem studies is often very limited.

Stella is an integrated SD modelling tool, which can be used to simulate any type of physical, environmental, financial or hydrological systems. It has the ability to run complex simulations in relatively short time and delivers results in graphical form during live simulations. In contrast to conventional hydrological modelling tools, the easy-to-use interface of Stella allows quick simulation of complex interactions of groundwater components (Whitten et al., 2014; Balai and Viaggi, 2015). Stella has the ability to simulate interrelationships among water, environment and economics, and therefore, it has been applied successfully in the development of integrated resources planning, policy negotiations and stakeholder decision-making in many parts of the world (Ouyang et al., 2015).

Though many of the studies from which the observations have been collated were published after work commenced using Stella, for all these reasons, a SD approach appeared to be a good option for the development of understanding for the Riyadh water system. To understand the whole Riyadh water flow and quality system, not only did groundwater flow have to be simulated, but also the wadi and component systems including the sewer system, the water supply system, the drainage system, and the solute transport system. In order to avoid the complex multi-model systems mentioned above, a SD seemed attractive and was subsequently confirmed by many publications. However, there are also potential disadvantages, including especially the difficultly of representing spatial distributions and spatially-dependent processes, and the related issue of numerical dispersion, for example tracking solute mass movement. In the context of Riyadh (and many other urban aquifers), data availability is limited and it may be possible that lumped modelling approaches are in fact more appropriate as inadequate data exist to define spatial distributions in any case. There are also problems with representation of various processes (e.g. sewer leakage), but these would be present whatever is the modelling approach. One of the aims in the study was, therefore, to assess the usefulness of the SD approach for urban groundwater assessment.

## 3.4 Stella Software

### 3.4.1 Choice of SD Software Package

A number of software packages have been developed to facilitate SD modelling such as, Stella, Powersim, Vensim, Anylogic, etc. Many of these have been successfully applied for simulation of complex systems.

However, among the SD software packages, Stella or Structural Thinking Experiential Learning Laboratory with Animation, is one of the most powerful and flexible software packages (Richmond, 1985). Stella was first released in August 1985 and rapidly become popular with upgrades and refinements. The intuitive icon-based graphical interface of Stella simplifies model building. Therefore, Stella facilitates SD modelling for those without computer experience and mathematical expertise (Richmond, 1985). It also supports diverse learning styles with a wide range of features providing highly powerful and flexible tools to discover relationships between variables as well as to create environments. The icon-oriented structure of Stella helps to model conceptualization and formulation in a realistic way (Richmond, 1985). For all of these reasons, Stella was chosen for the current study. A further advantage is that in future the code could be relatively easily extended to simulate socio-economic systems.

### 3.4.2 Basic Components of Stella

#### ***3.4.2.1 Introduction***

The description of Stella in this section is based on isee systems (2014).

Stella has three significant levels for its successful application in practical works and research activities.

(1) Management Panel (main user interface): This includes the graphical input panel, simulation selection, sensitivity analyses and output figures and graphs.

(2) Model Construction: It is based on the use of object-oriented programming, and hence, a system is created.

(3) Program Code: Stella software converts the object-oriented model to mathematical code, which is easier for debugging. The user normally uses only the management panel, but the code can be used if complex debugging is needed.

Stella presents four model-building blocks that are used in the modelling process which are, namely, stocks, flows, connectors, and converters (Figure 3-2). These building blocks can be utilized to draw a variety of processes and dynamic methods that constitute a system. Models are run for specified time steps (Section 3.4.3). The description of these building blocks is explained in the following subsections. As illustrated in Figure 3-2, in the Management Panel of Stella, the stocks are plotted as rectangles, the flows is double-line arrows, connectors are represented as straight or curved red lines, and converters as circles.

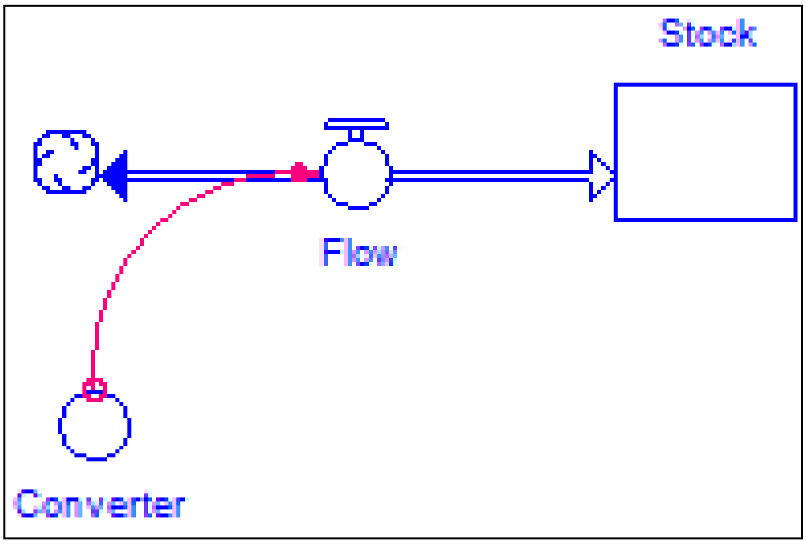



Figure 3-2 Basic components of Stella (Stella v 10.0.6 , isee systems,2014)

#### *3.4.2.2* ***Stocks***

Stocks are the basic building blocks of Stella and are used to represent stores or "accumulations" that capture the "state of the system". The stocks are tangible, countable, and usually physical accumulations. However, they can also be accumulations of non-physical objects like fear or knowledge, when for example a model is used for socio-economic simulations. Mathematically, stocks represent "state variables". Stocks in Stella possess have four characteristics.

(1) They have memory,

(2) They change with net amount of flows,

(3) They facilitate flow separation,

(4) They create delays.

The state of stocks can be measured at one instant in time. Changes in the amount of material stored in a stocks occur only by flows after a delay (time step) in the system.

At the start of a simulation, the stocks are set to have a finite amount of material stored in them and they can also be set to have a maximum amount.

In the models developed in this project, example stocks include groundwater volume in an aquifer; surface water volume in the wadi river; water volume in the sewer system; volume of water in the water treatment plant; mass of solute in an aquifer groundwater; mass of solute in surface water body and mass of solute in the sewer system.

#### *3.4.2.3 Flows*

Flows in Stella are used to model activities with inputs and outputs of stocks (Figure 3-2). The dynamic behaviour of the system arises due to the flows into, and out of, the stock. The amount stored in the stock increases if the inflow exceeds the outflow. On the other hand, the amount stored in the stock decreases when the outflow exceeds the inflow. If the outflow equals the inflow, the number of entities in the stock remains the same, which indicates a state of dynamic equilibrium. Theoretically, a stock in SD can have any number of inflows and outflows. However, in Stella, stocks can have a maximum of six inflows or outflows. Flows can be unidirectional or can be set to be bi-directional.

Flows are represented by user-defined equations, which can be simple constant rates, perhaps determined by a constant value held in a converter. They can be rates that depend on the amounts of materials in one or more stocks and can include conditional statements. For example, groundwater flow from a soil system to an underlying aquifer might be defined by Darcy's Law, with the rate dependent on the relative volumes of water stored in the soil water stock and the aquifer stock.

#### *3.4.2.4 Connectors and Converters*

Connectors in Stella are used to move information from one element of the system to another (Figure 3-2). Unlike Flows, a connector is like a wire that carries information. It originates at the point, where it "picks up" information and terminates at the place, where it delivers the information.

Converters hold information about the system that affects the rate of the flows, or the value of another converter (Figure 3-2). Converters contain state equations that create an output result from input during the simulation of each time interval. Thus it might contain a simple equation of the form Variable = value, but may also contain a rather more complex equation of the form Variable = f (range of values out put by several converters).

The connectors connect stocks to converters, like stocks are linked to the flow regulators and also converters are linked to other converters. Information is transmitted to regulate Flows by Connectors. Connectors in Stella can be linked to converters or flows, but it can never be connected into stocks. In Stella, only flows can affect the stocks magnitude; unlike connectors that is possible to affect both input flows and output flows. On the other hand, converters usually transform information to be used by another variable. In Stella, converters can also be used for storing constant values, as indicated above.

In the example of groundwater flow calculation described at the end of Section 3.4.1.2, the hydraulic conductivity for the Darcy Law calculation would be held in a converter (Variable = hydraulic conductivity value) and this converter is connected by using a connector to the (bi-directional) flow that actually does the Darcy Law calculation to move water from/to the soil water stock to/from the aquifer water stock.

### 3.4.3 Time Steps

Stella simulates the solutions of systems using differential equations, dealing with modelling of processes over time. The time step function of Stella allows the user to define the frequency at which the numerical integration is performed.

An example of a simple differential equation built in a Stella models is shown in Figure 3-3 with the equation (3.1) (Darcy law).

*Stock_of_water(t) = Stock_of_water(t - dt) + (-Q) * dt {m^3}*

*INIT Stock_of_water = 100 {m^3}*

where t is time and Q is flow rate.

*Q = A*K*((h1-h2)/L) {m^3/day}* **3.1**

where A is cross sectional area, K is hydraulic conductivity, and $h_1$ and $h_2$ are heads at locations separated by a distance L.

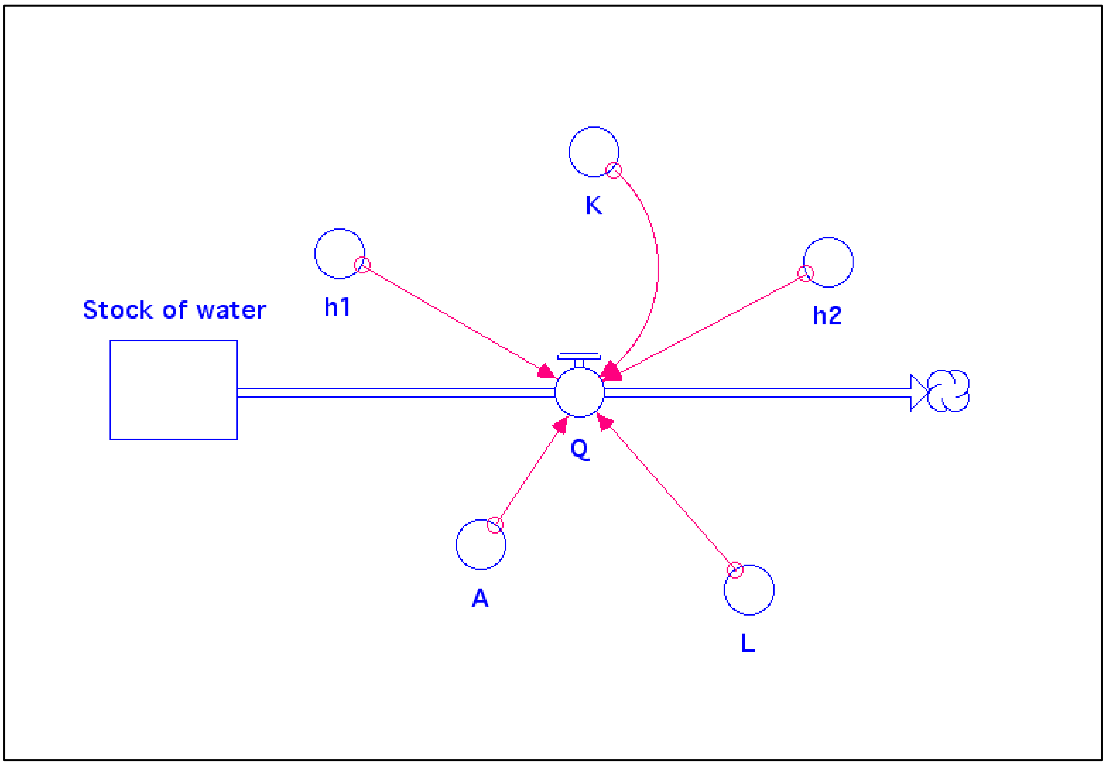



Figure 3-3 Diagram of example of Stella model(Darcy law flow) (stella v 10.0.6, isee systems,2014)

Thus, the volume of groundwater, for example, in an aquifer at time t is equal to the volume in the aquifer in the previous time step plus the inflow rate multiplied by the time step size. The initial volume of groundwater in the aquifer has to be defined, and in the example it is set at 100 $m^3$. The flow rate also needs to be defined, and in this simple example, it is set equalling a value calculated using Darcy's Law associated with the 'valve' icon (Figure 3-3). The value for the constants for Darcy's Law are held in converters, and the converters are connected to the flow by a connector.

There are two ways to move forward, namely, discrete time and continuous time. Stella is capable to run with both the continuous and the discrete times. In the continuous time views as a continuous variable, in the discrete time, the time has fixed reading and jumps to new next fixed reading.

The panel of 'Run Specs' shows the tools of run model such as the duration of simulation with time units, speed of simulation, integration mode and method. The small value of 'DT' gets accurate results for simulation, but the simulation takes more time.

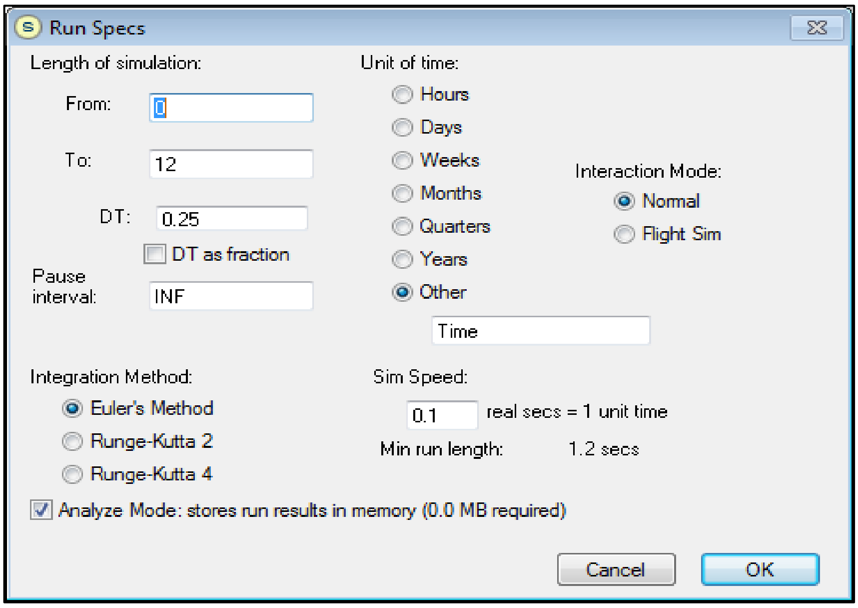



Figure 3-4 Time steps tools (Stella , v 10.0.6, isee systems, 2014)

# CHAPTER 4: FLOW MODEL

## 4.1 Introduction

Many cities in Saudi Arabia discharge urban waste water into urban wadi systems, where it either runs off or infiltrates into the wadi deposits or flows away through the groundwater system. In these wadis the discharge water is increased by natural runoff, which may dilute it, though not all natural runoff is good quality. It may flow out of the city to rural areas where it can be used for irrigation. In addition, irrigation may be used from wells in the wadi deposits within the urban area. If this works well, urban wastewater can be re-used, but what is not known is under what conditions such systems are sustainable and/or how they could be managed in an efficient way.

Some pollutants may seep into the precious groundwater reservoirs, which is the case in big cities with nearby drainage basins, such as the case in Wadi Hanifah next to Riyadh City. It is essential to control such seepages through scientific investigation in order to devise an optimum management approach. The runoff phenomena in such wadis are particularly important factors affecting the distribution of pollutants on the surface and in the aquifers. Although runoff is one of the factors, there are many other input factors that play significant roles in the process. It is rather a difficult task to take into consideration all of these factors precisely in a management programme, but effective ways of management must be found for successful control of precious groundwater reservoirs especially in arid regions. To determine effective ways of managing such systems, and understanding must be built up of how they work, and this can be achieved by developing a model. Apart from helping to develop understandings, if successful the model can be used to investigate possible management options.

This chapter describes the construction of a flow model for Riyadh using the systems dynamics approach described in Chapter 3. Chapter 5 will describe the extension of this model to allowing solutes to be tracked through the system, and Chapter 6 will describe an investigation of the model. In this present chapter, Section 4.2 describes further details of the water system in Riyadh, expanding on the outline given in Chapter 2. Section 4.3 describes the equations forming the model. Section 4.4 describes the running of the model. Section 4.5 compares the model with the little amounts of field data available. Section 4.6 describes the behaviour of the model system over the running period. Section 4.7 is a discussion, and Section 4.7 is the conclusion..

## 4.2 The Water System in Riyadh

As described in Chapter 2, the water system in the Riyadh-Wadi Hanifah area is complex. Figure 4-1 shows the flow diagram for water flow dynamics presented in Chapter 2, including water supply system, groundwater recharge, water demand, hydrological and sewage components. The initial hydrogeological conceptual model was presented in Chapter 2 and was summarised partly in Figure 2.18, here reproduced as Figure 4-2.

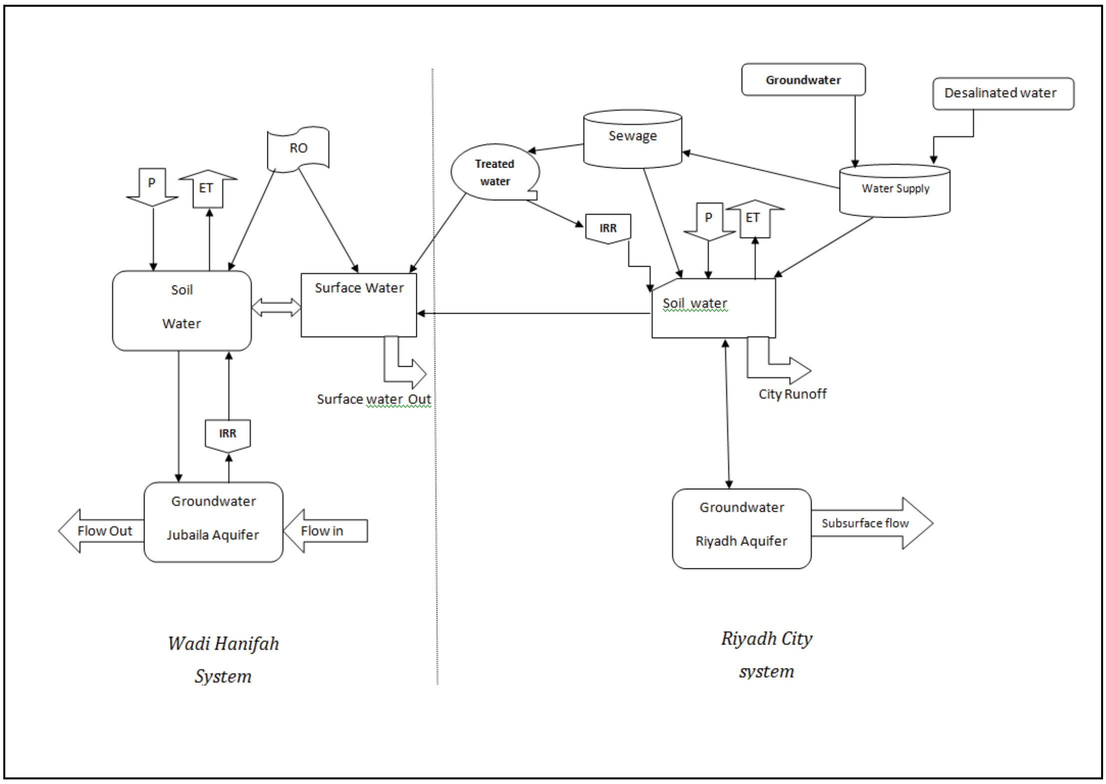



Figure 4-1 Riyadh City-Wadi Hanifah water supply model system

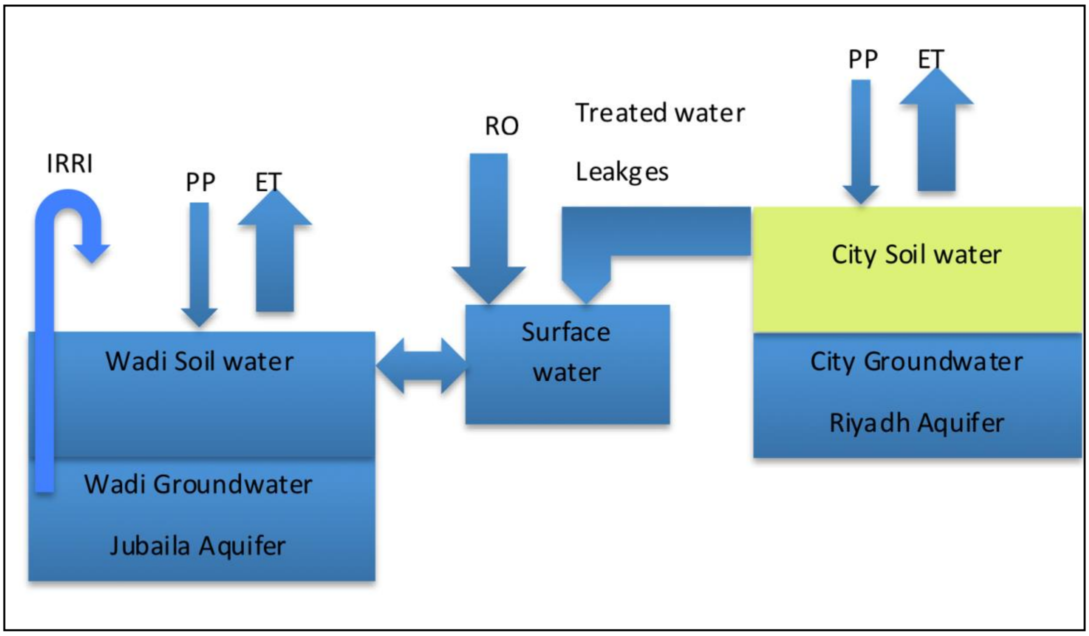


Figure 4-2 Initial conceptual model of the Riyadh system (Chapter 2)

Figure 4-2 can be converted into the basic flow system shown in Figure 4-3. This is the flow system that has been used to develop the system dynamics model, details of which are given in the following subsections.

## 4.3 Notes on the Methods of Estimating Some of the Flows

### 4.3.1 Estimating Some of the Surface Water Flows Used in the Model

In various places in the model it will be needed to estimate flows through part-filled pipes and open channels. This is sometimes done by using the Manning formula, and this is described below.

The Manning formula is an empirical method for open channel or free surface flow by gravity. The discharge rate through a partially-full pipe of a drainage network, for example, can be estimated as follows:

$$V = \frac{1}{n} R^{\frac{2}{3}} \sqrt{S_w}$$
$$Q_D = A * V \qquad \textbf{(1)}$$

where:

V= mean of flow velocity (m/sec),

R= hydraulic radius (the ratio of the cross sectional area ) (m),

$S_w$ = Slope of water surface (m/m),

n= Manning's coefficient (dimensionless),

$Q_D$= discharge rate ($m^3$/sec),

A= cross sectional area ($m^2$).

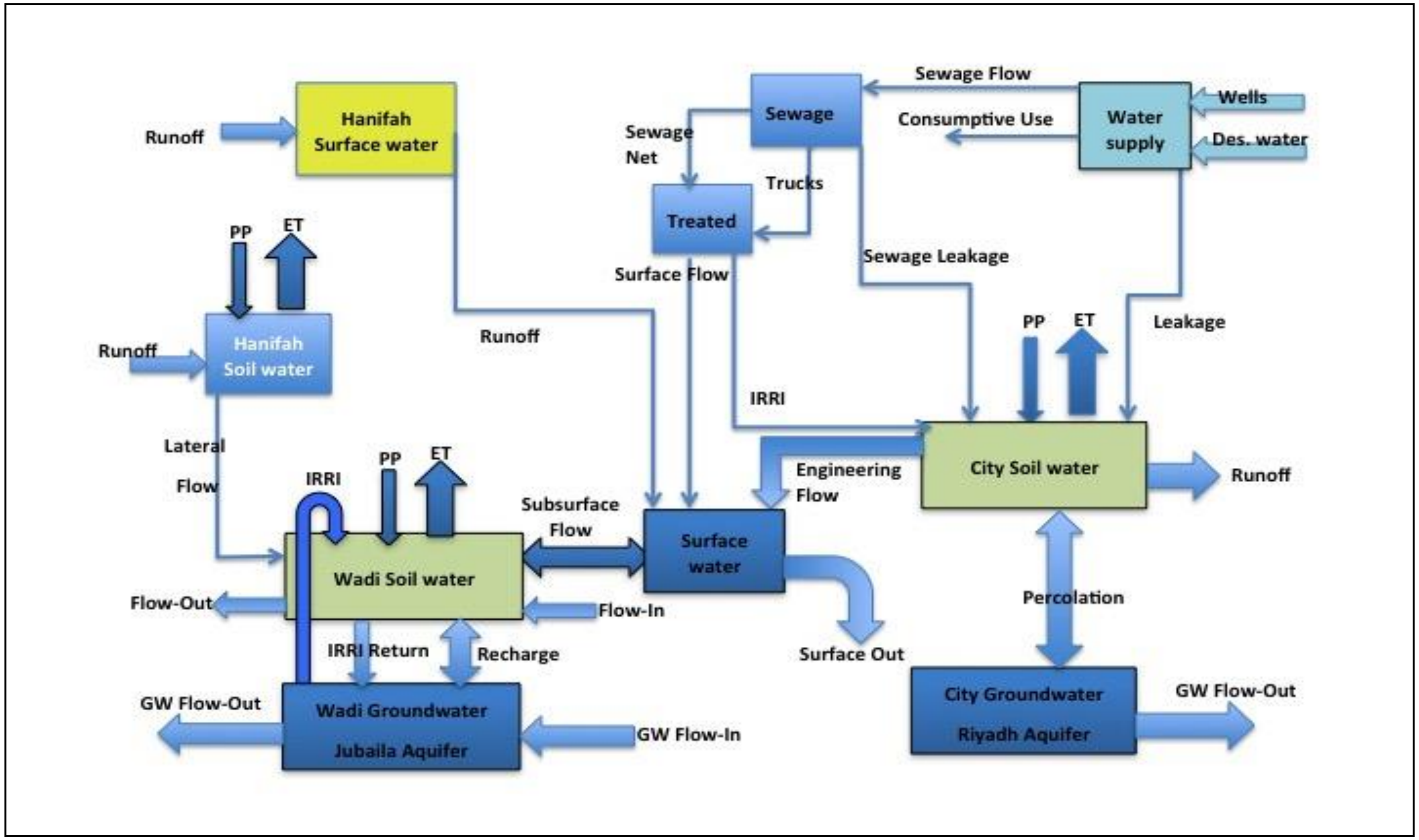



Figure 4-3 The flow system implied by Figure 4-2

Figure 4-4 is shown schematic diagram of horizontal drains, slope and diameter of each pipe, was estimated at the end points of drains. The Manning's coefficient values various with roughness of channel surfaces (Table 4-1). Values of the roughness coefficient (n) are assigned as 0.012 for new projects and 0.02 for old projects (Linsley et al., 1958). The values of water slope ($S_W$) values range from 0.00195 to 0.0021, and the discharge rate ($Q_D$) range between 0.018 and 1.82 ($m^3$/min) (Al-Othman, 2011).

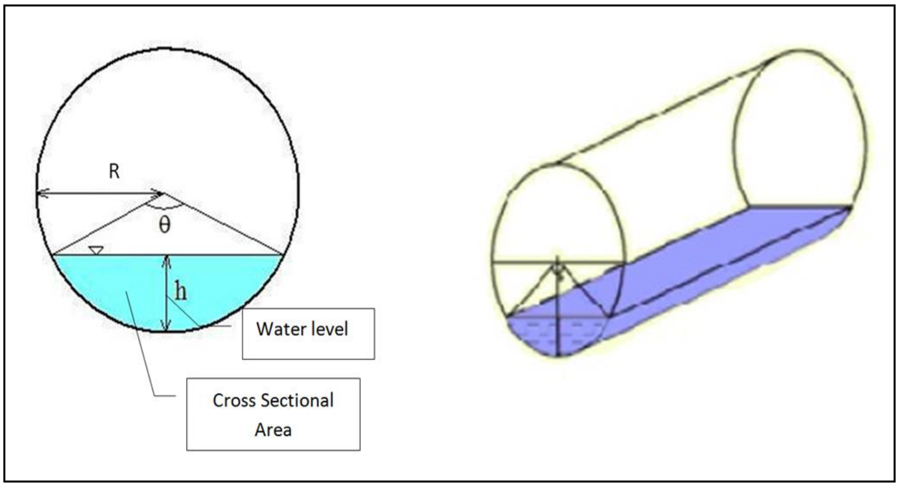



Figure 4-4 schematic diagram of horizontal drains (Al-Othman, 2011)

### 4.3.2 Estimating Runoff Using the Curve Number Method

The United States Soil Conservation Service ‘Curve Number’ method for estimating runoff have been used in the modelling. This is because it is a commonly used and tested approach for estimating runoff in urban areas (Cronshey et al.,1985; Thomas and Tellam, 2006).

Table 4-1 Manning Roughness Coefficient values (Chow, 1959)

| Channel Surface | Manning Roughness Coefficient, n |
|---|---|
| Asbestos cement | 0.011 |
| Brass | 0.011 |
| Brick | 0.015 |
| Cast-iron, new | 0.012 |
| Concrete, steel forms | 0.011 |
| Concrete, wooden forms | 0.015 |
| Concrete, centrifugally spun | 0.013 |
| Copper | 0.011 |
| Corrugated metal | 0.022 |
| Galvanized Iron | 0.016 |
| Lead | 0.011 |
| Plastic | 0.009 |
| Steel - Coal-tar enamel | 0.01 |
| Steel - New unlined | 0.011 |
| Steel - Riveted | 0.019 |
| Wood stave | 0.012 |

The method is the empirical method used to estimate the volume of runoff or infiltration from rainfall. This method was developed in 1985 by United States Department of Agriculture (United States Soil Conservation Service or SCS), it is based on the area's soil type , hydrologic conditions and land use.

The Runoff equation (Cronshey et al.,1985):

$$Q_R = \frac{(P-I_a)^2}{(P-I_a)-S_R} \quad \textbf{(2)}$$

…where:

$Q_R$= Runoff (in)

P= Rainfall (in)

$S_R$= Potential maximum retention after runoff (in)

$I_a$= initial abstraction (in)

Through many studies was found $I_a$ by following equation:

$$I_a = 0.2\, S_R$$

The S value related the soil conditions through the values of Curve number (CN), it is ranges from o to 100. The value of S by equation:

$$S_R = \frac{1000}{CN} - 10$$

## 4.4 Model System

### 4.4.1 Introduction

In any extensive modelling work, such as has been developed here for Wadi Hanifah, various factors must be taken into consideration. Among these factors the most significant ones include: 1) rainfall; 2) runoff; 3) channel flow; 4) recharge and loss from surface water; 5) evapotranspiration; 6) groundwater flow; 7) leaching of solutes; and 8) mass transfer of solutes between environmental compartments.

In the flow model, factors 1 to 6 inclusive are taken into consideration: factors 7 and 8 are considered in Chapter 5. In the following sub-sections, detailed information about the components of the model is given.

In general, water flow in model has been calculated using two main equations: Darcy's law for groundwater flow and Manning's formula (Manning, 1891) for surface water flow (Section 4.3). The curve number method (United States Department of Agriculture, 1986) was used to estimate runoff volumes (Section 4.3.2) and the Jensen-Hasie method, modified after Salih and Sendil (1984), was used to estimate potential evapotranspiration (Chapter 2).

### 4.4.2 Groundwater balance equations for the Riyadh Aquifer

Groundwater resources in any city can be written as a temporal dynamic equation with Δt difference time steps. For Riyadh's deep groundwater in the Arab Formation (the Riyadh Aquifer) Figure 4-5, with no inflows from upflow, this is as follows:

*Groundwater_City(t) = Groundwater_City(t - Δt) + (Percolation - Subsurface_Flow_To_South) * Δt* **(3)**

where *Groundwater_City(t)* is the volume of water in the Riyadh aquifer at time t, *Percolation* is the rate of recharge from the soil (alluvium) of the urban area to the aquifer, and *Subsurface_Flow_to_South* is the rate of groundwater flow to the south in the Riyadh Aquifer. Each term in this expression represents a volume and in practice the unit adopted has been [$m^3$].

The percolation (i.e. recharge) from the city soil system to the Riyadh aquifer was calculated using the hydraulic conductivity and the head gradient between the Groundwater and Soil water stocks (Equation (4) provided that the head in the Riyadh aquifer (*h_GW*) was above the elevation of the base of the aquitard (*Aquitard_base*) overlying the aquifer: if this is not the case, then the flow is calculated assuming the driving head gradient is the head in the soil (*h_city_water*) above the base of the aquitard divided by the aquitard thickness. Again all the terms are in dimensions of volume per time, which is the discharge [$m^3$/day].

*Percolation = IF h_GW<=Aquitard_base THEN*
*K_Sulaiy_Aquitard*((h_city_water-Aquitard_base)/Aquitard_Thickness)*Soil_Surface_Area{m^3/day}* **(4)**
*ELSE (K_Sulaiy_Aquitard*((h_city_water-h_GW)/Aquitard_Thickness)*Soil_Surface_Area){m^3/day}*

*Where:*

*K_Sulaiy_Aquitard* is hydraulic conductivity of Sulaiy aquitard.

Subsurface flow in the Riyadh aquifer to the south (Equation. 3) is estimated using a general head boundary type method:

*Subsurface_Flow_To_South =*

*Hydraulic_Gradient_Aquifer*K_Riyadh_Aq*Aquifer_width** **(5)**

*Water_Thickness__Riyadh_Aq{m^3/day}*

The water thickness in the Riyadh aquifer is calculated using the stock volume and a specific yield. The calculation of water thickness in Riyadh aquifer is:

*Water_Thickness__Riyadh_Aq =*

*Groundwater_City/(Soil_Surface_Area*Specific_yield_of_Riyadh_Aq) {m}* **(6a)**

*Where:*

*Specific_yield_of_Riyadh_Aq* is the specific yield of the Riyadh aquifer. The value of the specific yield is set at 0.13 (ADA,1990) And the piezometric surface height in Jubaila aquifer is:

*Piezometric_surface__of_Jubaila_Aq =*

*Groundwater_Wadi/(Soil_Surface_area_Wadi*SS_of_Jubaila_J2** **(6b)**

*Thickness_of_Jubaila_Aq ) {m}*

*Where:*

*SS_of_Jubaila_J2 is* the specific storage of the lower part of the Jubaila aquifer, set equal to $1.3\times10^{-4}$ $m^{-1}$(Italconsult, 1969).

The piezometric level in the Riyadh Aquifer is at all times below the upper boundary of the aquifer (Figure 4-5), so there is no effect of moving from unconfined to confined storage coefficient on the calculation of water volume in aquifer (the thickness of Riyadh aquifer is 124 m when the water thickness is around 70 m at all times). The piezometric surface in the Jubaila aquifer is always above the top of the aquifer. There is no groundwater inflow into the Riyadh aquifer as the aquifer has no up groundwater flow catchment.

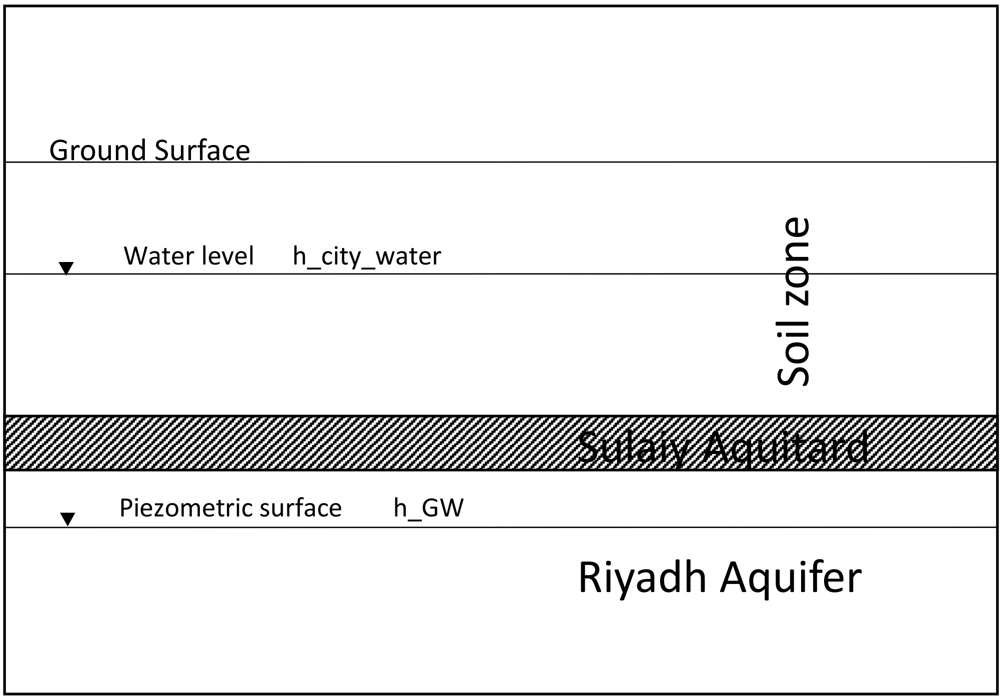



Figure 4-5 Cross section of groundwater stocks in Riyadh City

### 4.4.3 Groundwater balance equations for the Jubaila Aquifer in the Wadi Hanifah area

The groundwater balance for the Jubaila Aquifer ( Figure 4-6) in the Wadi Hanifah is:

$$Groundwater\_Wadi(t) = Groundwater\_Wadi(t - \Delta t) + (Recharge + GW\_Input + Wadi\_Irr - IRRI\_Wadi - GW\_Out) * \Delta t \quad \textbf{(7)}$$

where *Groundwater_Wadi* is the volume of groundwater in the Jubaila Aquifer in the Wadi Hanifah area, *Recharge* is the recharge from the wadi deposits via the upper lower permeability parts of the Jubaila Formation, *GW_Input* is the groundwater flow into the wadi Hanifah part of the Jubaila Formation from upflow of the section of the Jubaila Aquifer modelled, *IRRI_Wadi* is the irrigation abstraction rate from the Jubaila Aquifer, *Wadi_Irr* is an artificial flow to allow the modeller to change the proportion of irrigation abstracted from wadi deposits relative to from the Jubaila Aquifer and *GW_Out* is the groundwater flow rate out of the Jubaila Aquifer section modelled. Similar to Eq. (3) all terms end up with a volume dimension [$m^3$].

The recharge is dependent on the relative heads in the Jubaila Aquifer (*h_GW-wadi*) and the wadi deposits (*h_Wadi_Water*) and it is calculated in a similar way to the recharge for the Riyadh aquifer, given explicitly as:

$$\begin{gathered} Recharge = IF\ h\_GW\_wadi<=base\_of\_J1\ THEN \\ K\_J1*((h\_Wadi\_Water-base\_of\_J1)/J1\_Thickness) \\ *Soil\_Surface\_area\_Wadi\{m\verb|^|3/day\} \qquad \textbf{(8)} \\ ELSE\ -(K\_J1*((h\_Wadi\_Water-h\_GW\_wadi)/J1\_Thickness) \\ *Soil\_Surface\_area\_Wadi)\{m\verb|^|3/day\} \end{gathered}$$

where *base_of_J1* is the elevation of the base of the Jubaila Aquitard, *J1_Thickness* is the thickness of the Jubaila Aquitard, and *J1_K* is the hydraulic conductivity of the Jubaila Aquitard.

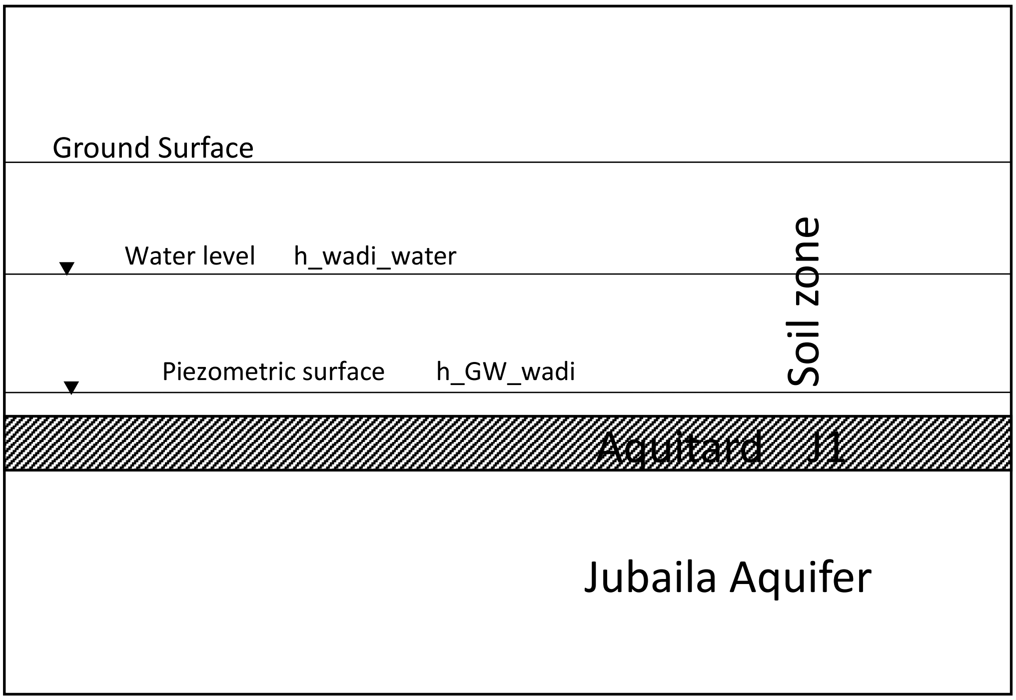



Figure 4-6 Cross section of groundwater stocks in Wadi Hanifah

### 4.4.4 Sewerage system

The sewage water balance can be expressed as:

$$Sewage\_Water(t) = Sewage\_Water(t - \Delta t) + (Sewage\_Flow - Sewage\_Leakage - Trucks\_Water - Sewage\_Net) * \Delta t \quad \textbf{(9)}$$

Here, *Sewage_Water* represents the volume of water in the sewerage system, *Sewage_Flow* is the supply rate of foul sewage from the population, *Sewage-Leakage* is the rate of leakage of sewage from the sewer system, *Trucks_Water* is the rate at which sewage is transferred by lorries from septic tank systems to the treatment works, and *Sewage_Net* is the rate of sewer flow to the treatment works. Data are available for *Trucks_Water* and *Sewage_Net*, the former being an order of magnitude smaller than the latter. *Sewage_Flow* is estimated as a proportion (= 1 - *Consume_Factor*, where *Consume_Factor* is the proportion of water consumed) of water supplied, the latter being a calibration variable.

*Sewage_Flow = (1-Comsume_Factor)*Population*Use_rate{m^3/day}* **(10)**

*Sewage_Leakage* can be exfiltration (flow out of soil and into sewer) as well as infiltration. Infiltration is estimated on the basis of difference between inflow and outflow to the sewer system, and exfiltration is calculated using a leakage constant:

*Sewage_Leakage = IF (Soil_Depth-City_Water_Thickness)>= Sewage_Net_Depth*
*THEN (Sewage_Flow-Sewage_Net-Trucks_water){m^3/day}*
*ELSE -(Sewage_Net_Depth-Soil_Depth+City_Water_Thickness)*Soil_Surface_Area*Sewer_Exfiltration_Factor {m^3/day}* **(11)**

Thus if soil water levels in the city rise above the sewer level (3m below ground level), then exfiltration occurs at a rate dependent on how high the sewer level is above the soil water level and a conductance constant (*Sewer_Exfiltration_Factor*). However, as there is a city drainage level at (5 m) below ground surface, normally there will be infiltration occurring, the rate being calculated as the difference between inflows and outflows to the sewage water system. This could in principle result in flow from soil to sewage system even when soil water levels are below the sewers but in practice this does not happen in the model runs.

### 4.4.5 Soil Water balance equations in the city

The water balance for shallow saturated zone (soil water) in Riyadh city depends on infiltration from surface flows, rainfall, and leakages from domestic networks. Discharge of soil water occurs to the deep aquifer and flow-out through a gravity drainage network. The overall water balance for the city soil system is thus:

$$Soil\_Water(t) = Soil\_Water(t - \Delta t) + (Leakage + PP + Sewage\_Leakage + IRRI - ET - Percolation - Engineering\_Flow - City\_Runoff) * \Delta t \qquad \textbf{(12)}$$

where *Leakage* is the leakage rate from the piped water supply system, *PP* is the rainfall, *IRRI* is irrigation from the treatment works discharge, *ET* is the evapotranspiration from the soil, *Engineering_Flow* is the flow through a specially designed deep (5m) drainage system below the city (Al-Othman, 2011), and *City_Runoff* is the runoff through the usual city drainage system.

Precipitation data are available from PEM (2013). The irrigation rate from the treatment works to the city soil system is known from monitoring data collected by ADA(2010). The method of estimating ET has been described in Chapter 2 using the method of Salih and Sendil (1984) and meteorological data from PEM (2013). Percolation has been described in Section 4.4.2.

The water supply network leakage is estimated as a fraction of the total water supply rate, the latter coming from groundwater (*Wells_Water*) and desalination (*Desalinated_water*):

$$Leakage = (Wells\_Water + Desalinated\_water) *Leakage\_rate\{m\^{}3/day\} \qquad \textbf{(13)}$$

Data are available for the supply rates from wells and desalinated water (SWCC,2013; Al-Othman, 2011). The leakage rate has been estimated by Al Zahrani (2009) as 25%.

The gravity drainage network work discharges soil water to Hanifah wadi, and is estimated using a Darcian approach:

$$\text{IF } (\mathit{Soil\_Depth}\text{-}\mathit{City\_Water\_Thickness}) <= \mathit{Network\_Depth}$$
$$\text{THEN } \mathit{Eng\_Hyd\_Rad}*3.142*\mathit{Eng\_L}*\mathit{City\_Soil\_K}*(\mathit{Network\_Depth}\text{-}(\mathit{Soil\_Depth}\text{-}\mathit{City\_Water\_Thickness}))/\mathit{Dist\_Between\_Drains} \quad \textbf{(14)}$$
$$\text{ELSE } 0\{m\hat{}3/day\}$$

where *Eng_Hyd_Rad* is the radius of the drains (0.475 m)(Alothman, 2011) and the area through which the flow occurs is taken to be the perimeter of the drains times their length and the distance over which the head difference occurs is half the distance between the drains.

*City_Runoff* is estimated using the Curve Number method described in Section 4.3.2. This water is discharged to the south and is assumed not to recharge the city soil aquifer. The curve number is taken as 89 because the type of soil is dirt with low infiltration rate (ADA, 1990)

### 4.4.6 Soil Water balance in Wadi Hanifah

The shallow wadi deposit aquifer water (soil water) balance in wadi Hanifah depends largely on volumes of surface water discharge from treated sewage waters and city network leakage waters, but other minor flows are also included:

$$\mathit{Soil\_Water\_Wadi}(t) = \mathit{Soil\_Water\_Wadi}(t - \Delta t) + (\mathit{PP\_Wadi} + \mathit{Hanifah\_Subsurface\_Lateral\_Flow} + \mathit{IRRI\_Wadi} + \mathit{Subsurface\_Flow\_Wadi} + \mathit{Flow\_in} - \mathit{ET\_Wadi} - \mathit{Recharge} - \mathit{Flow\_out} - \mathit{Wadi\_Irr}) * \Delta t \quad \textbf{(15)}$$

The first input is rainfall (*PP_Wadi*), which is known from field observations. Next there is subsurface lateral flow from the wadi catchment to the southwest of Riyadh. This is estimated using a stock representing the shallow catchment, with discharge to the wadi soil system calculated using Darcy's law. The conceptual model is for a very shallow weathered and fractured zone (see Chapter 2). Thirdly there is irrigation application within the urban part of the wadi, for which enough information (4 measurements over the time period 1990 to 2004) is available to make a rough estimate of amount pumped over the period modelled. Fourthly, there is subsurface flow from and in principle to the wadi stream (*Subsurface_Flow_Wadi*). This is described below. And finally there is subsurface flow from the upflow parts of the wadi (*Flow_in*), which is calculated using a Darcian expression. In terms of outflows, there is the evapotranspiration (*ET_Wadi*), estimated by using the method of Salih and Sendil (1984) and meteorological data from PEM (2013), direct recharge to the deep Jubaila Aquifer, a Darcian calculation, and subsurface flow out to downstream parts of the wadi deposits (*Flow_out*), again a Darcian calculation. Initial estimates of the permeabilities for each of these flows are obtained from the literature summarised in Chapter 2, but then modified if needed during the model fitting. *Wadi_Irr* is the fraction of irrigation water that comes from the wadi sediments, estimated during the 'calibration' of the model at around 73% of the total irrigation rate (*IRRI_Wadi)*. There is not much information on well depths and where the irrigation wells get their water from either the Jubaila Aquifer or the wadi sediments so this splitting of the source was designed to be convenient when developing the model. However this way of assigning irrigation rates between the Jubalia Aquifer and the wadi sediments though works for flows but will result in some numerical dispersion for solutes (Chapter 5).

The main sub-surface flows in or out from soil water stock is flow from/to the man-made channel using a method like in Modflow where there is a small thickness of sediment of defined hydraulic conductivity between the surface water and the groundwater:

*Subsurface_Flow_Wadi =*
*Wadi_Bed_K*WP*Wadi_Length*SWGW_i{m^3/day}* **(16)**

*Wadi_Bed_K* is the hydraulic conductivity of the wadi bed. No data exist for this so it had to be estimated from ‘calibration’ and considering the nature of the bed sediments. *WP* is the width of the channel. This is water level dependent. If the water is within the channel the width is the channel width (about 11m) but if the water level is above the channel bank side then the water spreads over the whole base of the wadi (Figure 2-16). *Wadi_Length* is the length of the urban part of the wadi (25,000m). And *SWGW_i* is the head gradient between the wadi stream and the groundwater in the wadi. If the water level is above the wadi bed sediment level, this is estimated by the difference in head between the stream and the wadi sediment groundwater divided by the wadi bed sediment thickness. If the wadi sediment water level is below the base of the wadi bed sediment the head gradient is estimated by the height of water above the base of the wadi sediment base divided by the wadi bed thickness. So this calculation is same idea as done for recharge to Jubaila Aquifer and percolation to Riyadh Aquifer.

### 4.4.7 Surface water balance

The *Surface_waters* stock represents the water in the Wadi Hanifah channel, the main volumes coming from treated sewage waters and runoff waters in rainy periods, as follows:

$$Surface\_Water\_Wadi(t) = Surface\_Water\_Wadi(t - \Delta t) + (Engineering\_Flow + Surface\_Flow + Wadi\_Runoff + Runoff\_Hanifah - Subsurface\_Flow\_Wadi - Surface\_Out - Evap) * \Delta t \quad \textbf{(17)}$$

*Engineering_Flow* has been discussed above, and *Evap* is evapotranspiration rate from the water in the stream and stream vegetation estimated as a factor multiplied by the potential evapotranspiration rate (last calculated as explained in Chapter 2). The factor used in the final model was 0.7. Potential evapotranspiration (PET) includes the amount of evaporation and transpiration from the soil surface provided that there is a continuous water supply for these two phenomena to take place. In case of insufficient water supply the plants cannot take enough plant water, and therefore, evaporation from soil surface is less than PET. However, as for the comparison of PET with free water surface evaporation (E) then E > PET.

*Surface_Flow* is the discharge of treated waste water to the surface channel, and is calculated from the known sewage streams entering the treatment works and the known irrigation discharges of treated water from the works. *Wadi_Runoff* is the runoff from the wadi area itself, and is estimated using a curve number approach (United States Department of Agriculture, 1986; see Section 4.3.2.

*Runoff_Hanifah* is the surface runoff from the wadi catchment to the south and west of Riyadh, and is estimated using the regional topographic slope and Mannings equation, with hydraulic radius estimated using a water balance that estimates the water level again using the curve number method (see Section4.3.2). The runoff water in catchment, both sheet and channel flow, is represented by a stock into which runoff calculated using the curve number method (Section 4.3.2) is sent. Evapotranspiration is estimated from the stock using the method of Salih and Sendil (1984) (Section 2.7.7). Water moves from the stock to the wadi channel (stream) using a Manning expression (n = 0.03). It is not a perfect representation but retains a water balance and later a solute balance. Total flows are not much (see below) but does represent images of runoff water seen on Google Earth (2011).

*Subsurface_Flow_Wadi* is the flow between the wadi channel and the wadi soil system, and has been described above. *Surface_Out* is the surface flow out through the wadi channel to sections of the wadi stream further to the southeast of Riyadh. In the wadi channel there are dam structures which mean that at low stages, water remains within the channel. So in model *Surface_Out* is not allowed to completely empty the stock *Surface_Water_Wadi*. Minimum volume in *Surface_Water_Wadi* is defined as a factor, eventually set at 0.2, and no downstream outflow occurs if the *Surface_Water_Wadi* volume gets to this value. This water would drain away by infiltration if it was not added to in the next time step.

### 4.4.8 Runoff and evapotranspiration estimation

In Riyadh city and Wadi Hanifah rainfall and runoff events have dominant effects on the overall water balance in the system. Runoff is, as indicated above, often estimated in the model using the curve number method. For example,

*City_Runoff = IF Rain_fall_inch>(0.2*S) THEN (((Rain_fall_inch-(0.2*S))^2/(Rain_fall_inch+0.8*S))/39.37)*Sulaiy_Area {m^3/day} ELSE 0* **(18)**

where *Rain_fall_inch* is precipitation in inches, *S* is the *S* factor in the curve number method (Section 4.3.2) and *Sulaiy_Area* is the area of the city runoff catchment to southeast direction in Riyadh.

Calculation of evapotranspiration, has been by using the Jensen-Hasie method after the modification proposed by Salih and Sendil (1984)(Section 2.9), with an extinction depth concept (i.e. no evapotranspiration occurs when water level are below a certain "extinction depth").

For example, for the city soil water system

*ET = IF City_Water_Thickness >=(Soil_Depth-Extinction_depth) THEN (ET_Coeff_City*(((1.16*PET)-0.37)/1000)*Soil_Surface_Area)*((Extinction_depth-(Soil_Depth-City_Water_Thickness))/Extinction_depth){m^3/day} ELSE PP/(PP+0.00000001)*(ET_Coeff_City*(((1.16*PET)-0.37)/1000)*Soil_Surface_Area){mˆ3/day}* **(20)** where *City_Water_Thickness* >=(*Soil_Depth-Extinction_depth*) determines if the water table in the soil zone is higher than the extinction depth. If it is, the actual evapotranspiration is set equal to PET estimated using the empirical relationship suggested by Salih and Sendil (1984). This actual evapotranspiration rate is then linearly decreased to zero at the extinction depth. If the soil water level is below the extinction depth, then there is no evapotranspiration unless rainfall occurs, and then the AET is assumed to be at the PET rate. This calculation is also undertaken for the wadi soil water as again here the water table may get near ground level.

In cases where there is no direct evaporation from the water table, the calculation of actual evapotranspiration was made by multiplying potential evapotranspiration (PET) by a factor:

$$ET = PET * ET\_Coefficient \qquad \textbf{(19)}$$

Values for the factor were obtained from Al-Sha'lan and Salih (1987) who estimated the AET correction factors in Riyadh city in the period 1965- 1986.

## 4.5 Running the Model

The model was run using a daily timestep from 1990 to 2012. Because the system was not necessarily in steady-state in 1990, the first year was cycled in order to obtain a nearly repeating transient start to the simulation run. A cycling of the first year of inputs four times resulted in the model values settling into a repeating pattern.

The water balance of the model was checked using a spreadsheet calculation and was always found to be within 1% of total flow.

The data used as input to the model were:

1. rainfall;
2. externally calculated evapotranspiration;
3. groundwater imported to the city;
4. desalinised water imported to the city;
5. population;
6. aquifer hydraulic properties, and topographic gradients;
7. sewage volumes received by the treatment works; and
8. various dimensions, e.g. wadi channel width, catchment areas.

The results were “calibrated” against the few number of measured heads, flows, qualitative observations (like flooding in the wadi) and later against concentrations in various environmental compartments.

## 4.6 Model Calibration

### 4.6.1 Introduction

“Calibration” data for Riyadh comprise the following: 1) head data for 6 wells (a third of which are abstraction wells and about two thirds of which are open in more than one aquifer unit); 2) 15 spot flow measurements of wadi channel discharge rate; 3) solute concentrations in various environmental compartments; 4) qualitative and semi-quantitative observations, e.g. the frequency of overbank flooding of the wadi, sewage and independent water supply pipeline leakage estimates.

This list of possible observations to check the model against is very few and often has significant uncertainty. So conventional quantitative approaches to plotting and assessing calibration are not possible. Instead, a qualitative assessment has been made of the agreement of model and field data. This is not ideal, as there may be many possible models that fit the data available. However, this chapter is the first part of a study that includes extending the model to predict water quality and more data become available for checking when concentrations are considered. The results presented here are the final model after the model has been compared with both flow and concentration data.

In comparing with field data, it must be remembered that the model is not a distributed groundwater flow model, but in effect a series of lumped parameter models, and that each compartment will represent potentially a significant difference in, for instance, head, from one end of the compartment (e.g. urban section of wadi which is 25 kilometres long) to the other. As discussed in Section 2.10, the general practical problem being trying to solve here is both dealing with the complicatedness of the urban system with lots of surface and groundwater and pipe flows, and also dealing with the limited amount of data available. The model at best can be only means of thinking through issues rather than an accurate quantitative prediction tool.

“Calibration”, or at least comparison of model results with field results to remove any obvious significant differences was a trial and error process. Initial work showed what parameters produced the largest differences in predicted values (see Chapter 6) and using these by trial and error the model was gradually developed. The limited field data mean that the constraints on the final model presented are also limited and there will be other descriptions that would fit the field data just as good.

Demonstration of the reasonableness of the model will be undertaken in two bits. Firstly (Section 4.6.2) a comparison of the model results and field data will be made. And secondly (Section 4.6.3) the flow systems in the model will be examined to see if they are consistent with what would be expected hydrogeologically.

### 4.6.2 Comparison of model results and field data

Field water level data exist for the wells indicated in Figure 4-8 and Figure 2-9 indicates the actual groundwater levels measurements from the field and the model output for the probably Jubaila Aquifer though wells could be open also in the wadi sediments. Three field measurements (wells 1341WH13, 1344S4, 1433WH5) reflect rather big differences in groundwater fluctuations that cannot be unified as a single record. They are affected by pumping, either of the wells themselves or nearby other wells.

For the wadi Hanifah the model performance is such that after some time it catches a certain groundwater level, which is slightly higher than the most continuous and reliable field measurements. The difference between the model and the longest well record is within two metres.

The fall in water level from about 3500 days in the well is because of abstraction. Ignoring this major change in water level the variability of the water levels at the sites shown in Figure 4-8 are not easy to interpret. There are periods of time where water levels are constant (1341WH13 and 1433WH5), and periods where there is a possible seasonal variation (1341WH13 and 1344S4), but the seasonal variation appears to be added to by pumping. Looking closer there are possible periods where the timing and variation in the model water levels are close to those in the field data (rectangles on Figure 4-8). Given the quality of the data available it was considered that the model heads were consistent with the available field data.

As for the groundwater level in the Riyadh City, Figure 4-9 shows the field measurements with model output trace and one can appreciate that in this case the model has similar predicted water levels within the range of the data available for wells 1312GP3 and 1241HP1.

The data available has little information about the wells (e.g. depth, pumping rate, casing depth). Most of the few well-monitored wells are either pumped or close to pumping wells. Therefore as calibration targets they are not ideal, and they are expected to show differences even with a perfectly accurate model. Furthermore, the lumped nature of the model means that there is no representation of the change in water level over the different distances represented by each stock. So, when choosing the wells for the calibration of water level in the city and wadi Hanifah, the wells chosen were those that were judged to represent the average groundwater level best within the region represented by the stock, but as there was so little data on well design this aspect did not form part of the choice. Agreement even with well constrained observation wells in a distributed model may not be better than may be 2m, but here the correspondence may not be expected to be better than several meters.

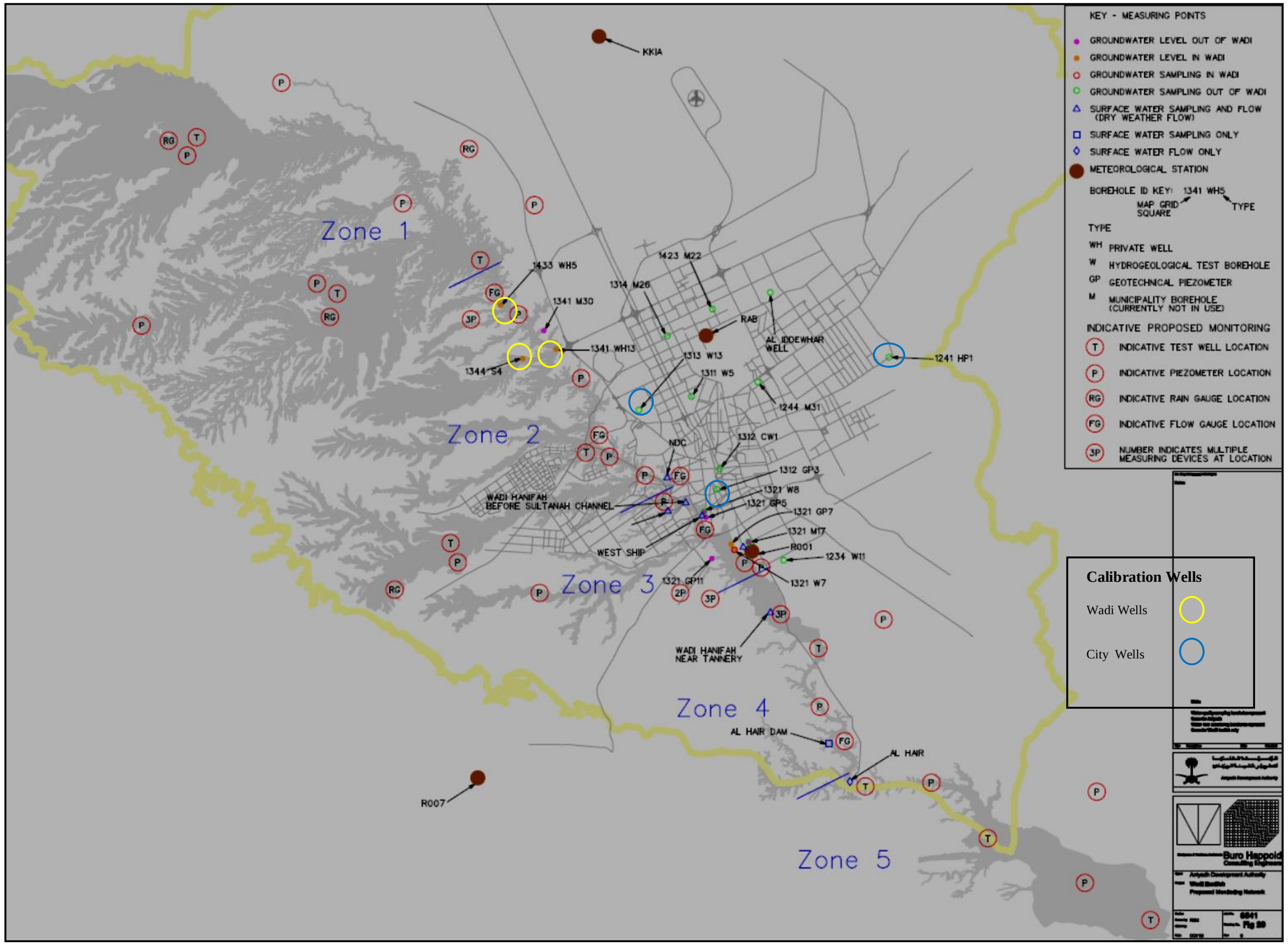



Figure 4-7 Location of wells. Wells with hydrograph data are indicated using yellow (wadi) and blue (city) circles.(ADA,2002)

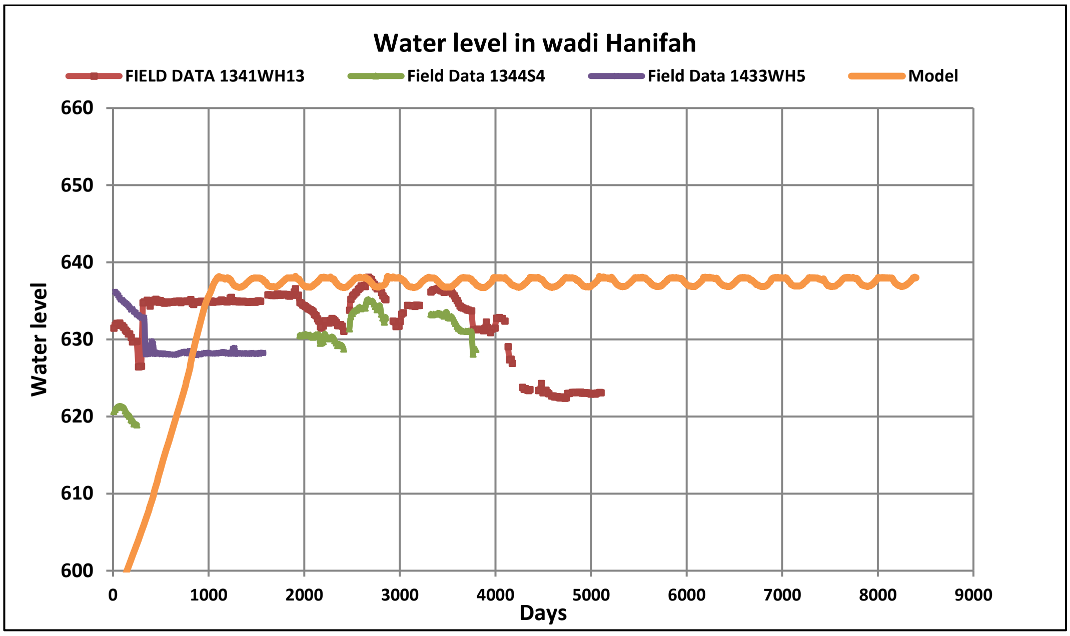



Figure 4-8 Daily groundwater level fluctuations in Wadi Hanifah

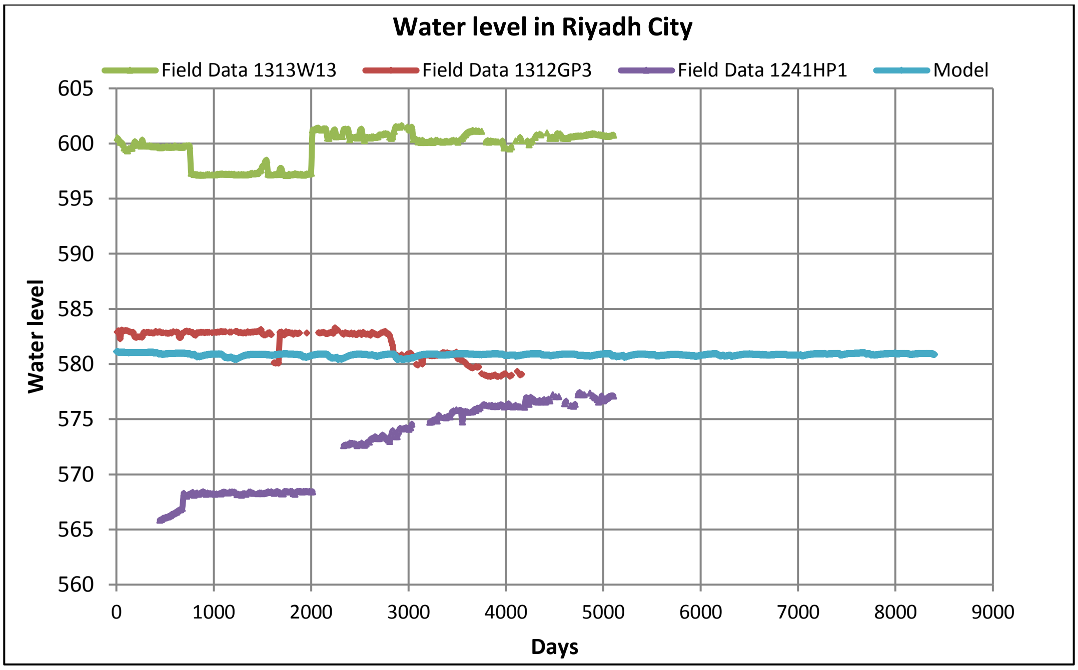



Figure 4-9 Daily groundwater level fluctuations in Riyadh City

Other data to compare against other than solute concentrations (see Chapter 5) include:

1. that flooding occurs in the wadi,
2. frequency of flooding,
3. the flow rate in the wadi stream,
4. the fact that the flow in the wadi stream is perennial,
5. that overland flow sometimes occurs in the Hanifah catchment to the west,
6. the water level in the wadi sediments is below ground level
7. that water levels in the city soil system are high enough that the engineering drainage system is needed
8. the hydraulic properties estimated by previous workers
9. the reasonableness of some of the factors used including water usage and irrigation distribution between aquifers.

The model does predict flooding to occur in the wadi as it does in reality. The flooding occurs due to rainfall and roughly every 4 years for model running time (1990-2012). Qualitative information indicate that flooding occurs every 4 to 5 years for years (1965 to 1996)(ADA,2002), thus agreeing with the model.

The model predicts flow rates in the wadi stream of around 700,000 cubic metres per day rising to just over 1,000,000 cubic metres per day over the time interval modelled. This agrees with the estimate of Al-Othman (2008) of one million cubic metres per day.

The flow in the wadi stream is predicted as perennial. The model predicts that overland flow occurs from the east of the wadi Hanifah catchment roughly every 3 years. Overland flow seems to happen based on the evidence from Figure 4-10.

Figure 4-10 Image from wadi Hanifah catchment to east of the wadi
(Google Earth accessed Sept 2011)

The model predicts that the groundwater level in the wadi sediments is about 2 metres below ground level.

The deep engineering drains required for keeping city soil water levels below ground level are predicted to be necessary in the model too with flows occurring from leakage of domestic and sewage networks.

The hydraulic conductivity and storage coefficient values used in the final model for the upper Jubaila Formation, the Jubaila Aquifer, the Riyadh Aquifer and the wadi sediments are all within the ranges given by previous authors and/or literature values for the rock types.

Factors have been used for evaporation relative to PET, the proportion of water supply that goes to waste, the proportion of water pipe leakage, the proportion of irrigation that comes from the Jubaila Aquifer relative to the wadi sediments amongst other things. For each of these there is no measured values, but there is information on likely realistic ranges. In all cases the values used are consistent with the semi-quantitative or qualitative data available.

### 4.6.3 Examination of the model output

The dynamic model system that is operated by the Stella software has given results concerning different aspects of the Wadi-City system. In this section the results produced are reviewed to get an indication of how the system works according to this model representation. However, water balance issues are looked at mainly in Chapter 6. The purpose of this section is to check that the general description of the system does not contain results that are obviously incorrect. Hence it is other method of checking model is reasonable.

Figure 4-11indicates four water thicknesses, namely, in the Jubaila and Riyadh aquifers in addition to Wadi Hanifah and Riyadh City soil systems. This and subsequent plots show results from after the first year has been repeated four times. Under the modelling circumstances there is stable conditions in the Riyadh Aquifer but a slight decline in levels in the Jubaila Aquifer. There is insufficient field data to know if this is correct, but it would be a good idea to monitor both aquifers in future. Any seasonal variation is almost completely removed by the fact that the recharge comes through an overlying leaky system. Again some monitoring at small time scale would be useful to see if the seasonal variation is removed in the real system.

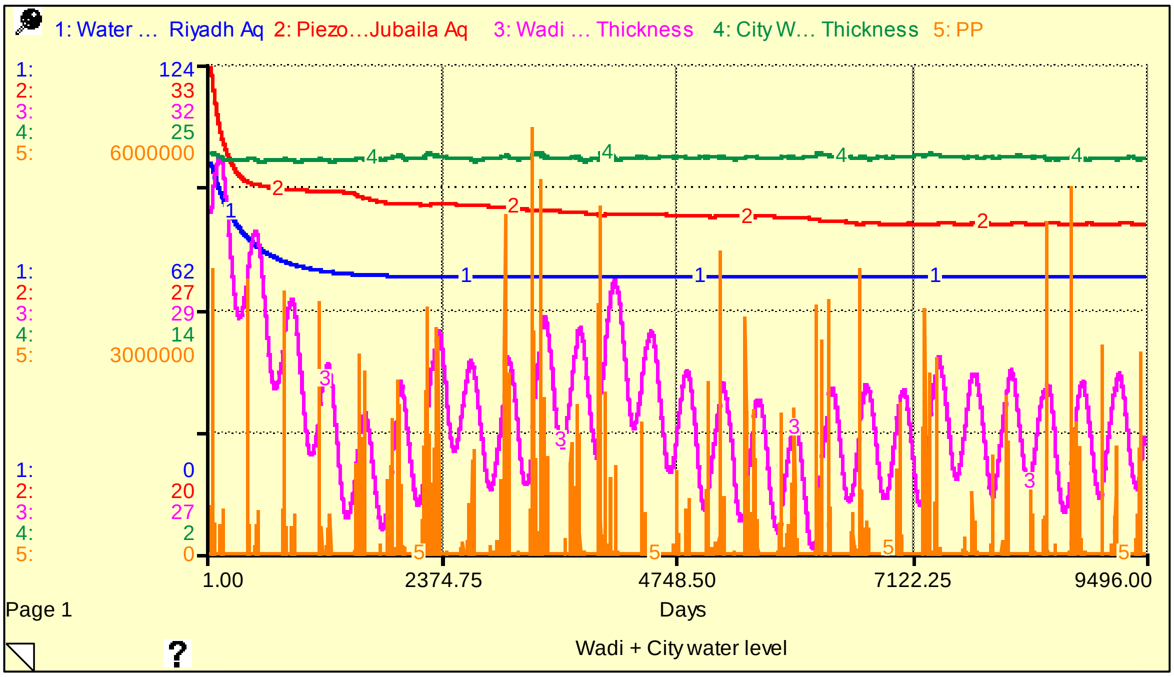



Figure 4-11 The groundwater thickness in Wadi Hanifah and Riyadh City (m)

As might be expected a seasonal variation is seen in the soil water system of the city. This is not as big as variation in the wadi sediments and this is assumed to be because the city recharge is more constant as it comes through water pipe leakage which is missing from the wadi system. The city levels are almost constant after the initial part of the plot and the latter change may be because of the starting conditions of the model need to settle down. But more likely the rise may be because the precipitation increased. The longer wavelength water level variations in the wadi sediments seem related to the rainfall and in particular to the low rainfall of the first few years. See rise in water levels from about day 2700 following a wetter time. This rise is not seen in the Jubaila Aquifer. Seasonal water level variations are clearly seen and are consistent from year to year though plot scale is larger than for other plots. The stability of the system, if confirmed, is good news.

Figure 4-12 shows how percolation to the Riyadh aquifer varies with rainfall. In general when it rains the water level in the city soil aquifer rises and percolation increases quickly, though the % change is small so individual rainfall events make little impact on the deep groundwater flow system as expected. As soon as the rainfall stops the rate drops slightly but suddenly. The flow in the Riyadh Aquifer to the south is of course very much controlled by the groundwater level in the aquifer.

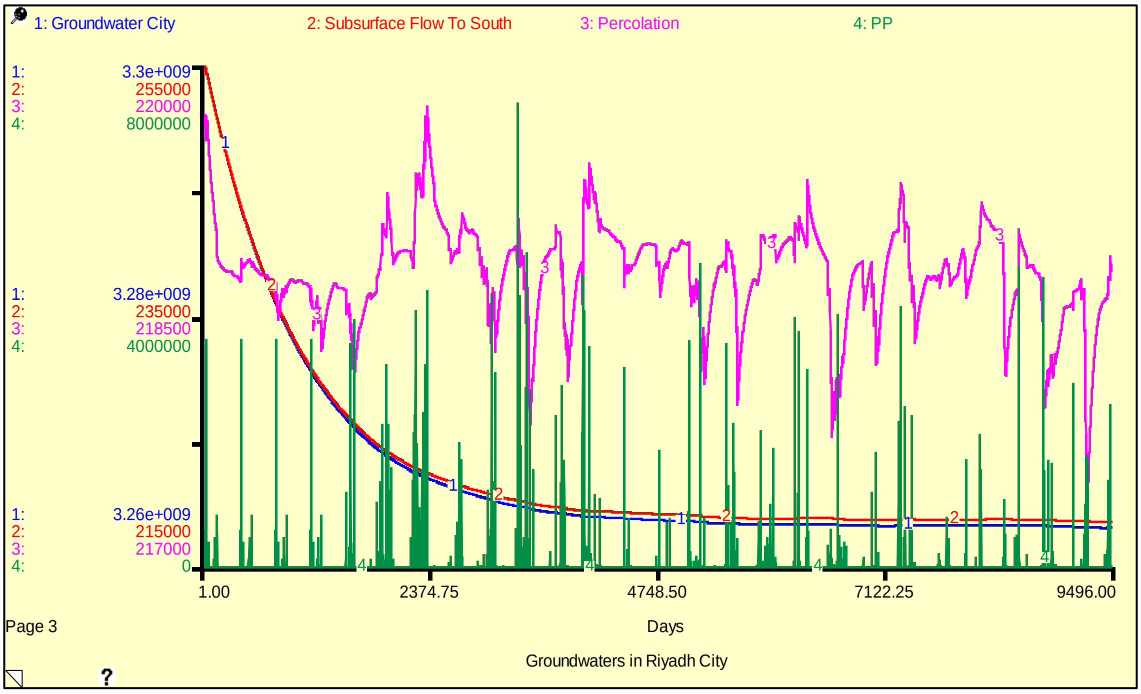



Figure 4-12 Groundwater balance components in Riyadh City ($m^3$)

The water flow rates results from the model are given in Figure 4-13 for Wadi Hanifah by considering the precipitation over the wadi, groundwater input and output, recharge to the Jubaila Aquifer. The long term adjustment to equilibrium of the Jubaila Aquifer seems to be mainly controlled by the irrigation abstraction rate. Nearly equilibrium conditions are reached in the first five years when the abstraction rate is roughly constant. Increase in rate (and rainfall) causes another period of transient balance and drop in water levels and this happens too from about 7000 days when abstraction rates again increase. It seems that the Jubaila Aquifer system as modelled takes about 3-5 years to adjust to changing conditions.

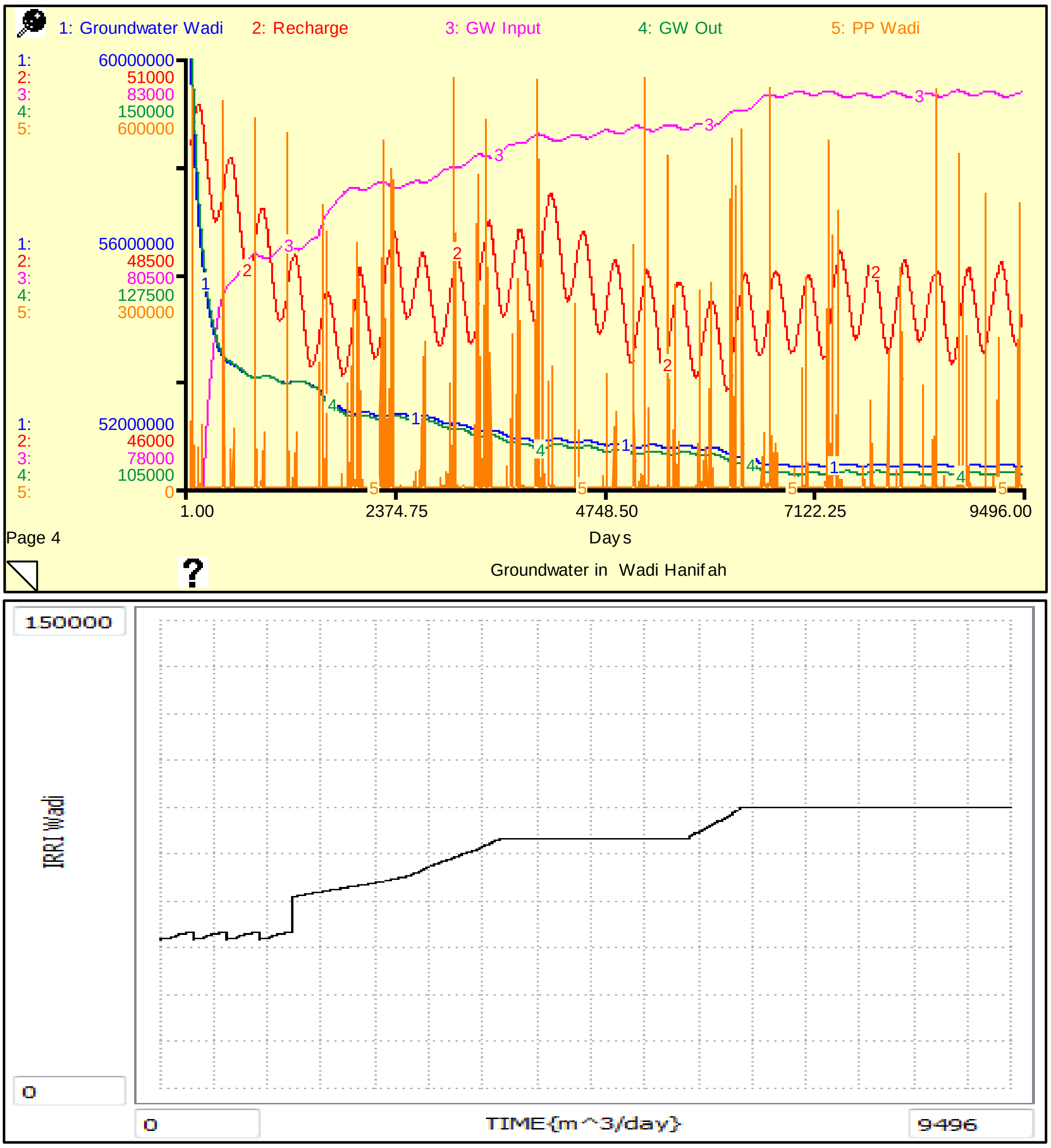
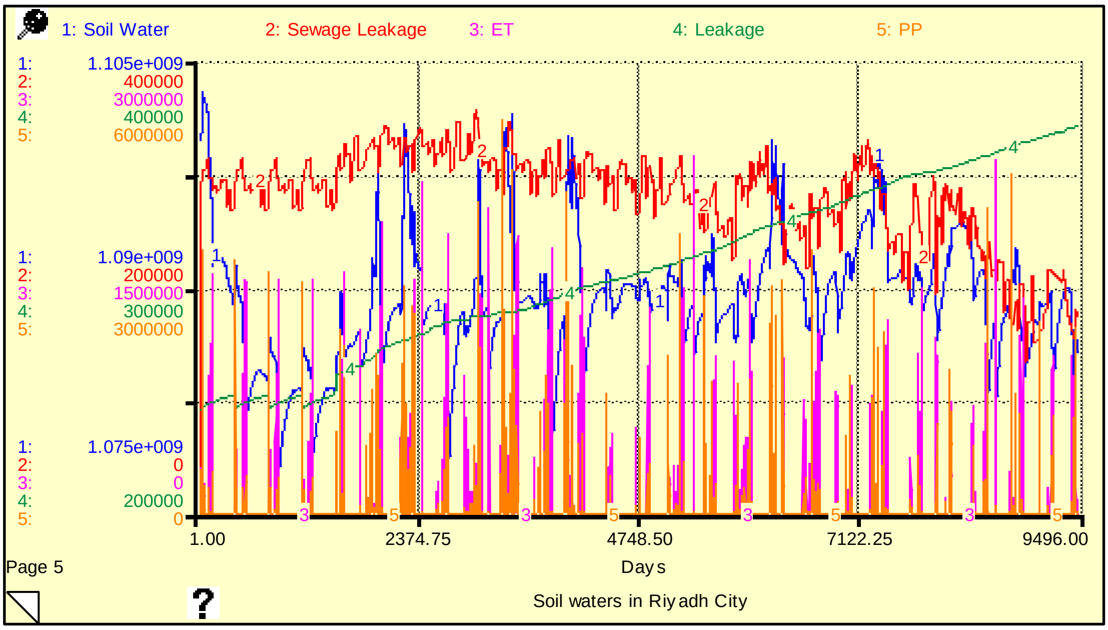



Figure 4-13 Above - Wadi Hanifah groundwater balance components ($m^3$/d and $m^3$ for Groundwater_Wadi). Below – irrigation abstraction rates ($m^3$/d).

Figure 4-14 shows the temporal relationships among precipitation, soil water, piped water leakage, sewage leakage, and evapotranspiration (ET) rates for the city soil aquifer. The only continuously increasing component is the piped water leakage and this depends on increasing volumes of water supply, whereas all other flow rates follow the change in pattern of the precipitation. The sewage water leakage rate generally decreases over the modelled period even though the amount of water supplied has increased. This is because the amount of sewage treated increases faster than the rate of increase of waste water produced. It is uncertain if this is a real effect or is the result of error in estimation of these two flows. The soil water volume changes quickly to changes in precipitation and ET but the amounts that change are small compared with the amount of water in the soil.

Figure 4-15 is for the urban area of Wadi Hanifah and it shows the temporal relationships between the precipitation on the wadi, surface flow, surface outflow, soil moisture and the sub-surface flow. The surface water flows increase steadily with time reaching a little over 1 million cubic metres per day at the end of the modelling period. Seasonal variations are seen that are the result of both catchment flows and urban runoff channelled to stream. Occasionally there are much higher flows due to rainfall events and floods occur across the whole of the wadi floor. Records of flooding in the wadi are rare and there is no quantitative data but ADA(2005) indicates that for the period 1965-1996, flooding occurs every 3-5 years. The model over the period 1990-2012 has eight events that appear to be floods. Eight floods in 23 years mean one flood every 3 years. This is consistent with ADA (2005).

Surface water flow to the south increases proportionately to the flow in the urban wadi section. Higher flows in the wadi stream result in greater subsurface flows to the wadi sediments.



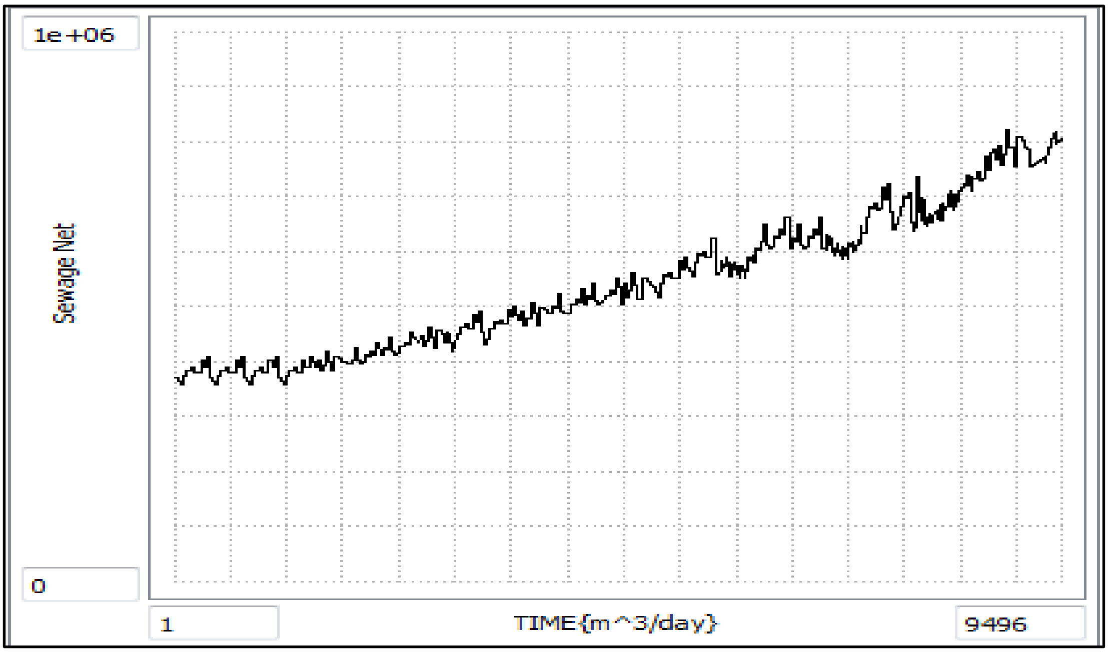




Figure 4-14 Above - flow rates for soil water system in Riyadh City ($m^3$/d) and the soil water volume ($m^3$). Below – treated sewage flow ($m^3$/d)

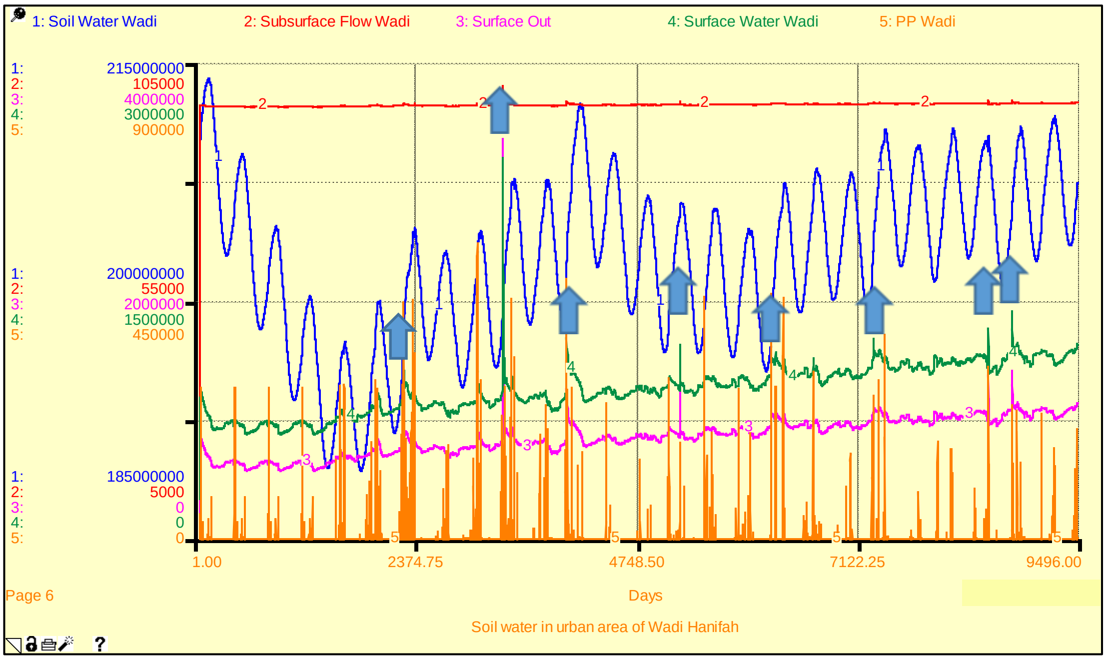



Figure 4-15 Soil water flows in the urban areas of Wadi Hanifah (flooding events, blue arrows) ($m^3$/d) and the volume of water in the wadi sediments ($m^3$)

Figure 4-16 gives information about the temporal variation in the non-urban (western) part of the Wadi Hanifah catchment. Surface water runoff stock volume, soil water stock volume, precipitation volume across the whole non-urban catchment and evapotranspiration volume components are shown. As expected the runoff water volumes increase and decrease rapidly. This is like in Figure 4-11. The major flood in the Wadi Hanifah stream around day 3800 seems due at least in much part to runoff from the non-urban catchment. The soil water is slow to build up volume and slow to discharge, probably because of the relatively low hydraulic gradients.

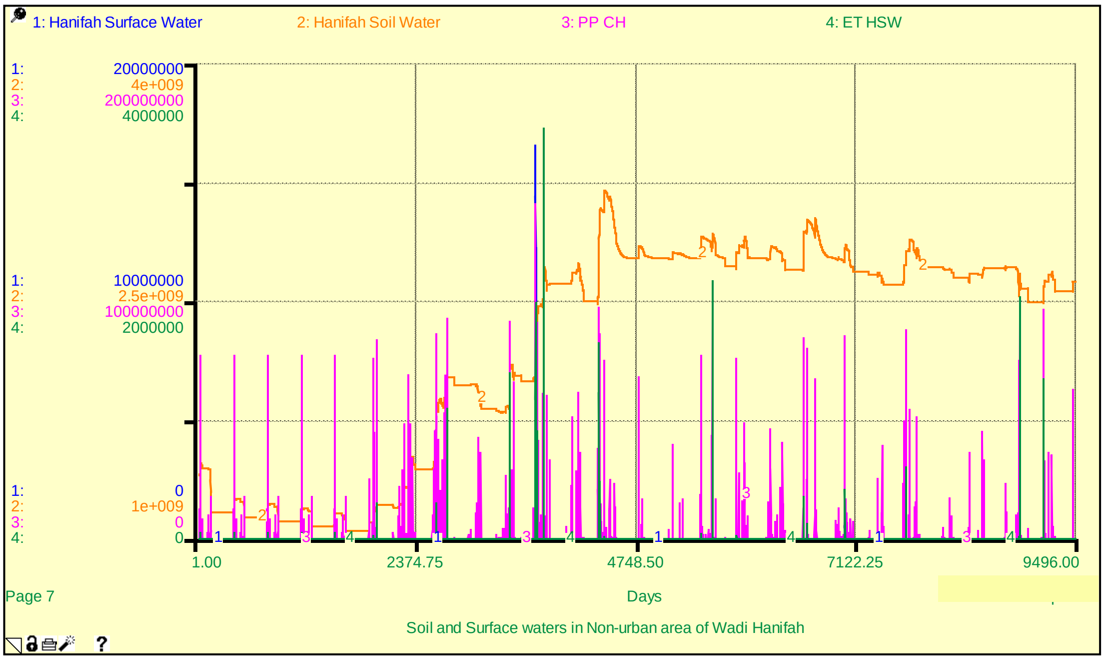



Figure 4-16 Soil and surface water volumes in non-urban areas of Wadi Hanifah ($m^3$), precipitation on catchment ($m^3$) and evapotranspiration ($m^3$)

## 4.7 Conclusions

Though a conventional calibration has not been possible there are quite a few features of the model that are not inconsistent with the real system as shown in Section 4.6.2, including groundwater levels and surface water flows. In addition, the model is also consistent with the inputs, including the geometry, the amounts of water supplied, the amounts of water treated, the amounts of water dealt with by sewage trucks, the rainfall, the other meteorological data and the total irrigation abstraction rates. Finally, an examination of the flow systems as described by the model in Section 4.6.3 indicates that largely the flows are understandable and make hydrological sense. Though the model presented will not be the only model consistent with the data, it is a possible broad explanation of the system and is worth more investigation and subsequent testing in future. In next chapter it will be used as the basis for a solute transport model.

# CHAPTER 5: SOLUTE TRANSPORT MODEL

## 5.1 Introduction

Interest in understanding the mechanisms of contaminant transport into groundwater has increased dramatically in recent years in order to protect groundwater resources from pollution. Unsustainable anthropogenic activities in recent decades have caused significant damage in groundwater quality in different parts of the world. Therefore, the major focus in hydrogeological research has shifted from assessment of groundwater available or production capability to pollution transport. In the last four decades numerous studies have been carried out to model of fate and transport of pollution through porous media. Generally, solute transport models are used to simulate the mechanism of the movement of chemical or organic substances through soil and groundwater. With the increase of interest on pollution transportation through soil and groundwater, several solute transport models have been developed and successfully applied to simulate mechanism of solute transportation, dispersion, retardation, and degradation. However, most of these software packages require information that is usually not available, including things like details of permeability distributions, pollution sources and dispersivities. Here the SD approach is extended to include mass transfer of example solutes, using a lumped representation despite the potential issues of numerical dispersion.

Riyadh city discharges urban wastewater into the urban wadi Hanifah system. A major portion of discharged wastewater infiltrates into the groundwater system through the wadi deposits. It is expected that the wastewater will be naturally treated by the soil materials when it flows through the wadi sediments. Therefore, groundwater at the abstraction locations in the wadi may have, ideally, sufficient quality for irrigational purposes. This will allow reuse of urban wastewater for irrigation, where water is the major constraint for agricultural activities. However, recharging of the groundwater system using wastewater can cause environmental and health hazards, if it is not naturally purified properly. Simulation of solute transport through porous media of wadi deposit can provide a better understanding of potential pollutant movement and problems. The objective of the present study is to develop a solute transport model for wadi Hanifah in order to provide a clearer understanding of solute transport processes that can then be used to help develop management strategies.

Different approaches have been used by different researchers for the development of solute transport models. Physical models were used by most of the researchers to model chemical movement through saturated or unsaturated zones using advection-dispersion equations (Hazen and Sawyer, 2010). Some researchers also used stochastic solutions in order to consider more heterogeneity in for example the unsaturated zone (Jury, 1982; White et al., 1998). A number of solute transport models have also been developed based on lumped mass balance methods in saturated zone. These models consider pollution source, land use, and the specific geometry of the groundwater system to model pollution movement through porous media (Taylor, 2003). Other models have been developed using analytical and statistical methods.

The numerical or analytical solutions for solute transportation through multi-layered soils often show poor performance (Leij and Van Genuchten, 1995). Therefore, they appear to have less advantages over simpler, lumped mass balance methods than at first may appear likely. The lumped mass balance method is the simplest form among all the models used to understand groundwater contamination and movement (Hazen and Sawyer, 2010). Numbers of studies have been conducted to simulate solute transportation using this method. DeSimone and Howes (1998) developed a lumped mass balance simulation model to predict fate and migration of pollutant in porous media. However, lumped mass-balance models are sometimes criticized due to their lack of inclusion of subsurface dynamics and transport processes, and may suffer from numerical dispersion problems.

System dynamics (SD) approach can be used for the implementation of mass balance equations, and can include, at least in lumped parameter type ways, the subsurface dynamics processes (as in Chapter 4). The SD approach has been widely used to investigate watershed hydrological processes (Saysel and Barlas 2001; Li and Simonovic2002; Elshorbagy and Barbour 2007; Chapter 2). However, SD model has been less widely used, until very recently, to develop solute transport models (Chapter 2).

The objective of this chapter is to describe the development of an extension of the system dynamics flow model for Riyadh to represent solute transport. This chapter continues by giving a description of the model formulation and the model evaluation. Finally, the results of the model are presented and discussed with a conclusion.

## 5.2 Development of the Solute Transport Model

In the present study, it is considered that solute in the city-wadi system transfers through groundwater, soil water, drainage water, sewage water, and surface water. It is also considered that advection is the major process of solute transport in Riyadh-Hanifah urban system. However, reaction will be included in the form of dissolution and precipitation. Reaction modelling is described in Section 5.3.

Solute movement depends on the flow of water through subsurface as groundwater and soil water, and surface as drainage water, sewer water, and surface runoff. The solute model consists of effectively a parallel model to the flow model, but with all water volume stocks ($[L^3]$) replaced by solute mass stocks ($[M]$), the water volume flows being replaced by mass flows ($[MT^{-1}]$), and the converters being replaced by appropriate mass-related converters. The mass transported can be represented by a flow using the following relationship.

*Mass of Solute Transported Per Unit Time = Concentration of Solute * Rate of Water Flow* **5.1**

*Concentration of Solute* is either an input value from a converter (e.g. in the case of the desalinated supply source) or comes from a stock (see Equation 5.2 below). *Rate of Water Flow* is obtained from the flow model.

The mass of solute in a stock can be estimated as

*Mass of Solute = Concentration of Solute * Volume of water* **5.2**

*Concentration of Solute* is obtained from mass in the stock and volume in the corresponding stock in the flow model.

Thus, for example, the solute mass (g) in the water supply mass stock (Water_Supply_1) is calculated using:

$$Water\_Supply\_1(t) = Water\_Supply\_1(t - dt) + (Desalinated\_water\_1 + Wells\_water\_1 - Leakage\_1 - Sewage\_flow\_1 - Consumptive\_Use\_1) * dt \quad \textbf{5.3}$$

where the mass flows, labelled ‘XXXX_1’, are for the equivalent water flows (‘XXXX’) in the flow model. Thus for the solute mass flow from the groundwater supply,

$$Wells\_water\_1 = Wells\_water * SO_4\_Wells \; \{g/day\} \quad 5.4$$

where *Wells_water_1* is the mass transfer rate (g/day) of (in this case) $SO_4$ to the water supply stock, *Wells_water* is the groundwater supply volume rate from the flow model, and $SO_4\_Wells$ is the $SO_4$ concentration (g/m$^3$) in the groundwater supplied to the city. All the mass transfers through the system were represented in a similar way.

## 5.3 Representation of Reactions in the Solute Transport Model

Two reactions have been represented in the system: dissolution and precipitation. Other reactions could be represented as appropriate, but these were the only ones that were thought necessary for tracking $SO_4$ through the aquifer (see Section 5.4). This was because in the case of $SO_4$, little sorption or reduction was thought to occur in this aquifer (Chapter 2), but if evaporation was extensive, for example, concentrations could rise and precipitation of gypsum occur. Dissolution can also occur, for example through flushing of the precipitated gypsum during the next rain storm. This has been investigated by Maher (2013) for the Riyadh system as part of the current study and has been found to be a possible mechanism.

The basic method for representing precipitation and dissolution is shown in Figure 5-1. A stock represents the store of precipitated mass. Mass is transferred to this stock from the mass stock representing a given body of water when the concentrations in the body of water exceed solubility. If the concentrations in the water body stock fall below solubility, mass already precipitated is transferred back to the water body. Equilibrium is enforced at all times, in effect dissolution and precipitation are assumed to be instantaneous compared with the timestep. For gypsum dissolution and precipitation, this is a reasonable assumption, but it would not be for example for dolomite precipitation as this is very slow indeed (e.g. Apello and Postma, 2002).

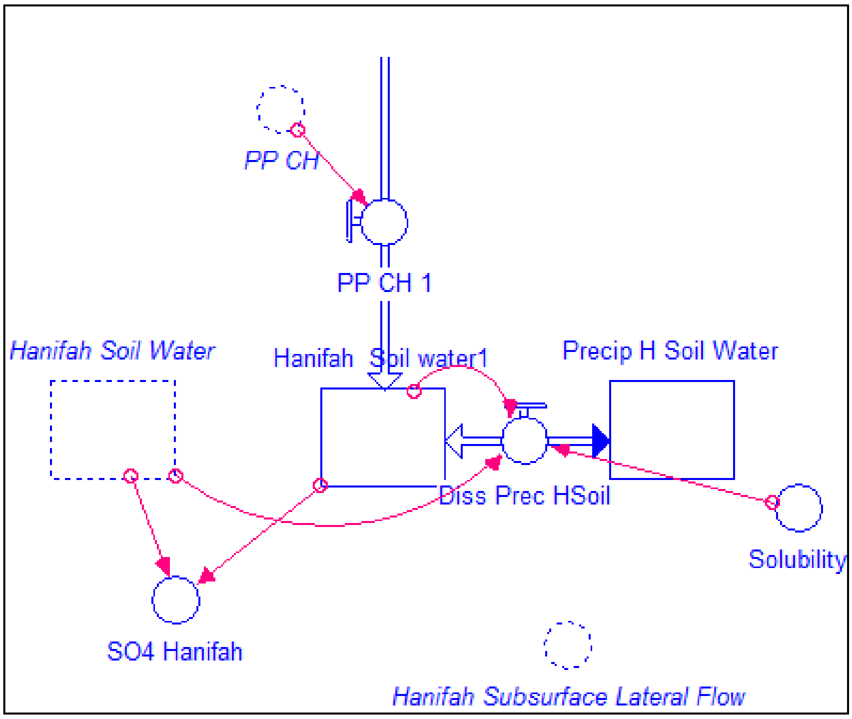



Figure 5-1 Solute precipitation stock

To illustrate the calculation, the example of the wadi soil water will be taken, though similar calculations were also used for all soil water systems represented. The following equation was used to represent solute precipitation in the wadi soil.

$$Precipitation\_Soil\_W = Soil\_water\_wadi\_1 - Solubility * Soil\_Water\_Wadi / DT \qquad \mathbf{5.4}$$

where:

*Precipitation_Soil_W :* a stock representing the mass of solute precipitated in wadi soil (g/day)

*Soil_water_wadi_1* : a stock representing the mass of solute in wadi soil water (g)

*Solubility :* a converter representing the solubility of solute (g/$m^3$)

*Soil_Water_Wadi* : the flow model stock representing the volume of wadi soil water ($m^3$)

*DT* : timestep (days).

The dissolution/precipitation representation was used in the city soil water, the soil water in the wadi, the wadi Hanifah catchment soil water and the wadi catchment runoff.

For species other than $SO_4$, sorption and degradation would need to be included. Sorption can be represented in a very similar way to dissolution/precipitation, i.e. by using a stock to represent the sorption capacity. Degradation is more complicated if the daughter product masses are to be tracked, but the parent could be quite easily represented by having a stock for the daughter product, but with only one directional mass movement possible and the rate being controlled by a kinetic equation. This has not been attempted.

There are a few cases in the system where mass may be transferred only in one direction to or from the water, and this has been included in the model. These cases are:

1. when water supply water is used it will be degraded and concentrations increase before it is discharged;
2. treating water may remove some mass;
3. mass may be added to soil systems (e.g. fertilizer) that then is dissolved.

In the case of 1 and 3, flows were included for mass to be transferred to the appropriate stocks. In case 2, for the example of $SO_4$ removal was thought inappropriate, and hence no $SO_4$ was removed. Details are given when describing the inputs in Section 5.4.2.

## 5.4 Sulfate Transport Model Set Up

### 5.4.1 Choice of Solute to Model

Sulfate occurs extensively in both natural and anthropogenic water systems. Sulfate is the completely oxidized form of sulfur, and it is the most stable aqueous form of sulfur under aerobic conditions. Decreases in sulfate concentrations can be caused by sulfate reduction, dilution and precipitation of sulfate-bearing minerals. As the waters appear to be oxic (Section 2.9), sulfate reduction can be discounted, meaning that only dilution (mixing) and dissolution/precipitation reactions are likely to be occurring. Given this relatively simple chemistry, sources both natural and anthropogenic, and the fact that concentrations may be sensitive to evaporative processes, $SO_4$ was chosen as the solute to model.

### 5.4.2 Development of Sulfate Model

Based on the framework solute transport model described earlier, a model was developed to represent the sulfate in the surface and subsurface systems in the study area.

The solute model was run in a similar way to the flow model, but the first year was repeated 10 times to ensure as near to appropriate initial (transient) conditions as possible. The model was run for 11686 days over the time period 1990 to 2012 with a time step of one day.

The initial values for the masses in the solute stocks were estimated from typical solute concentrations and were as follows:

- City soil water = 445 mg/l.
- City groundwater ( Riyadh aquifer) = 1200 mg/l.
- Wadi soil water = 1100 mg/l
- Wadi groundwater ( Jubaila aquifer) = 1100 mg/l
- Surface water = 800 mg/l.
- Treated water = 800 mg/l.
- Water Supply = 110 mg/l.
- Runoff water = 203 mg/l
- Rain water = 15 mg/l

It was assumed that the sulfate mineral that would be precipitated would be gypsum. To calculate the concentration needed to precipitate a mineral requires estimation of activity coefficients and ion pairs, and a know of the concentrations of rest of the dissolved chemicals. This calculation would be possible in the model, but it would also be awkward to do as both Ca and $SO_4$ concentrations would need to be recorded. So a simple approximate way was made where a concentration limit was set for $SO_4$ above which it was assumed gypsum became saturated. Based on the solubility product for gypsum, estimates of activity coefficients and assuming the presence of the $CaSO_4$ ion pair a value for $SO_4$ concentration at saturation of 1500 mg/l was chosen. This is too high if there are other sources of Ca in solution.

Mass was added to the water used by city as it was assumed that during use the water dissolved mass. This was done by multiplying the mass in the supplied water by a factor that during development of the model was chosen to be 1.5.

Mass was added to the water percolation to the Riyadh Aquifer below city to represent dissolution to saturation by anhydrite in the upper parts of the Arab Formation (Table 2-1).

Mass was added to represent dissolution in the city soils to represent made ground and especially demolition waste (Bottrell et al., 2008). The value chosen during the testing of the model against field data was 200 mg/l.

The concentrations of the groundwater and desalinated water supplied to the city were set at 400 mg/l and 93 mg/l respectively. Very limited data came from National Water

Company (NWC), and SWCC(2013) and no information was available on how these concentrations changes with time.

The concentration of the water upflow in the wadi sediments was set equal to the concentration in the urban wadi section based on limited groundwater data from upstream of the urban area (ADA,2010; Hussein et al.,2012)

Concentration of water in the wadi area deep Jubalia Aquifer groundwater arriving from upstream was set at 100 mg/l based on evidence from Al-Shaibani (2008).

The concentrations in the runoff and shallow groundwater flows in the Hanifah catchment was estimated using precipitation sample concentration data of 15 mg/l (Section 2.9) and the evaporation processes modelled.

## 5.5 Model Calibration

### 5.5.1 Approach

As with the flow model data there are few data to "calibrate" the model against. So the "calibration" is more like a check against the evidence and the final model is probably just one of many possible that is as consistent with the evidence. It is though a starting point for understanding the system and overall it has to be consistent for both flows and concentrations.

The model was developed using $SO_4$ concentration data from wadi Hanifah soil water and groundwater in the Jubaila Aquifer obtained from the ArRiyadh development Authority (ADA) (1990, 2005, 2008, 2009, 2010) and Hussein (2012). Furthermore,

$SO_4$ concentration data were available for the surface water (wadi Hanifah stream) from ADA (2005), Al-Othman (2008), and Al-Ghanim and Al-Akel (2008) and for groundwater in the Riyadh Aquifer from Al-Arifi et al. (2013) and Loni et al. (2013). These data have been reviewed and are presented in Chapter 2 (Section 2.9 and Table 2-4).

### 5.5.2 Comparison with concentration data

Figure 5-2 shows the field data (blue markers and connecting lines) and the final values at the end of the modelling period for the final model. In the figure, $SO_4$ Surface represents the $SO_4$ concentration in surface water, $SO_4$ GW Wadi means $SO_4$ concentration in the groundwater in the Jubaila Aquifer, $SO_4$ GW represents the $SO_4$ concentration in the groundwater in the Riyadh Aquifer, $SO_4$ Wadi means $SO_4$ concentration in the soil water in the Wadi and $SO_4$ Soil water represents the $SO_4$ concentration in the soil water in the City Area.

Very little is known about the conditions of sampling or even the design of the wells sampled. The concentrations are for usually different wells at each time, so even the trends, if any, seen are uncertain. Also each well will represent some local integrated concentration value whereas the concentrations from the model represent stock-averaged values so measurements at different scales. Finally the model values have been affected by an unknown degree of numerical dispersion. For these reasons there has been no attempt to match concentrations with times but just to consider whether the concentrations approximately match. Model can at best then be used to look at changes than exact prediction.

Figure 5-2 shows that the model is obtaining approximately the correct concentrations including the relative levels of the parts of the system for which data exist. The concentrations of $SO_4$ in the wadi sediments ($SO_4$ Wadi) are, though a bit high though within the range observed. The ability to predict the variations in concentration said in the field data will be talked about in next section.

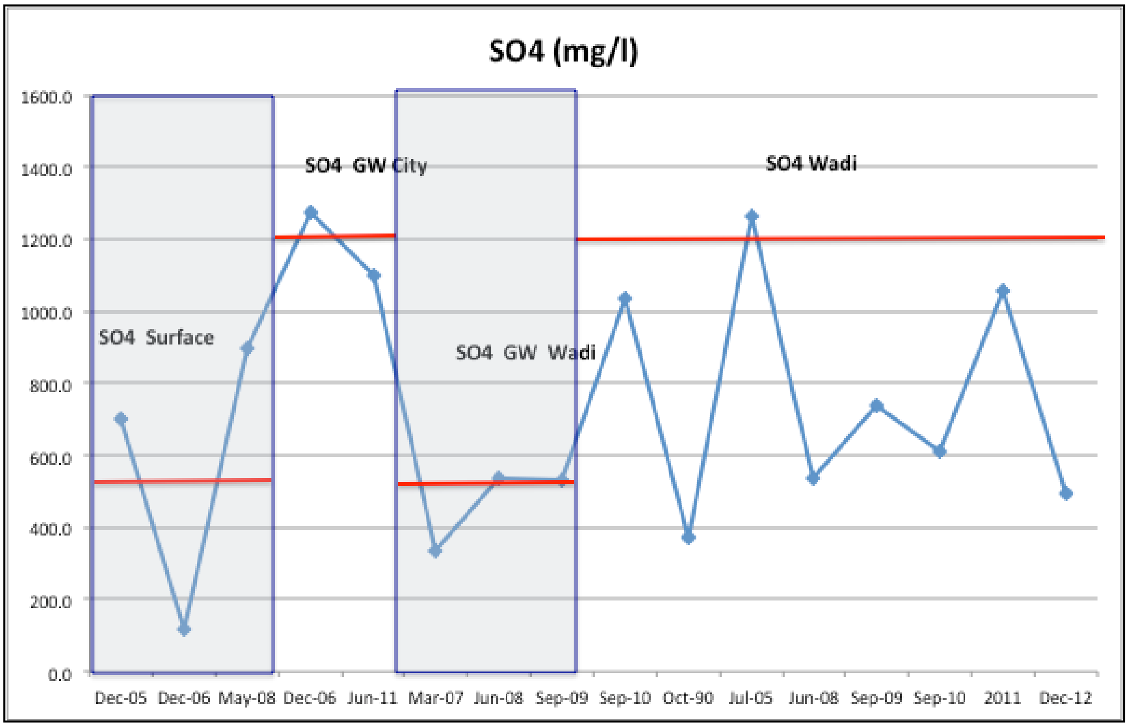



Figure 5-2 $SO_4$ concentrations in the various waters and the values from the final model at the end of the model period (red lines)

## 5.6 Results

The main reason for examining the results here is to check whether they are reasonable and as expected. So another part of the checking of the results against reality. In Chapter 6 the behavior of the model in terms of what is controlling concentrations will be looked at in more detail.

The calibrated SD model outputs $SO_4$ concentrations in the surface water in the wadi, groundwater in the Jubaila Aquifer, groundwater in the Riyadh Aquifer, soil water in the Wadi area and soil water in the Riyadh city area. The results obtained are shown in Figure 5-3. The cycling of ten years at the start of the plot has been included to show the time to initial approximate equilibrium. It may be that concentration equilibrium has not been achieved for $SO_4$ GW, $SO_4$ Wadi and $SO_4$ Soil Water.

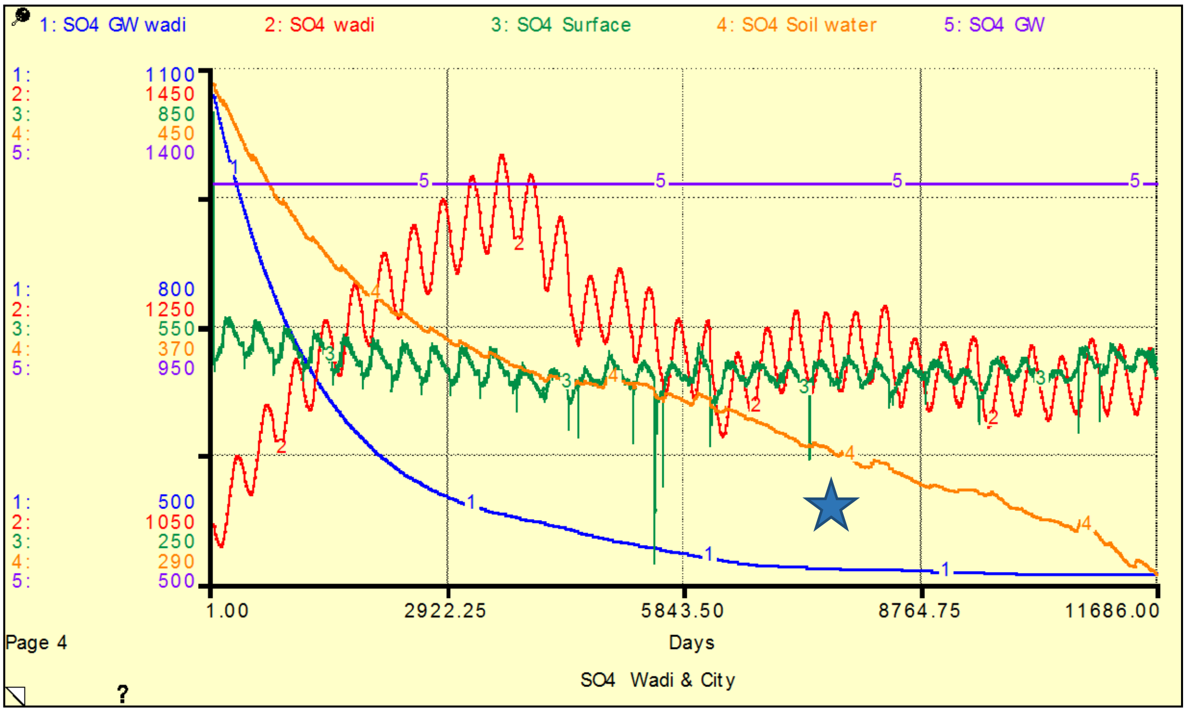



Figure 5-3 Simulated $SO_4$ concentrations ($g/m^3$)

The data from the surface water show the effects of first ten years repeating of the first year flow inputs. Almost repeating concentrations are seen after 10 years. The pattern is seasonal showing effects of rain fall. The surface waters have the biggest variation of any of the waters, as expected as least buffered. But variation is not as much as seen in field data and this may be because of the lumping of the representation. The trend of concentration over time in the model suggests that concentrations do not became worse. The influence of the volume of water is indicated in Figure 5-4. Though the two are closely related the volume increases more than the mass and concentration falls slightly.

It is not too clear why this is the case but could be due to water main leakage increase but sewer flow and leakage decrease affecting engineering flows to the surface waters. Figure 5- 5 and comparing Figure 5- 3 and Figure 5- 4 shows the effect of rain fall and evaporation on the surface water concentrations. When flows increase suddenly because of rain fall the concentration might drop (e.g. two time just before 5843 days labelled in each figure with star).

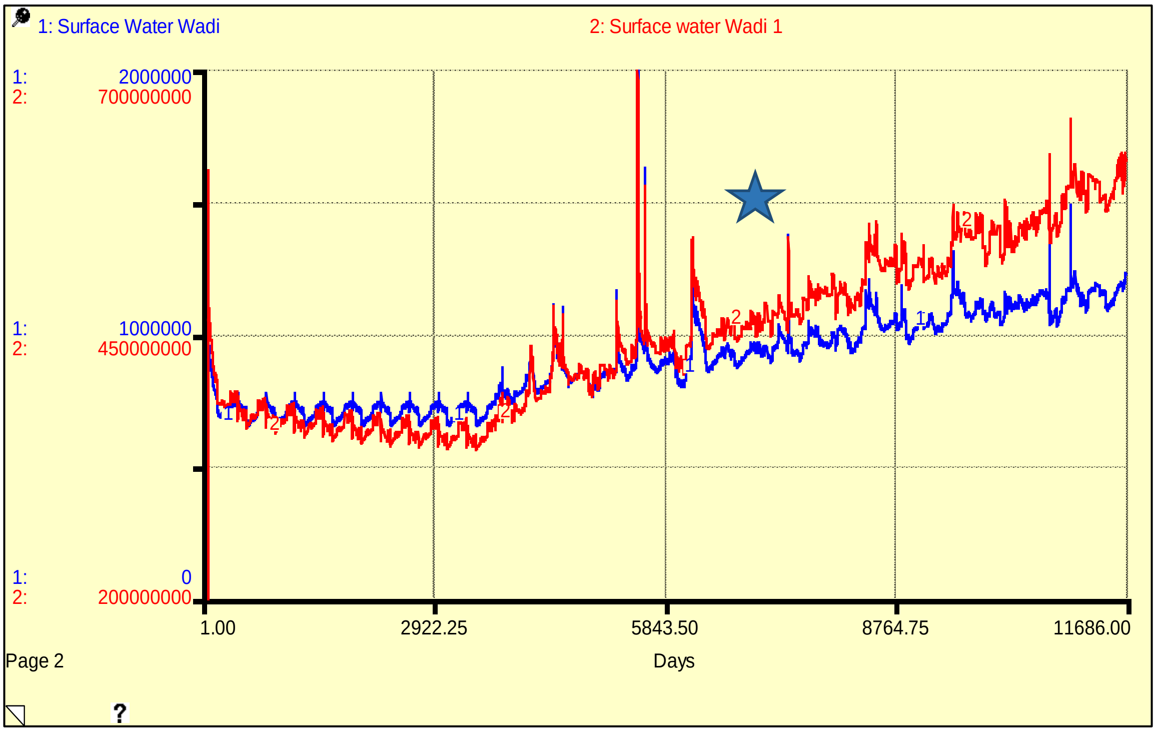



Figure 5-4 Comparison between the mass of $SO_4$ (Surface_water_Wadi_1) and volume of water in the surface water course in the wadi ($m^3$ for water volumes, g for mass of sulfate)

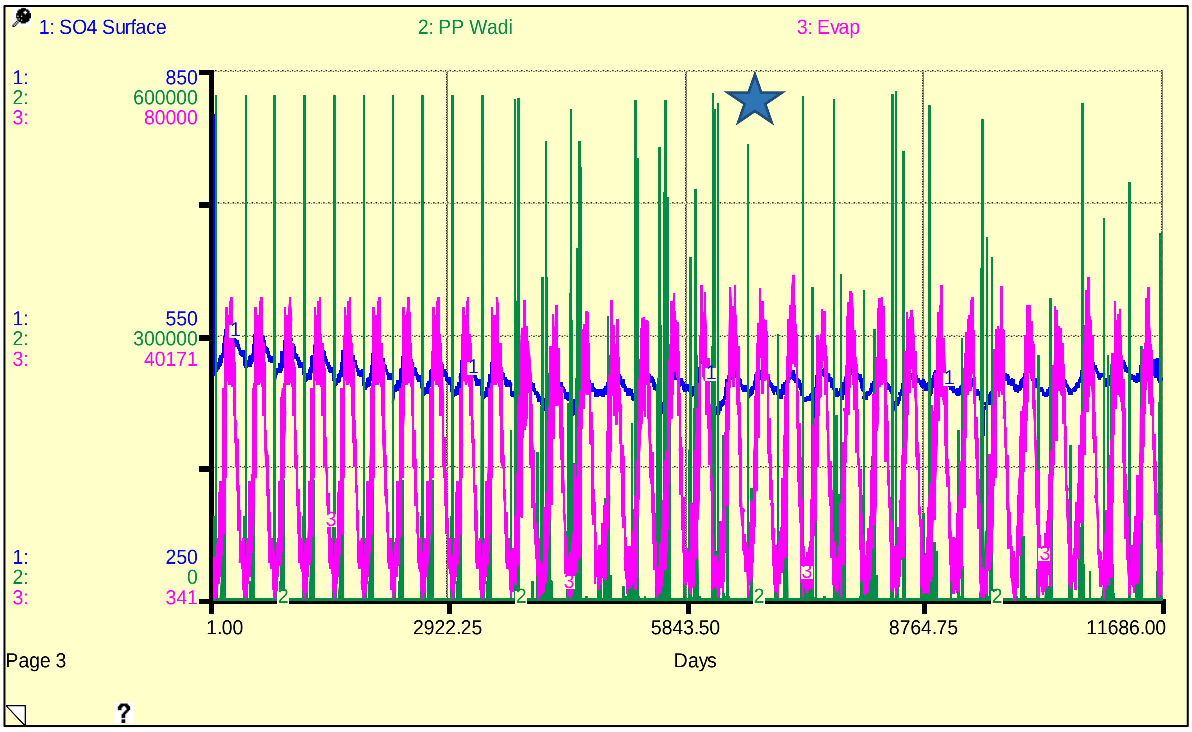



Figure 5-5 Effect of rainfall and evapotranspiration on concentration of the surface water ($m^3$ for water volumes, g for mass of sulfate)

$SO_4$ concentrations in the groundwater of the wadi sediments vary with season. This is expected as they are very close to ground surface with ET and river flows reacting to runoff events. Initially during the ten year repeats of the initial year conditions the concentrations rise but this may be an effect of the initial stock values being wrong and it takes some time to adjust. Then the concentrations stabilise though still respond to changing rain fall. In comparison with field data though in both field data and model the variability is greatest for these waters the variation is lesser. It is clear that the model does not reproduce the variation observed and also average concentrations are a little high. However because of the large volumes represented by stocks it could be that cannot expect to see quick changes in concentration that might be happening in field through local pollution sources or mixing of layered waters in the aquifer. Unfortunately this is difficult to resolve and tell if the model is performing well.

$SO_4$ concentrations in the groundwater of the Jubaila Aquifer are much less variable with time as might be expected as they are damped by going through the upper low permeability parts of the Jubaila Formation and are not so affected by seasons at the ground surface. The concentrations decrease over time but stabilize before the end of the modelled period. The final concentration is just over 500 g/m$^3$ and this is near the field values (Figure 5- 2). This value will be the average weighted by the flow of the recharge from the overlying wadi sediments and the upflow coming into the aquifer.
The concentrations in the city soil water ($SO_4$ Soil Water) are predicted to have decreased with time (Figure 5-3). This seem to be mainly because the sewage leakage mass rate becomes less and the water pipe leakage becomes more with time. Piped water leakage increase is because of greater supply to the city as populations increase. Smaller sewer leakage is due to a greater proportion of sewage water being treated. It is not sure whether that is a real effect or due to the way leakage is calculated. There are no data from the soil water to test against.

The concentration in the Riyadh aquifer are constant. This does not give much information as dissolution of gypsum in the higher parts of the Arab Formation is included in the model. This fixes the concentrations in the percolation to the Riyadh aquifer and as there is no dilution from upflow water as the aquifer starts in the city the concentrations in the Riyadh aquifer are fixed. It is possible that modelling the sewer leakage in a different way the concentrations might rise in the city soil water and that this may result in higher concentrations in the Riyadh aquifer. However during calibration various ways of representing the sewer leakage were investigated but none found enough to raise city soil water high enough to match the concentrations seen in the Riyadh Aquifer and hence dissolution was inferred. It is justified by anhydrite being present in the Arab Formation.

The presence of $NO_3$ in the deep groundwater field samples indicated modern recharge has got to the deep systems in a significant amount. This is also what the model suggests.

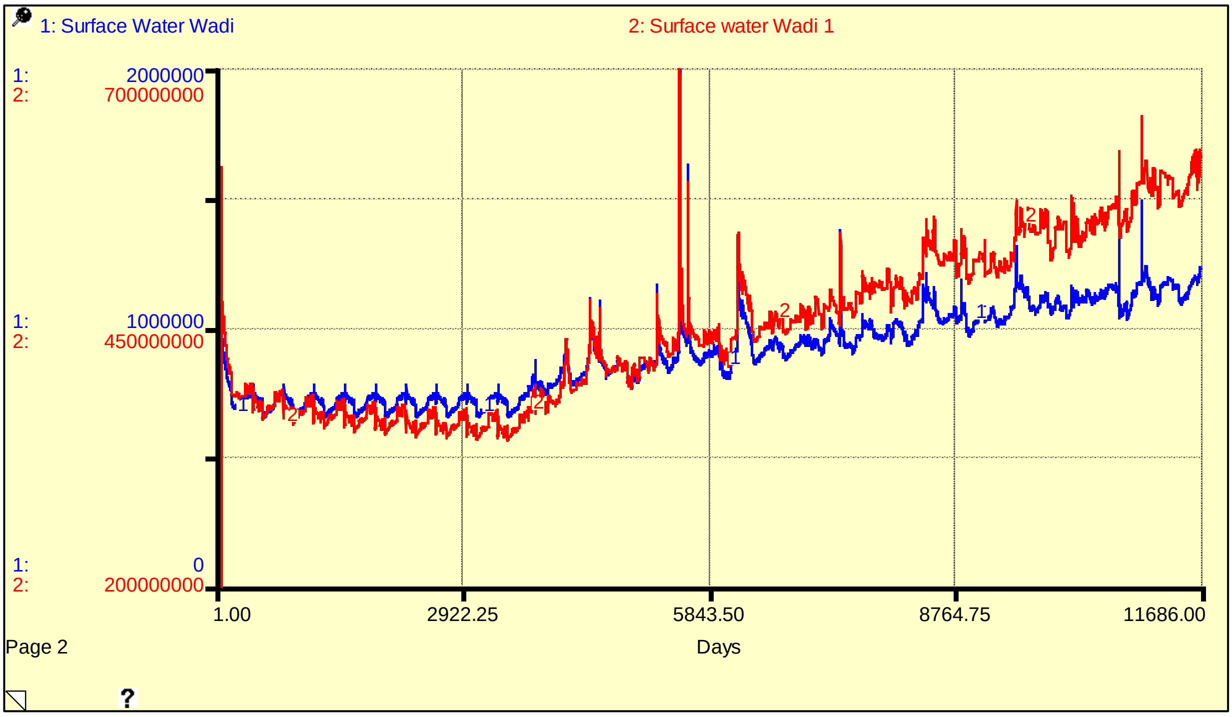



Figure 5-6 Comparison between the mass of $SO_4$ (Surface_water_Wadi_1) and volume of water in the surface water course in the wadi ($m^3$ for water volumes, g for mass of sulfate)

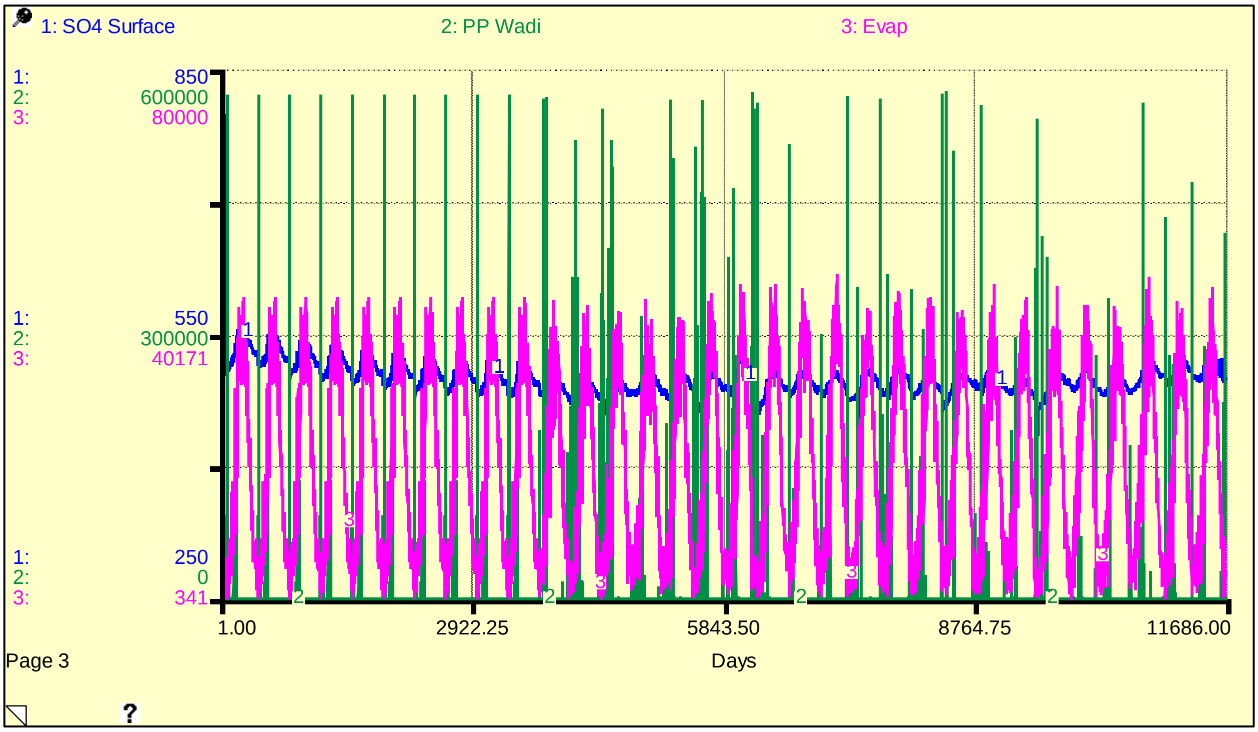



Figure 5-7 Effect of rainfall and evaporation on concentration of the surface water

The sensitivity of the model to the initial values for sulphate was investigated. The concentration values are not well constrained by field data, as discussed in Sections 2.9.2.3 to 2.9.2.5, because of the differences in well depth, variability in values with time and the generally limited size of the data sets. Figure 5-8 shows an example run with initial concentrations as indicated in Table 5-1 which also shows the initial concentrations used in the standard model. The values used for this run were chosen to illustrate what happens even with significant changes in initial values. Comparison of Figure Figure 5-3 with Figure 5-8 shows that the variation in time of the concentrations is similar though in the first few years there is a difference. The final concentrations in both models are shown in Table 5-1.

Table 5-1 Comparison of $SO_4$ concentrations between standard model & an example sensitivity test model

| Time (Day) | $SO_4$ Concentrations (mg/l) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $SO_4$ GW Wadi | | $SO_4$ Wadi | | $SO_4$ Surface | | $SO_4$ Soil water | | $SO_4$ GW | |
| | standard model | Test model | standard model | Test model | standard model | Test model | standard model | Test model | standard model | Test model |
| 0 | 1100 | 800 | 1100 | 800 | 800 | 600 | 450 | 600 | 1200 | 800 |
| 2922 | 601 | 571 | 1343 | 1188 | 497 | 514 | 366 | 398 | 1200 | 870 |
| 5843 | 534 | 537 | 1243 | 1165 | 490 | 493 | 347 | 352 | 1200 | 929 |
| 8764 | 514 | 519 | 1224 | 1185 | 497 | 497 | 321 | 321 | 1200 | 977 |
| 11686 | 510 | 513 | 1200 | 1186 | 501 | 501 | 293 | 293 | 1200 | 1017 |

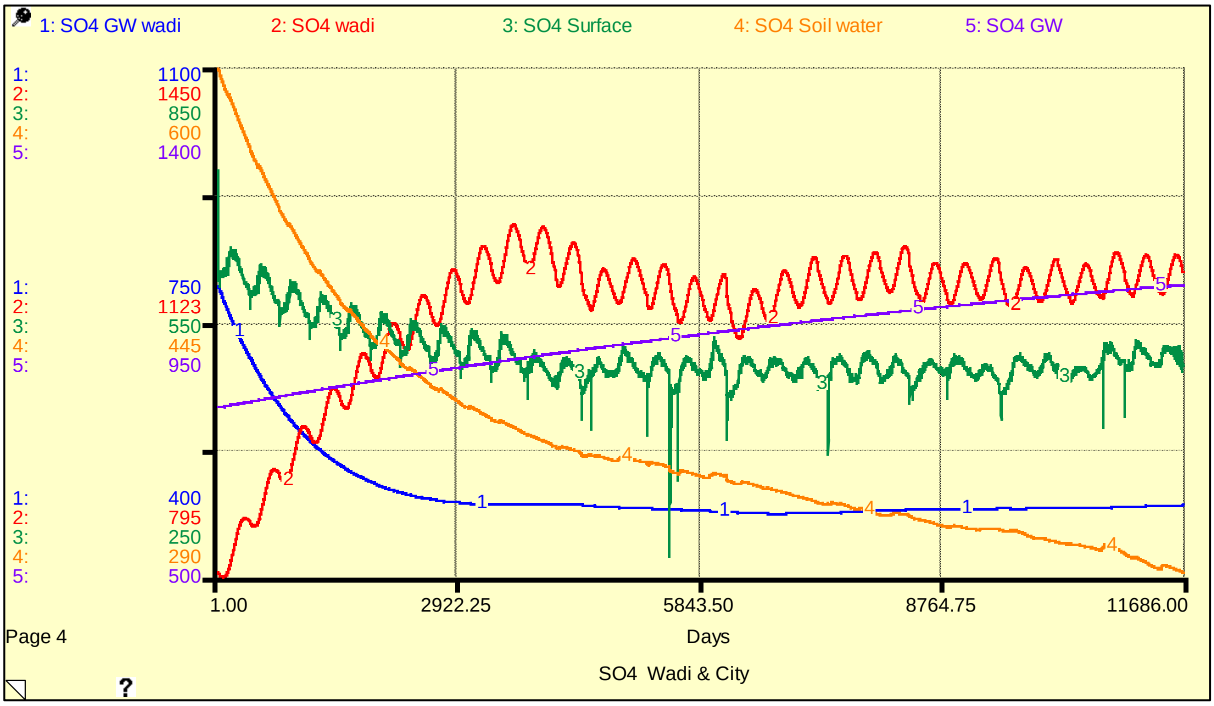



Figure 5-8 An example of the sensitivity of solute model to initial $SO_4$ concentrations

Table 5-1 and Figure 5-9 show the initial $SO_4$ concentrations of Wadi groundwater and city soil water are close to the concentrations of the standard model from time 2992 days to the end time of the model run. This suggests that the final salt balances in the system are not very sensitive to differences in the initial concentrations that reflect possible uncertainty in initial concentration values.

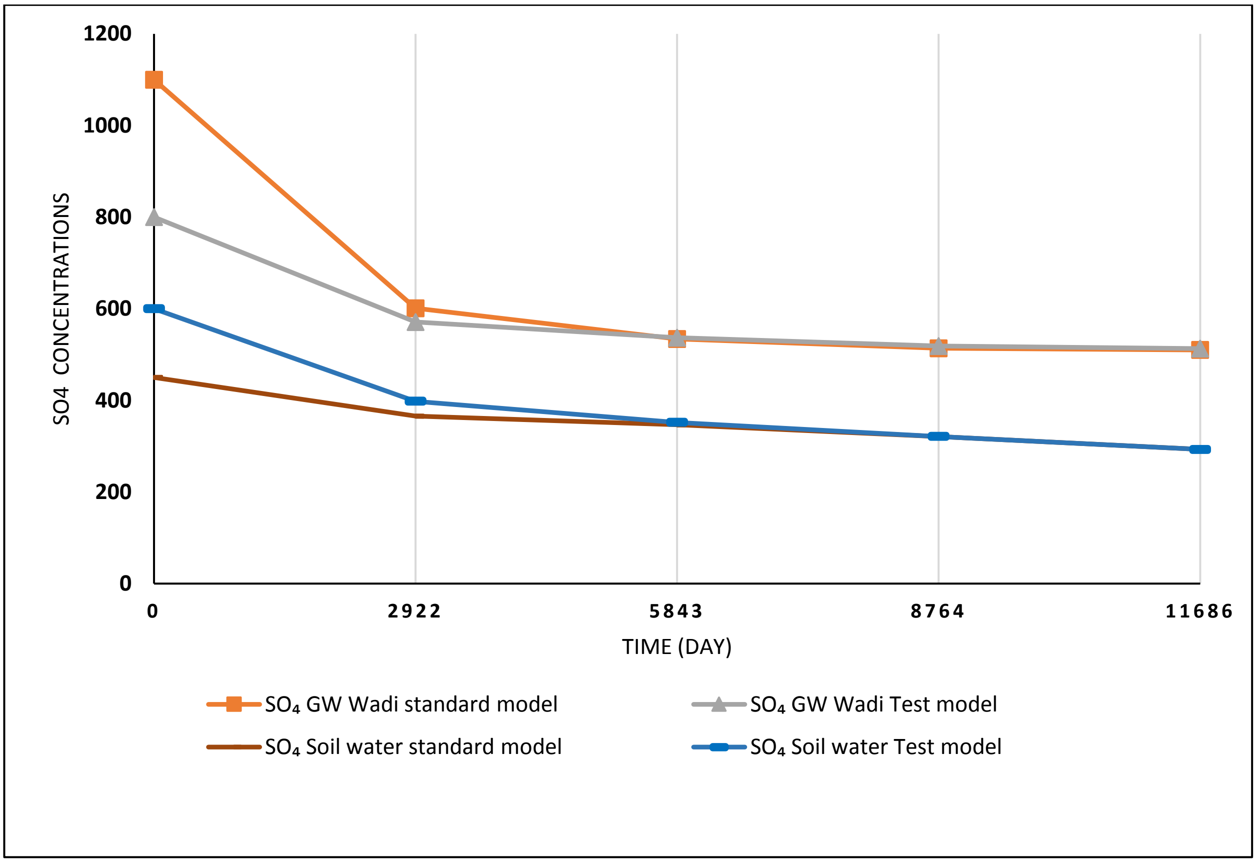



Figure 5-9 Comparison $SO_4$ GW wadi & $SO_4$ Soil water between standard & example sensitivity test models

## 5.7 Conclusions

The model appears to be generally consistent with the field evidence and appears to make general sense. However, it does not produce the spatial or time variation that the real system does but this could be because of the coarseness of the discretizing of the system. It would be useful to try out a range of other determinands especially Cl and $NO_3$ to see if the model is consistent with these. It would be useful to try out cations but would probably have to add in ion exchange. An EC survey of the city waters would perhaps help.

The model indicates a drop in concentration in the urban soil area and this needs to be investigated. Elsewhere there is no indication of rapidly rising concentrations of any determinand. The effects of rainwater and evapotranspiration clearly appear within the results of solute model, even if rain fall by itself directly does not cause recharge significantly.

# CHAPTER 6: : MODEL APPLICATIONS

## 6.1 Introduction

### 6.1.1 Purpose of chapter

This chapter presents an exploration of the dynamic system flow and solute model for the Riyadh City urban water in the Kingdom of Saudi Arabia. There are two main contexts for this exploration: 1) examining the hydrogeological implications of the model; and 2) considering the sustainability of the system. The exploration will be achieved by two means: examining the output from the 'standard' model in detail, and undertaking a sensitivity analysis involving a number of factors.

### 6.1.2 Hydrogeological implications of the model

The model equation system may result in implications for hydrogeological processes, and these need to be examined partly to check the likely validity of the model, though much of this been done in Chapters 4 and 5, and partly to see what might be learnt. The model has a potential ability to predict results that would not be apparent from considering each process represented in it separately, i.e. it has a potential 'complexity' that should be examined. This has been done by undertaking sensitivity analyses based on two 'scenarios' described in Section 6.2 and using result and results from Chapters 4 and 5.

### 6.1.3 Sustainability

#### *6.1.3.1 **Introduction***

The water system for Riyadh, as with any other city, has to be sustainable, i.e. it has to be sustainably managed. It is necessary for the water demand of the area to be satisfied in a continuous manner. This requires consideration of factors such as social, climatic, urban, technological innovations, water demand and consumption futures, policies, new sustainable paradigms and precautions against terrorism activities. Four example drivers of this have been chosen for investigation, as follows:

1. water demand (or supply);
2. urban decay;
3. climate change; and
4. management action.

These drivers are detailed in the following subsections.

#### *6.1.3.2 **Water demand***

Water supply will increase as populations increase and this is already in the standard model as population has increased through the period modelled. Also demand often increases as economic development occurs (e.g. Kayaga and Smout, 2011). To investigate the effects of demand increase the supply has been increased and the period of modelling remodelled (Scenario 4 below). The predicted effects on flow and water quality have then been examined.

#### ***6.1.3.3 Urban infrastructure decay***

Urban area water distribution and infrastructure needs maintenance works progressively and continuously to ensure sustainable structures with minimum failures. However, there are two main problems that are associated with urban maintenance. First, water distribution mains decay over time, and therefore, need careful checking, control and maintenance and replacement work. Second, the sewerage system can also decay and cause leakage into subsurface. Malfunctioning of sewerage works in cities like Riyadh can also cause sewage polluting materials leaking into the groundwater aquifer systems though this is not investigated here. Here increase in leakage from domestic water supply will be looked at as an example of decay of infrastructure (Scenario 5 below).

#### ***6.1.3.4 Climate change***

Global warming and consequent climate change are causing additional problems for water resources. Many areas around the world have reported generally increasing trends in precipitation intensities. The effect of climate change in KSA is predicted to be a significant decrease in the annual average amount of rainfall (Almazroui et al., 2012) but knowledge of likely changes in intensity is not available. Here we will look at both increase and decrease in total rainfall amounts over the same period as the standard model (Scenario 3 below).

#### ***6.1.3.5 Management actions***

Management of systems includes implementing water saving strategies. There are few possible water saving strategies including: use of different water quality types e.g.

reuse of grey water; rainfall harvesting; reduction in volumes used for flushing toilets and showers; educating public; reduction in irrigation rate; artificial recharge. These all could be included in model (with some development in places) but here we look at one example management action of leakage reduction. The effects of leakage reduction in sewers and domestic water supply pipes will be examined (Scenarios 6 and 5 below). In these cases this means that in effect demand increases as total supply will be kept constant.

### 6.1.4 Structure of chapter

Both the hydrogeology and the sustainability contexts have been investigated partly by using sensitivity analyses as indicated above, the latter grouped into six ‘scenarios’: the first set of scenarios is related to investigating the hydrogeological implications of the model; the second set relates to sustainability issues. These scenarios are defined in Section 6.2. Section 6.3 describes the model water balances for the main components of the system for the ‘standard’ model developed in Chapter 4: this is the first part of the investigation of the hydrogeology of the model system. Section 6.4 deals with sensitivity investigations of hydrogeological parameters, the first of the sets of scenarios. So Sections 6.3 and 6.4 together deal with the hydrogeological implications of the model. Section 6.5 then presents the model results for the sustainability scenarios, the second set of scenarios. Section 6.6 is a discussion drawing together the hydrogeological and sustainability results.

## 6.2 Model Scenarios

Details of six scenarios used in the analysis are based on rock hydraulic conductivity (related to understanding the hydrogeology), and rainfall, water supply and leakage of urban water (all related to sustainability, but also provide hydrogeological insights). To investigate all possible aspects is not possible in thesis and the results are illustrations only of what could be done. The sensitivity analysis only considers change in each of these parameters one at a time. Also for this purpose of illustration the changes has been made to the modelled period up to 2012 rather than to attempt to model into future. The range of values for each parameter are given in the appropriate subsection below.

The individual scenarios are summarised as follows:

(a). Scenario 1 is for hydraulic conductivity of upper part of the Jubaila Formation that controls the recharge from the wadi sediments to the deep aquifer,

(b). Scenario 2 is for hydraulic conductivity of Sulaiy Formation that controls the percolation from the city soil aquifer to the Riyadh Aquifer (Arab Formation),

(c). Scenario 3 is rainfall change,

(d). Scenario 4 is water supply change,

(e).Scenario 5 is leakage of domestic water networks,

(f). Scenario 6 is leakage of sewerage networks.

## 6.3 Water Balances

The water budget is divided into three sub-water balances, which are shown in Figures 6-1, 6-2 and 6-3: the water balance/groundwater budget for the city soil; the wadi soil / sediments; and the surface water in the wadi. In each case the balances are for the last day of the model calculation (31-12-2012).

The water budget shown in Figure 6-1 and Table 6-1 is for the city soil. The total water balance on 31$^{st}$ December, 2012 happens to be that inflows are almost exactly equal to the outflows. Irrigation and leakage can be seen as the major recharge sources, rather larger than the rainfall input, and engineering flow is the main discharge component followed by the percolation to the Riyadh Aquifer. The leakage value from water supply and sewerage networks is the most significant inflow (~83%) in the water balance as shown in Table 6-1. Also, it was found that 15% of the rainfall amount is diverted to the city runoff. The remaining 85% can be divided into ET/atmospheric (~71%) discharges and subsurface/surface systems (~14%).

Losses from the sewerage system represent an input in the water balance, which is estimated to be about 42% of the total inflowing water. The quantity of return from irrigation is equal to the difference between the water supplied for irrigation and the actual evapotranspiration (for this one day the value would be at minimum 65% of the irrigation, and though this seems high, over-irrigation has been blamed for local flooding in Riyadh by Rushton and Othoman (1994)). However, this could represent an inaccuracy in the ET calculation method suggested by Salih and Sendil (1984) and used here.

The water movement through Riyadh city soil daily is both lateral and vertical. The lateral flow joins into the gravity drainage networks (Engineering_Flow) while the vertical flow is for soil water percolating into the deep Riyadh Aquifer, which equals half of the lateral flow. A large amount of water flows in the city soil as a result of leakage from the domestic networks and city irrigation water. Evapotranspiration in the city soil is about 4% of the total soil water volume, which represents nearly 71% of the rainfall water.

Table 6-1 Water balance budget for city soil on 31-12-2012

| **Water inflow/ outflow** | **$m^3$/day** | **% of subtotal** | **% of total** |
|---|---|---|---|
| *Inflow* | | | |
| 1. City Irrigation | 79625 | 11.41 | 5.7 |
| 2. Rainfall | 39316 | 5.64 | 2.8 |
| 3. Water networks leakage | 296698 | 42.53 | 21.3 |
| 4. Sewage leakage | 281960 | 40.42 | 20.2 |
| Subtotal 1 | 697599 | 100 | 50 |
| *Outflow* | | | |
| 1. Storm-water drainage/city runoff | 5904 | 0.85 | 0.4 |
| 2. Engineering flow/drainage system | 445249 | 63.76 | 31.9 |
| 3. ET | 28122 | 4.03 | 2.0 |
| 4. Percolation/infiltration | 219055 | 31.36 | 15.7 |
| Subtotal 2 | 698330 | 100 | 50 |
| TOTAL | 1395929 | | 100 |

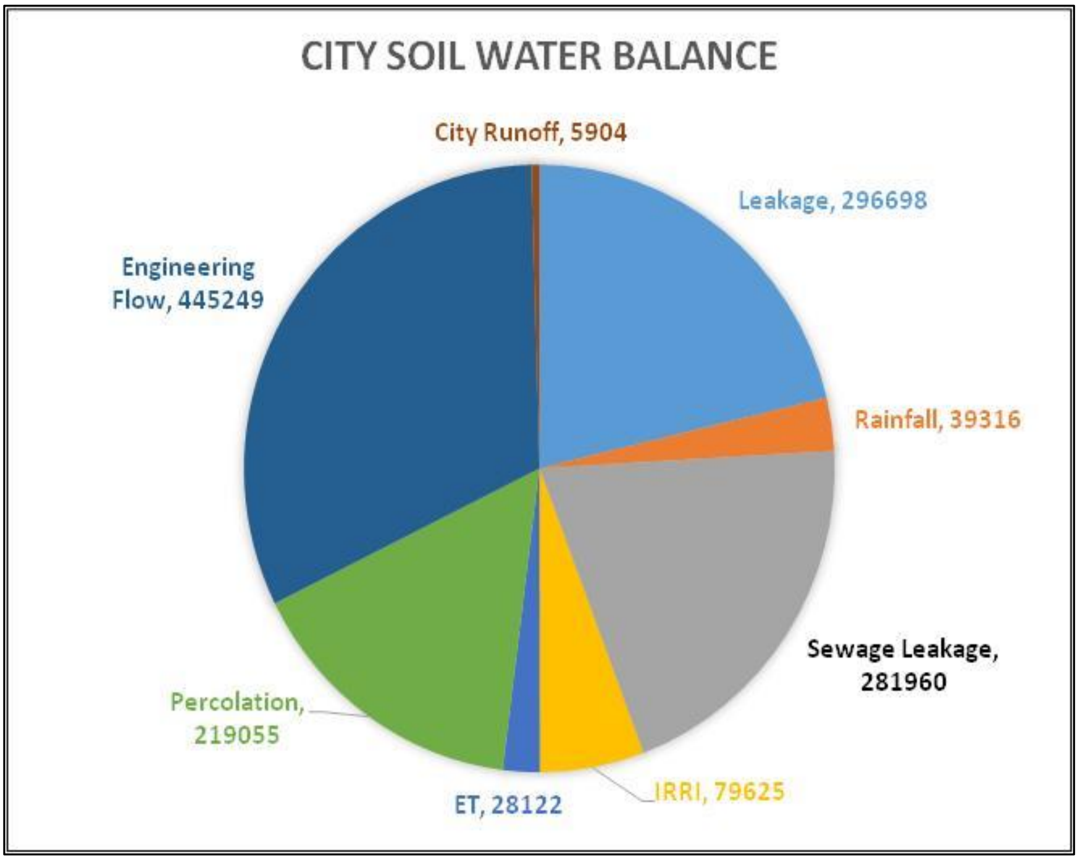



Figure 6-1 City Soil water balance ($m^3$/day) for 31-12-2012

In summary the city soil system is mainly inflows from leakage of piped water supplies and sewers with a little irrigation and less rainfall. Outflow is dominates by the deep drainage network and by percolation down to the Riyadh Aquifer. The deep drainage seems to keep water levels low and so limit ET to a small amount. The percolation is the only source of recharge in the Riyadh Aquifer in this area as Riyadh is the up dip part of the aquifer. So all flow is from the city and so all groundwater quality in aquifer is controlled by discharge from city and so from urban leakage in general. This fits with Foster et al. (1999) view that cities increase recharge and the case looks similar to the case they cite of Lima. This water balance indicates an annual recharge of about 500 mm despite annual rainfall being less than 200mm.

The water balance for the sediments in Wadi Hanifah for 31-12-2012 is given in Table 6-2 and Figure 6-2. The balance on this date is such that the outflows are less than 1% higher than the inflows. The water flow in the soil layer in Wadi Hanifah behaves differently to the city soil system as shown in Figure 6-2.The main inflows to the wadi sediments are from the wadi river, followed by irrigation from the Jubaila Aquifer, then rainfall. Outflows is by evapotranspiration and recharge to the Jubaila Aquifer mainly. The lateral inflow and outflow is very little, less than 0.2% of total inflows or total outflows or about 260 $m^3$ /day. This suggests that the natural system would have low groundwater levels with water discharging downwards.

Evapotranspiration in the wadi area is substantial, which represents a large percentage of soil water (21%). This is due to the presence of large green areas that increase the effect of evapotranspiration: the water level in wadi Hanifah has come close to the ground surface and this further increases the rate of evapotranspiration. The lateral groundwater flow from rest catchment in west is predicted by the model to be negligible.

The main characteristic of the urban section of wadi Hanifah is that the flows are mainly vertical. Water enters and leaves vertically and almost none flows laterally. This will mean that all the mass from the urban discharges moves vertically. However the system is not closed system completely as there is lateral flow in the deep Jubaila Aquifer that may slow the rise in concentrations in the wadi sediments. Solute concentrations are not generally rising in the wadi sediments (Figure 5- 3) so this dilution seems to be important. The total flows in the wadi system are much smaller than in the city system. But this expected as city area is greatly more than wadi area.

Table 6-2 Estimated water balance for the wadi soil for 31-12-2012

| Water inflow/ outflow | $m^3$/day | % of subtotal | % of total |
|---|---|---|---|
| Inflow | | | |
| 1. Irrigation from Jubaila aquifer | 19139 | 15.6 | 7.8 |
| 2. Recharge from surface water | 96359 | 78.7 | 39.2 |
| 3. Subsurface inflow | 210 | 0.2 | 0.1 |
| 4. Rainfall wadi | 5911 | 4.8 | 2.4 |
| 3- Lateral sub-surface flow | 748 | 0.6 | 0.6 |
| Sub-total | 122367 | 100.0 | 49.8 |
| Outputs | | | |
| 1- discharge to GW | 47487 | 38.5 | 19.3 |
| 2- Subsurface flow out | 308 | 0.2 | 0.1 |
| 4- ET Wadi | 75473 | 61.2 | 30.7 |
| Sub-total | 123268 | 100 | 50.2 |
| TOTAL= | 245635 | | 100.0 |

The balance of surface water flow along wadi Hanifah is shown in Table 6-3 and Figure 6-3 for 31-12-2012. The inflows and outflows are almost identical for this day. Large volumes of treated water discharge from Riyadh city (26% of total flows) and then flow out as surface water discharge to the non-urban wadi areas towards the southeast (44%). Little (around 5%) surface water is discharged to the wadi soil. Almost all of the surface water flows out towards the non-urban areas of the wadi (as surface out flow). Direct evaporation from surface water is about 20,000 $m^3$ / day or about 1% of the volume of surface water.

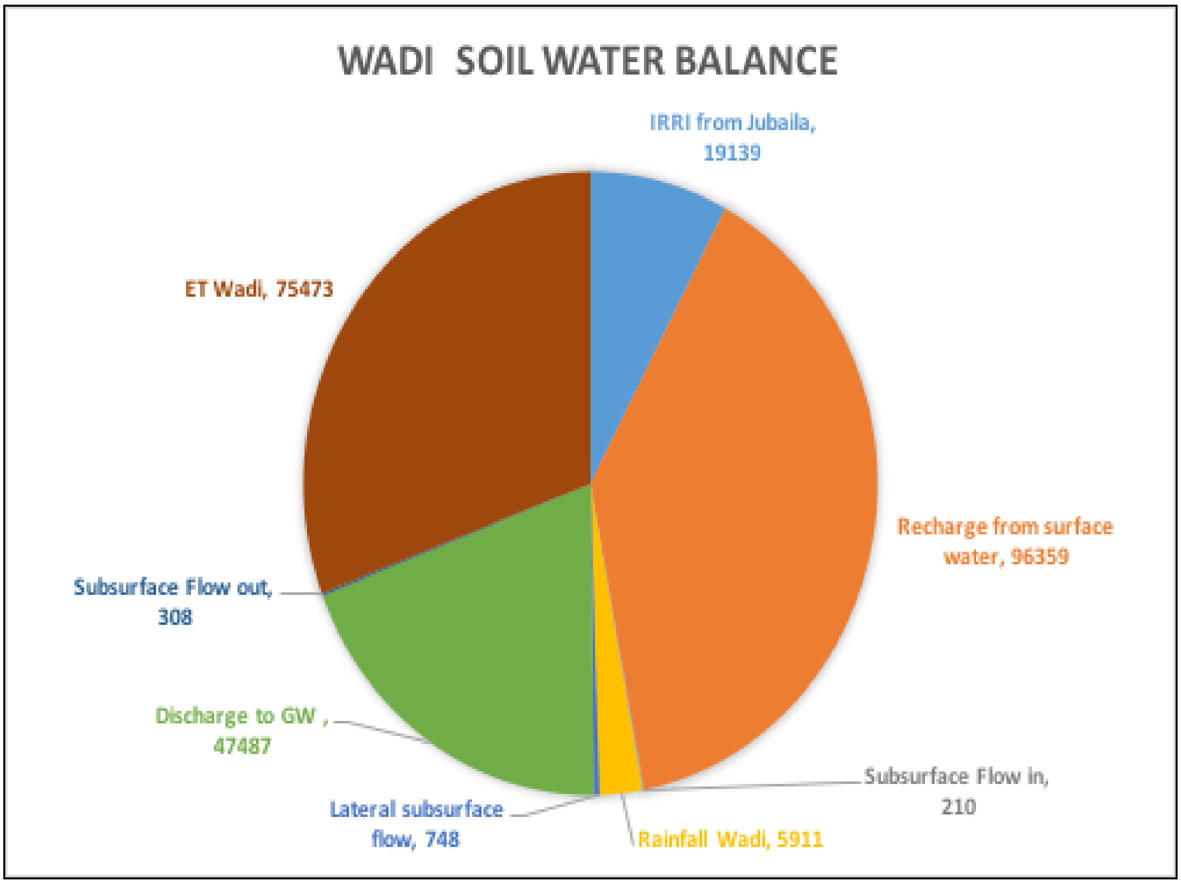



Figure 6-2 Wadi Soil water balance ($m^3$/day) for 31-12-2012

Table 6-3 Estimated water balance for wadi surface waters on 31-12-2012

| **Water inflow/ outflow** | **m$^3$/day** | **% of subtotal** | **% of Total** |
|---|---|---|---|
| *Inflow* | | | |
| 1-Urban wadi runoff | 572 | 0.1 | 0.0 |
| 2-Surface water discharge from city (treated water) | 483950 | 52.0 | 26.0 |
| 3-Non-urban wadi runoff | 874 | 0.1 | 0.1 |
| 4-Sub-surface flow from city (Engineering flow) | 445249 | 47.8 | 23.9 |
| Sub-total | 930645 | 100 | 50 |
| *Outputs* | | | |
| 1-Discharge water to wadi soil | 96359 | 10.4 | 5.2 |
| 2-Surface water flow out urban wadi | 814025 | 87.5 | 43.7 |
| 3-ET | 20178 | 2.2 | 1.1 |
| Sub-total | 930562 | 100 | 50 |
| Total | 1861207 | | 100.00 |

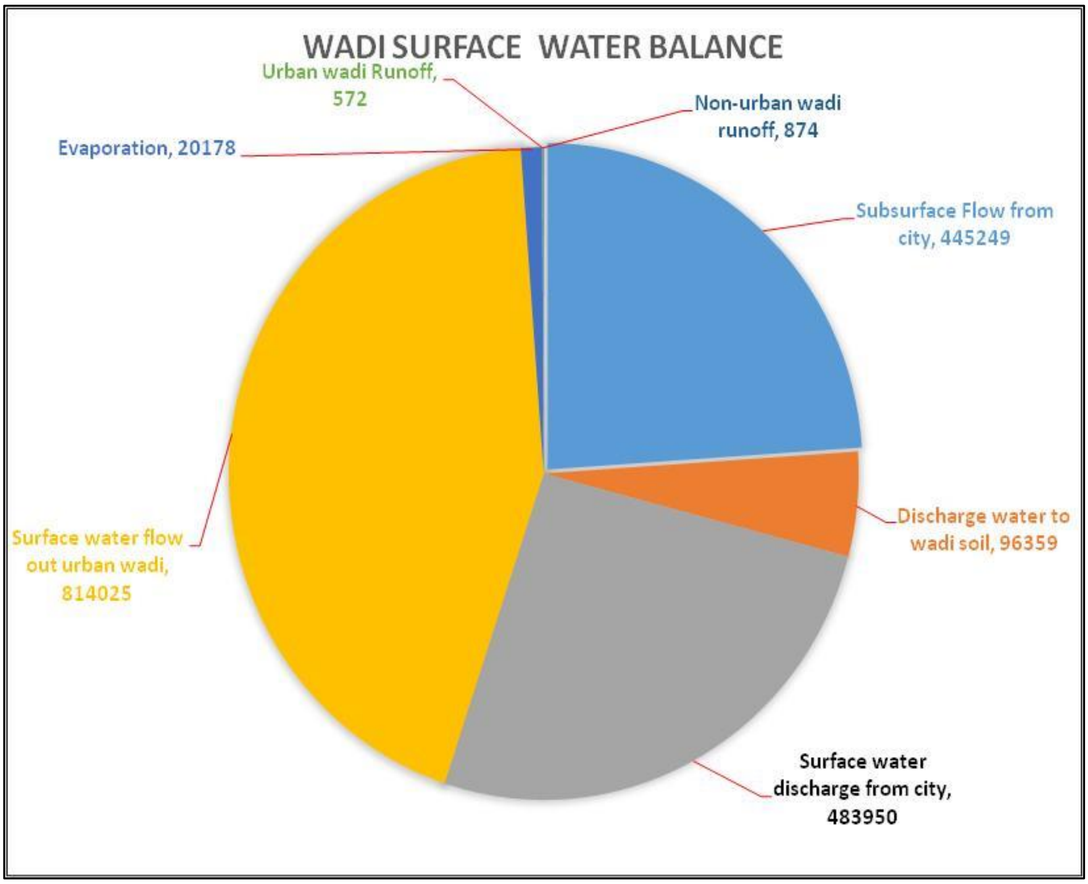



Figure 6-3 Wadi Surface water balance ($m^3$/day) for 31-12-2012

In summary the significant water flows are summaried in Figure 6-4. The system is connected through all main stores of water even though flow in aquifers discharges in different directions. Artificial flows (red) are dominant. Recharge to both Jubaila Aquifer and Riyadh Aquifer are artificial. So the system is a major artificial recharge scheme and also could be considered a soil water treatment system for the wadi stream water infiltration (thoughs most water from treatment works discharges as surface water from the urban section of wadi). Under natural conditions there would be only rainfall and evapotranspiration and periodic surface flows which infiltrate. A simplified model of the system might be possible to make based on Figure 6- 4.

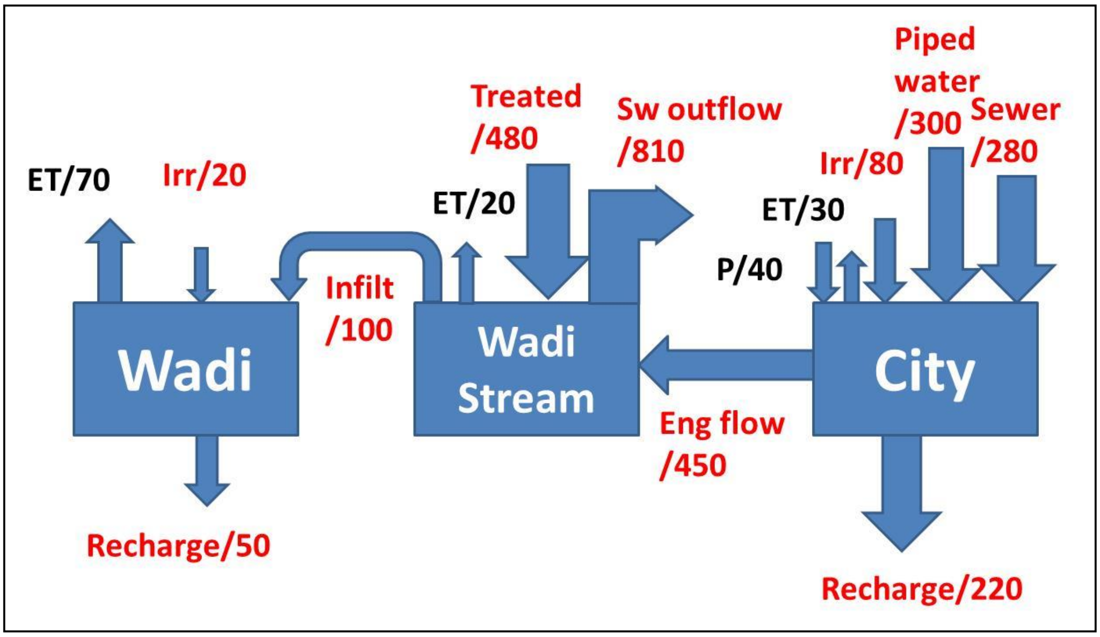



Figure 6-4 A summary of the main water flows from model at end of run. Red indicates non-natural flows. Number is flow in thousands of cubic metres per day.

## 6.4 Hydrogeological implications Scenarios

### 6.4.1 Scenario 1: Hydraulic conductivity of Jubaila Formation

The average value of hydraulic conductivity of the upper part of Jubaila Formation is set at 0.001 m/day in the standard model. This value has some support from the work of Italconsult (1969) but GDC (1979) suggested higher values. To investigate the sensitivity of the model predictions to this parameter, it has been varied over the range 0.001 to 0.1 m/d (i.e. 0.001, 0.01, 0.03, 0.05, 0.07 and 0.1m/day). Lower values were not considered as the model predicted extensive flooding which does not occur and the literature indicated possibly higher values.

Figure 6-5 shows the changes of water volumes in the stocks of waters under scenario 1. It can be seen that the volume of wadi soil water drops when the hydraulic conductivity increases from 0.001 m/day to 0.01m/day. This is expected as higher hydraulic conductivity at the base of the wadi soil will result in more leakage. It seems very sensitive as the volume drops to almost zero with a small change in hydraulic conductivity and after this the changes are very small as head in soil cannot decrease any further significantly. Recharge to the Jubaila Aquifer depends on the head in the wadi soil and with higher hydraulic conductivity almost all the water is transferred until heads are very low. As expected there is no impact on the city soil or Riyadh Aquifer. There is only a very minor effect on the surface water flows again as expected. There is some effect on Jubaila Aquifer heads (note log scale is used). So the determination of the hydraulic conductivity of the upper Jubaila Formation can be made by properly calibrating the model, or a simplified version of it against the measured heads in the wadi soil. So these should be monitored.

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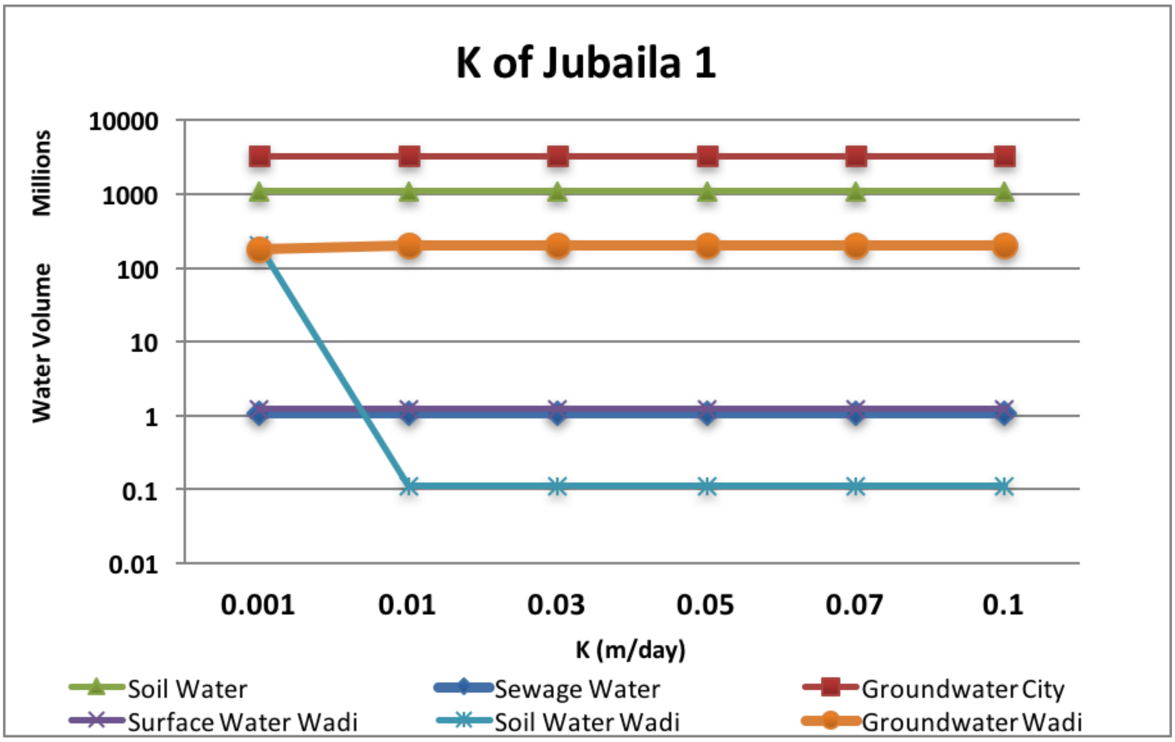


Figure 6-5 The changes of water stocks under scenario 1 (volumes in cubic metres)

The sulphate concentrations - in the soil water in the city ($SO_4$ Soil water), surface water wadi ($SO_4$ Surface), sewage water ($SO_4$ Sewage), soil water wadi ($SO_4$ Wadi), groundwater city in Riyadh aquifer ($SO_4$ GW) and groundwater wadi ($SO_4$ GW wadi) in Jubaila aquifer - are presented in Figure 6-6.

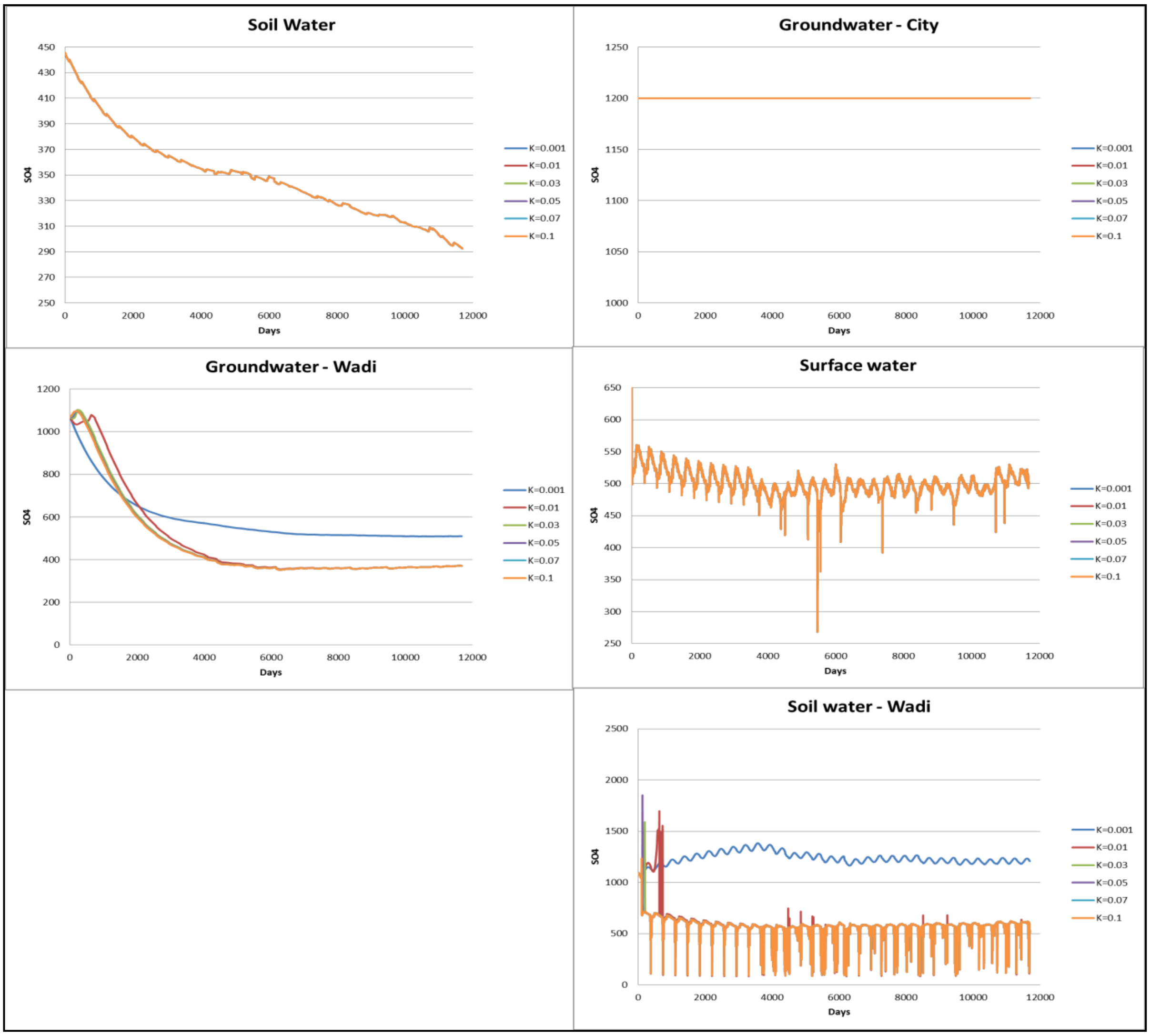


Figure 6-6 Sulphate concentrations (mg/l) in waters in scenario 1

The effects on the concentrations in the city soils and the Riyadh aquifer are negligible, as might be expected. Likewise the effect on the treated water discharge concentrations is negligible, again as expected. All these parts of the system are separated from the wadi system unless water flows back into the city, and this does not happen.

Between permeabilities of 0.001 and 0.01 m/d, there is a significant effect on concentrations, and variation in time of concentrations, in the wadi soil water, and therefore in the Jubaila Aquifer. The concentrations drop from about 1200 mg/l to about 500 mg/l in the wadi sediments, and from >500 mg/l to less than 400 mg/l in the Jubaila Aquifer. At the same time the variation in concentration with time in the wadi sediments becomes much more pronounced. Increasing the hydraulic conductivity above 0.01m/d makes little difference to the concentrations at the end of the run. The more flashy nature of the concentrations might be expected as a result of increasing the hydraulic conductivity by a factor of 10. This variation is more agreement with field data but concentrations are lower than field data. The lower average value of the concentrations in the soil are due to less evapotranspiration as discussed above, under low water content in wadi soil (Figure 6-6). Lower concentrations in the wadi sediments will result in lower concentrations in the Jubaila Aquifer. The surface water concentrations are unaffected by the change in hydraulic conductivity as there is very little flow from the aquifer sediments to the wadi river even when hydraulic conductivity was set at 0.001 m/d (Table 6-3).

So the concentrations are sensitive to the hydraulic conductivity of the upper Jubaila Formation so this too could be used to determine a better hydraulic conductivity for the upper Jubaila Formation and in the model here the best hydraulic conductivity is that chosen in final model.

### 6.4.2 Scenario 2: Hydraulic conductivity of Upper part Arab Formation

The average hydraulic conductivity value in the upper member of Arab Formation has been suggested to be about 0.001 m/day by ADA,1990. However, this hydraulic conductivity may change in different locations depending on the lithology of rocks or as a result of cracks and joints, and obtaining a reliable average value for use in the model is uncertain. Determining the sensitivity of the model predictions to the value of hydraulic conductivity used in the model will indicate its relative importance, the security of the value used in the model and may provide insight into how the system works.

Figure 6-7 shows the changes of volumes of water stocks in the flow model due to changes of hydraulic conductivity in the upper part of Arab Formation. It can be seen that there is a decreasing volume of city soil water as expected and there is an increase in percolation to city groundwater (Riyadh Aquifer) as expected. The same behaviour in scenario 1, the water dropping in city soil when the hydraulic conductivity increases. On the other hand, the volume of surface water drops from around one million cubic metres to 800,000 cubic metres, as a result of reduction in the volume of water flowing from city soil through the deep city drains (Engineering flow) to the surface water in the wadi. This also then reduces the water in the wadi soils. As indicated in Figure 6-4 above the system is well connected.

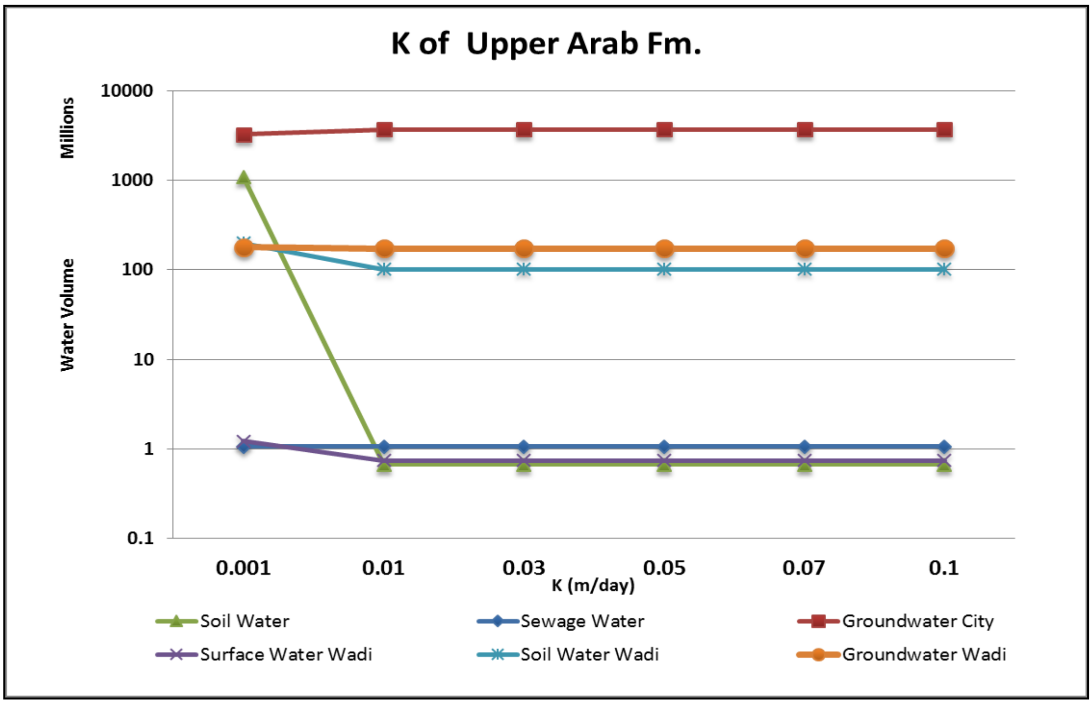


Figure 6-7 The changes of water stocks under scenario 2

Figure 6-8 shows the changes of sulfate concentration when the hydraulic conductivity is increased to 0.01 m/day and higher values. The biggest changes in sulfate concentration occur when hydraulic conductivity values change from 0.001 to 0.01 m/d. Changes in concentration appear in soil water and groundwater within the city area, and also in soil water and groundwater in wadi and in surface water. The change in concentration in city soil water is strong from 400 mg/l to around 1200 mg/l depending on the change of water discharge volume to groundwater in the city. Also, the concentration in the surface water changes from about 540 mg/l to 650 mg/l, because little water comes from soil of the city.

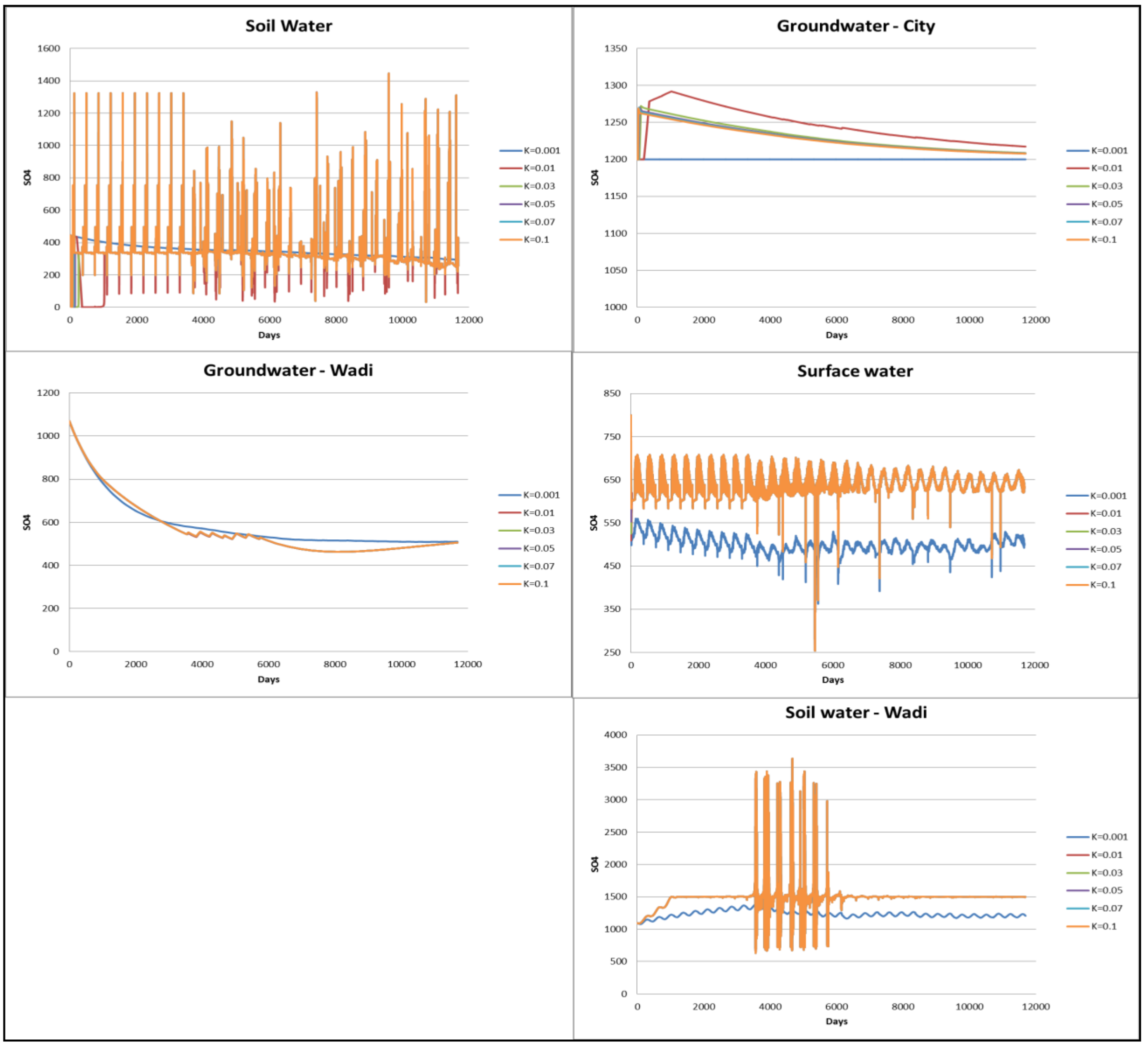


Figure 6-8 Sulphate concentration in waters in scenario 2

In the city soils (Soil Water, Figure 6-8) concentrations become much more variable with strong annual cycles relating to rain fall. This is because the flow away from the soil is faster than percolation to the Riyadh Aquifer. Though the "baseline" concentration the variations trend towards is lower, the concentration average is greater. This means that the concentration in the percolation water down to the Riyadh Aquifer is greater though with time this trends to a value close to the concentration calculated by the standard model. It is uncertain here if perhaps the initial conditions are still affecting this concentration and more investigation is needed.

The surface water concentrations are greater because the average concentration of the city soil water is greater and because the flows to the surface water are less and so the percent of treated water in the wadi stream is bigger. The variations of the surface water concentrations are greater because there is less stabilising from the flow from the deep drains.

The concentrations in the wadi soil waters rise to saturation and are controlled by precipitations. This results in some numerical instability in a period in the middle of model period. Though concentrations in the soil wadi sediments is increased the head in the wadi sediments is less so flow to the Jubaila Aquifer is less and concentrations are not significantly changed.

Scenario 1 and Scenario 2 have helped to explore the effects of flow on solute concentrations. As noted above with flows the system is quite well connected and even changes in hydraulic conductivity affect quite well change in concentration both average and variations. This would means that monitoring data if collected could be used to get much better calibration of a model. Also means that care is needed when managing the system. Latter is discussed in preliminary way in next few sections.

## 6.5 Sustainability scenarios

### 6.5.1 Scenario 3: Rainfall change

Climate change impact may occur through change in various meteorological variables. Here rainfall variation will be examined. The effects on concentrations of changes in rain fall are shown in Figure 6-9and Figure 6-10. Rainfall amount changes from -10% to +20% were modelled.

The Figure 6-9 shows no important changes in the volume of waters. This is because rain fall is not a significant contribution to the flow system as Figure 6-4 indicates.

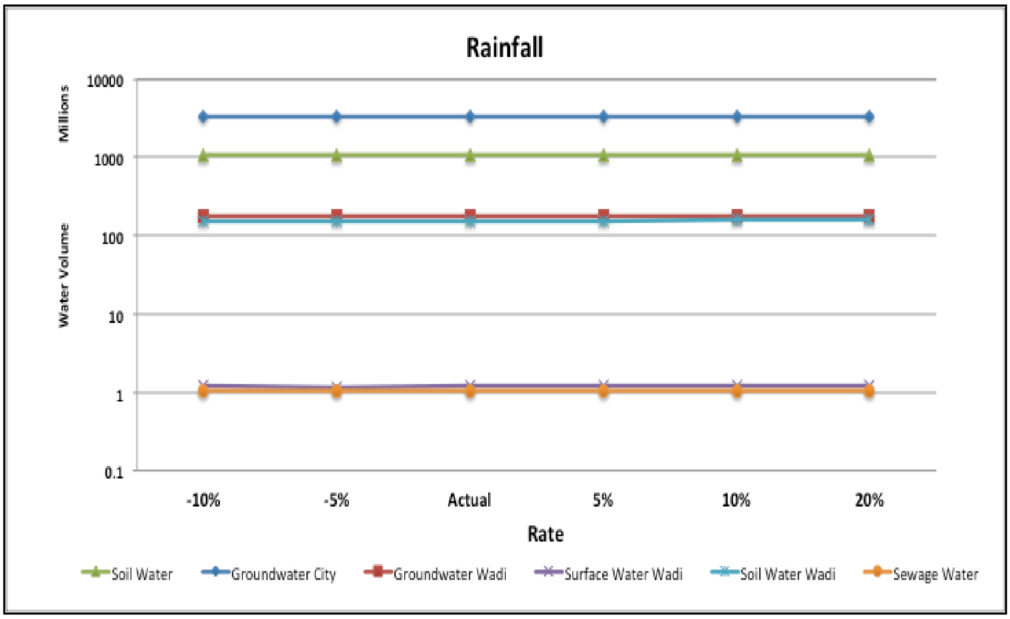


Figure 6-9 The changes of water stocks under scenario 3. Volumes in cubic metres. Actual means the standard model (0% change)

Figure 6-10 shows what the changes in rainfall do to the concentration of sulfate. The changes in concentration are only small in all stocks. It seems that this aspect of climate change is not too important.

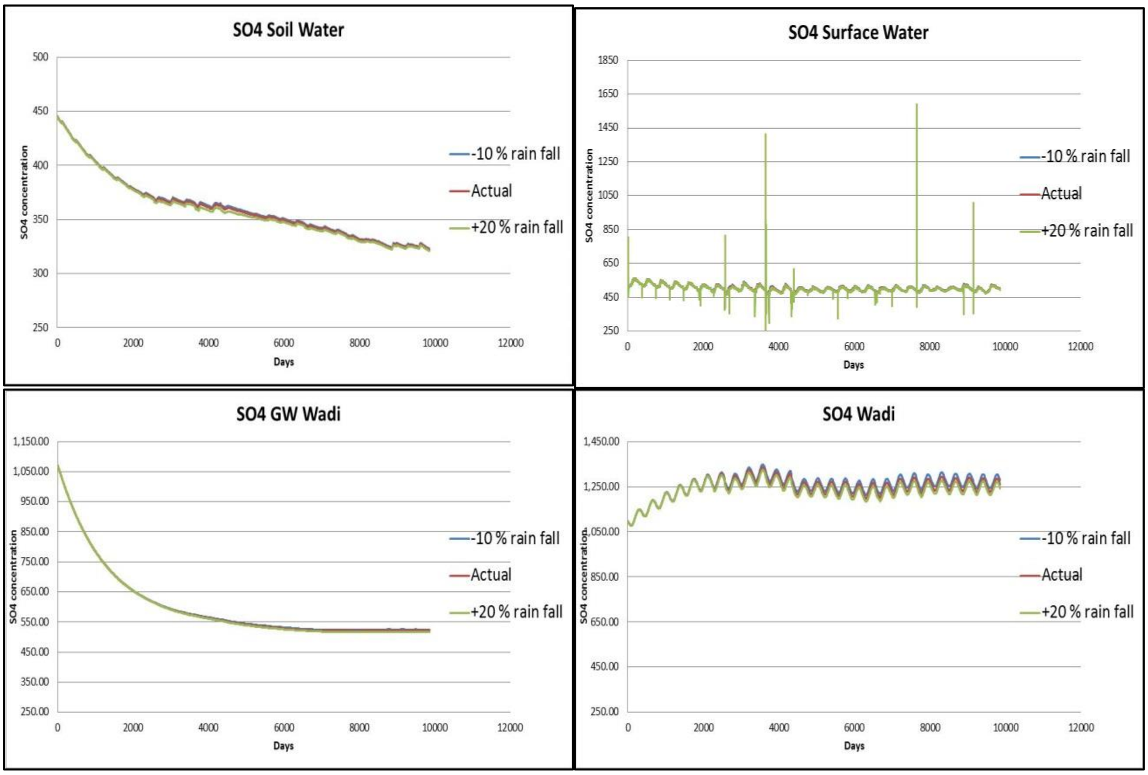


Figure 6-10 Various variations of sulphate concentration in scenario 3

### 6.5.2 Scenario 4: Water Supply change

The water supply is main source of water in the urban area, so any change in this water will affect the wadi-city system. Various scenarios including change in the water supply in Riyadh city are presented in Figure 6-11.

The main changes of sulfate concentration are in the city soil water and wadi soil water in addition to changes in surface waters and the Jubaila Aquifer groundwaters (see Figure 6-11 and Figure 6-12). All concentration changes are relatively small. The largest changes are in the city soil waters and here the differences are only about 25 mg/l from the standard model to case where supply was decreased by 20%. The concentration changes in accordance with the water supply volume. In case of the city soil water there is lower concentrations with lower supply. The decrease with more supply is because the mass coming into the city soil is proportional to the supply but the mass going out and the volume is not. In case of the surface water the concentration rises slightly with decreased supply for similar reasons. The concentration risen slightly in the wadi sediments and in Jubaila Aquifer water because the wadi stream concentration is slightly higher. However in general the concentration changes are not very dependent on the water supply rate.

### 6.5.3 Scenario 5: Leakages in Domestic Water networks

Leakages from the domestic water networks may reach the soil water in the wadi–city system. Here a range of leakage rates in terms of the percentage supplied were considered. 15% to 35% of supplied water leakage was modelled. The standard model used 25%.

The sulphate concentrations are presented in Figure 6-13and Figure 6-14. As expected the largest differences are in the city soil water, with concentrations decreasing as the % leakage increases. The sulphate concentrations have dropped from 360 mg/l (leakage rate 15%) to 230 mg/l (at leakage rate 35%) by the end of the modelled period. There is also a drop in concentration in the surface water in the wadi, as water is supplied to the wadi river from the city soil water via the deep drains (engineering flow). The drop in concentration in the surface water as the leakage increases is then passed onto the wadi soil water and from there even changes are seen, but small changes, in the Jubaila Aquifer groundwaters.

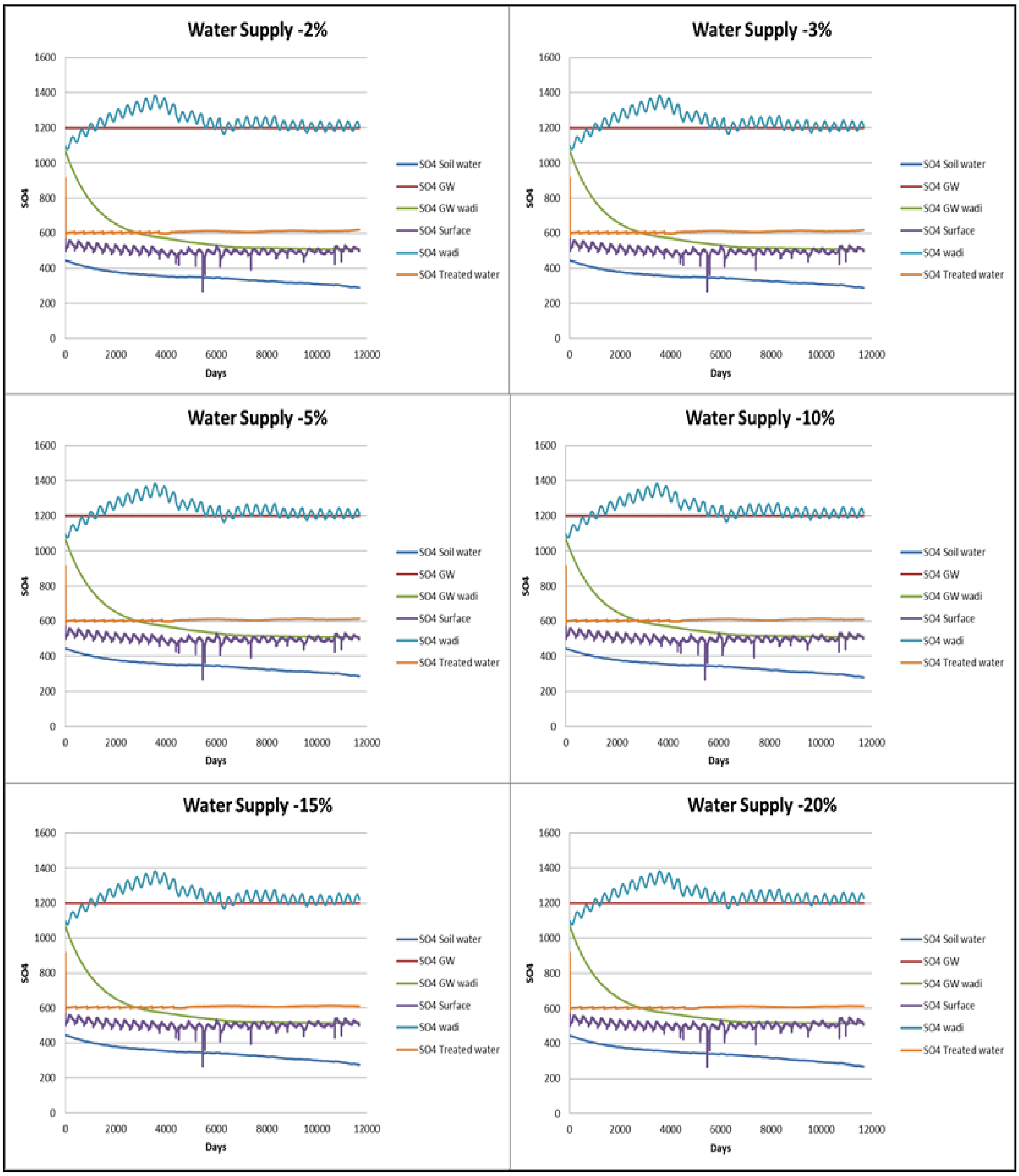


Figure 6-11 Sulphate concentrations (mg/l) in scenario 4 plotted for various % change in water supply

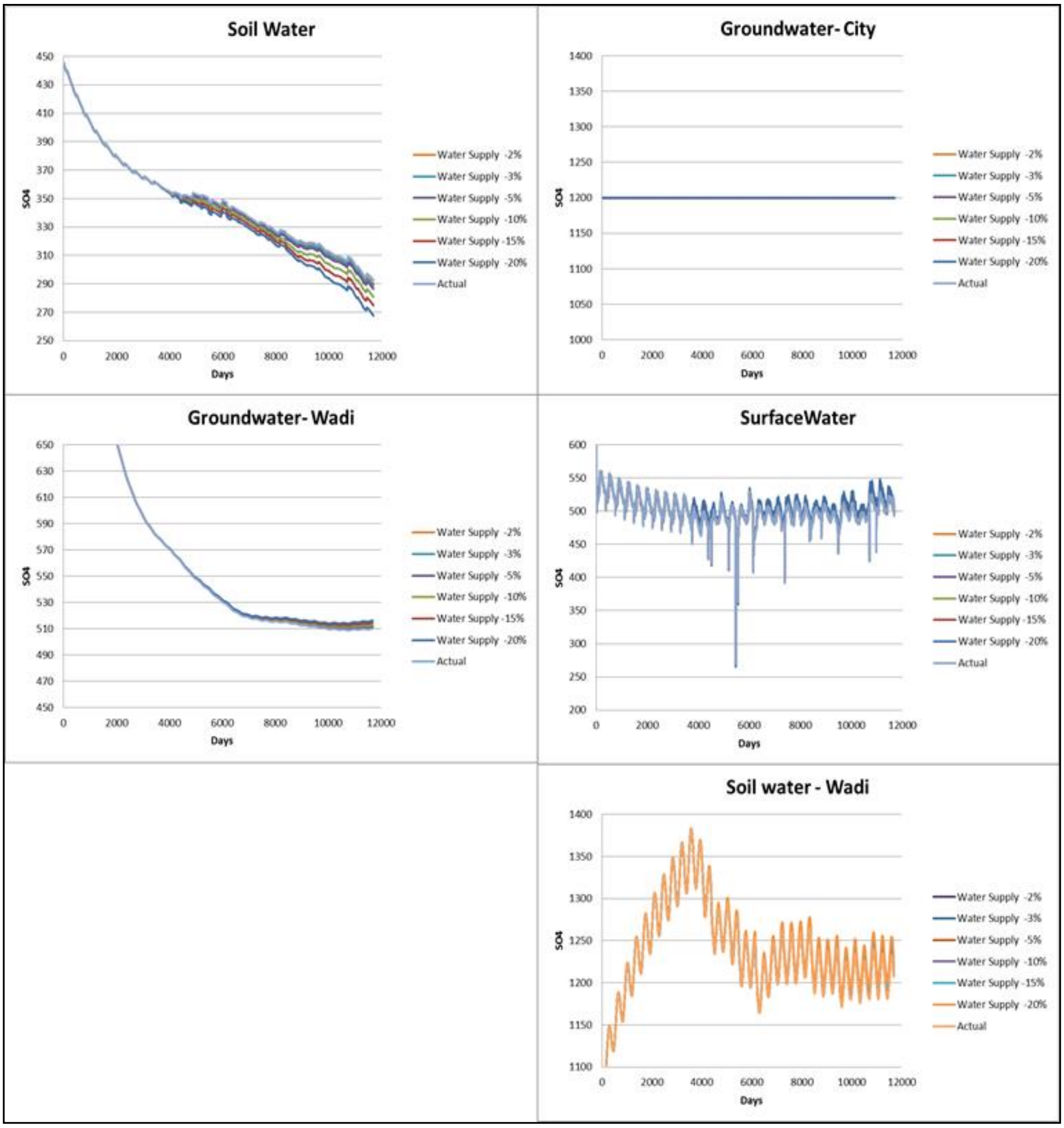


Figure 6-12 Sulfate concentrations (mg/l) in scenario 4 plotted for various stocks

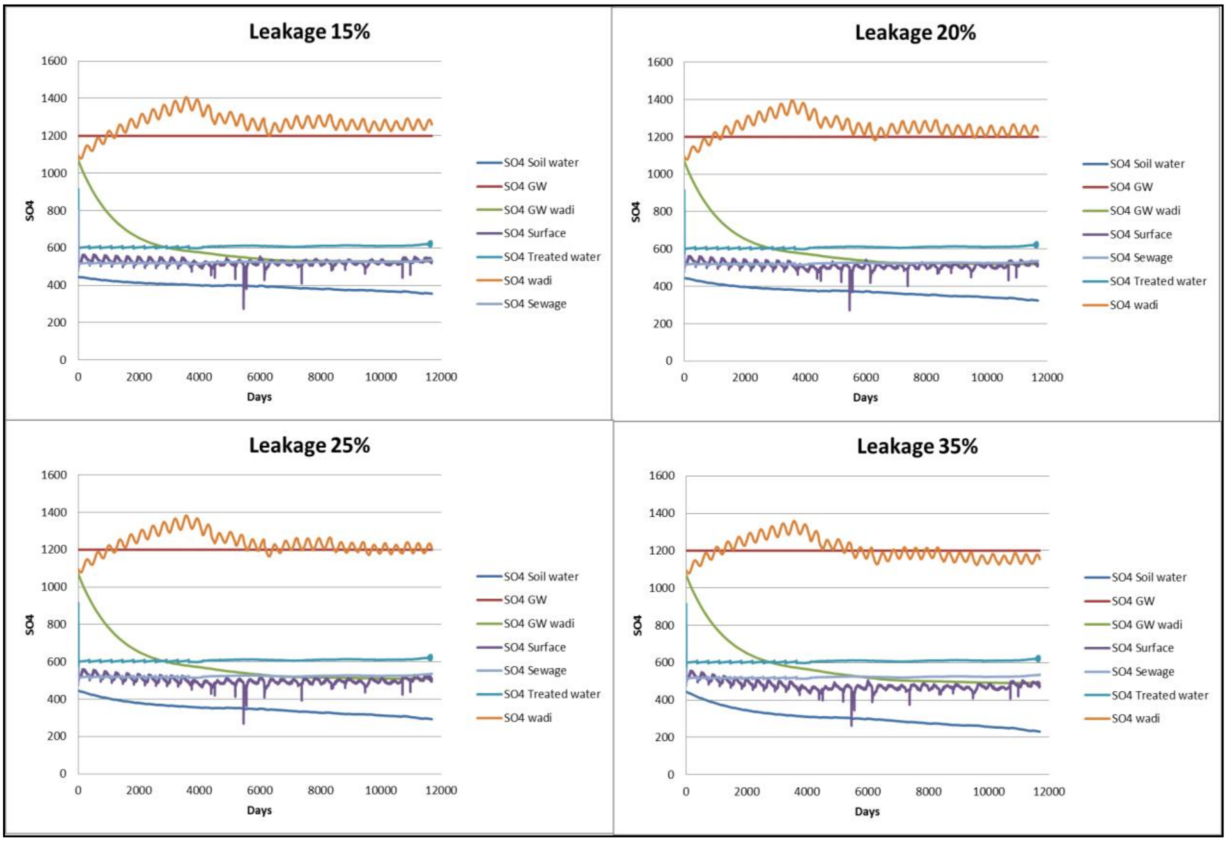


Figure 6-13 Sulfate concentration (mg/l) in scenario 5 divided according to leakage

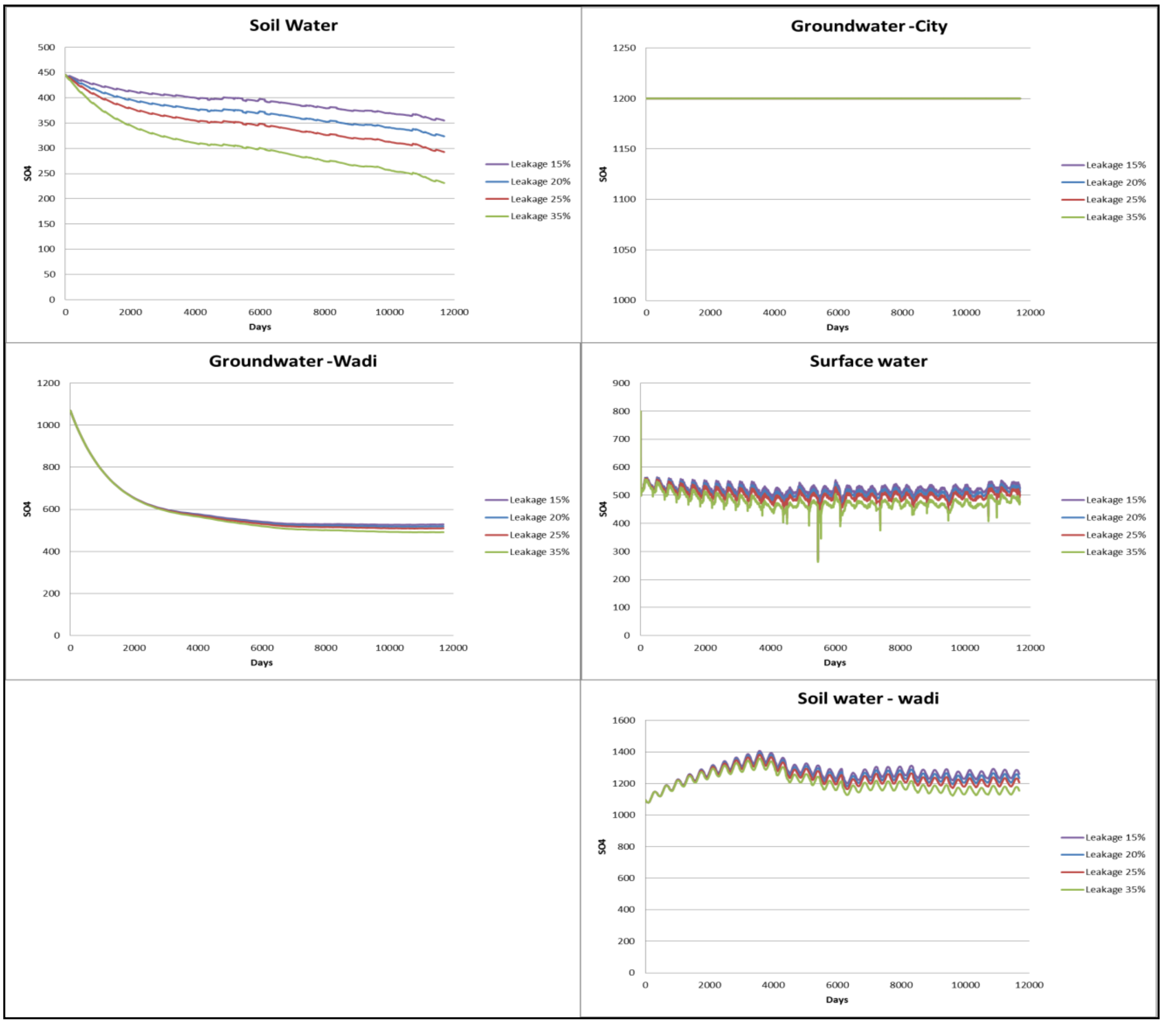


Figure 6-14 Sulfate concentration (mg/l) in waters in scenario 5 divided according to stock

The decrease in concentration as the leakage rises is because the leakage water is relatively good quality. At the end of the modelled period the relationship between the concentration in the city soil water and the leakage rate is almost linear [$SO_4$ concentration (mg/l) = -6.29(% Leakage) + 451.17, $R^2$= 0.9991]. A management option may be to reduce leakage. In the extreme (and impossible) case of reducing leakage to 0% it would be expected that the sulfate concentration in the city soil rises to about 450 mg/l from about 300 mg/l, and the surface water to a little less than 600 mg/l from about 500 mg/l.

### 6.5.4 Scenario 6: Leakage of Sewage Networks

Leakages from the sewerage pipes will deteriorate the water quality in the system. The rate of leakage has been varied from 18 to 35% of the flow in the sewer system by including a factor that adjusts the usual leakage (this is calculated as the difference between the sewage flow and the treated water flow). The standard model average leakage is 37%.

The effect on concentrations is shown in Figure 6-15 and Figure 6-16. As leakage increases concentrations increase as expected. The largest effect is on the concentrations in the city soil water as is expected. As the amount of leakage increases from 18 to 35% the concentration at the end of the model period is about 40 mg/l greater (290 mg/l in contrast to 250 mg/l). It seems to take many years before this concentration change works through the system, and the differences seem to be increasing with time, i.e. steady-state has not been achieved.

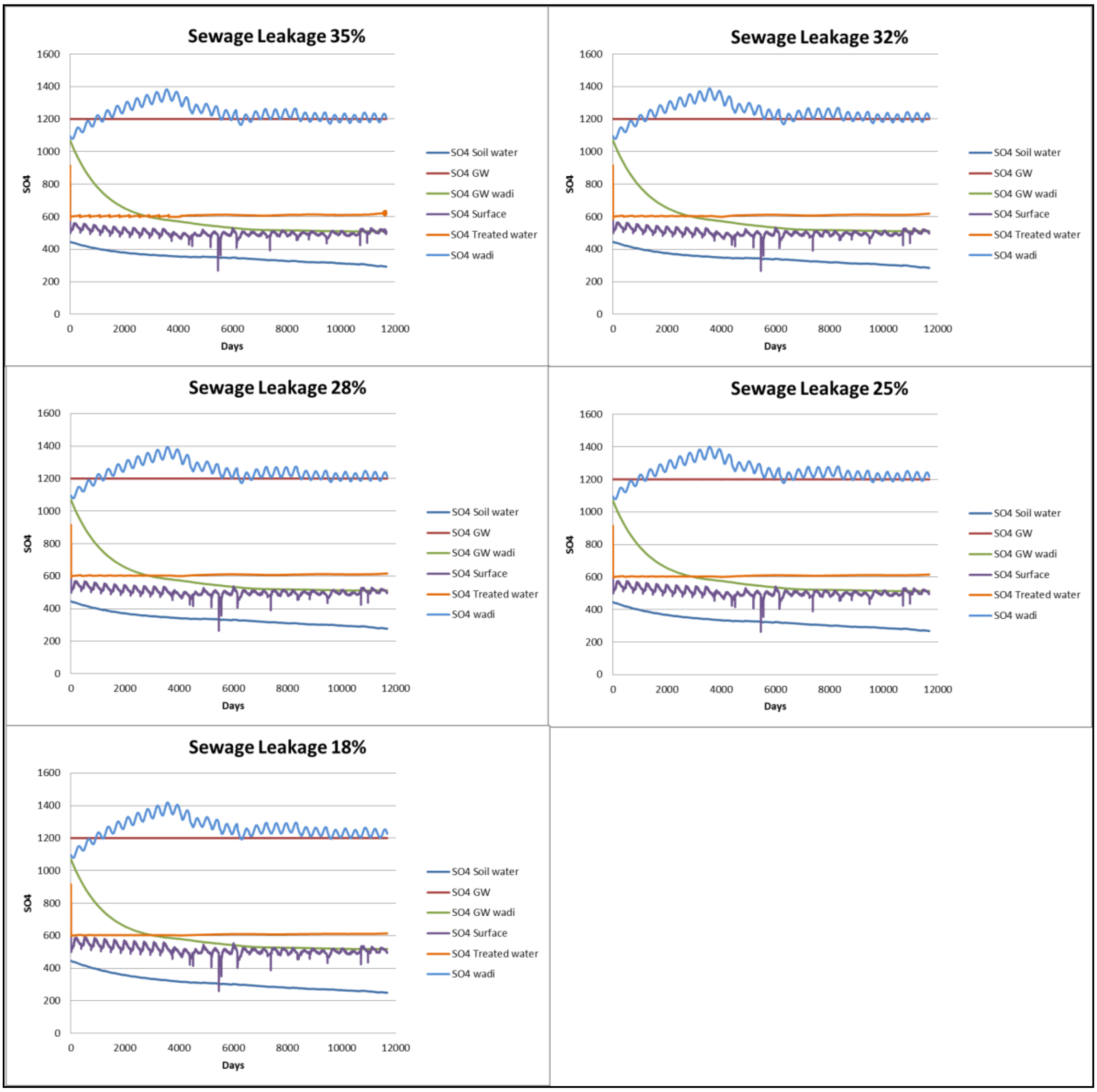


Figure 6-15 Sulphate concentration (mg/l) in scenario 6 divided according to leakage rate

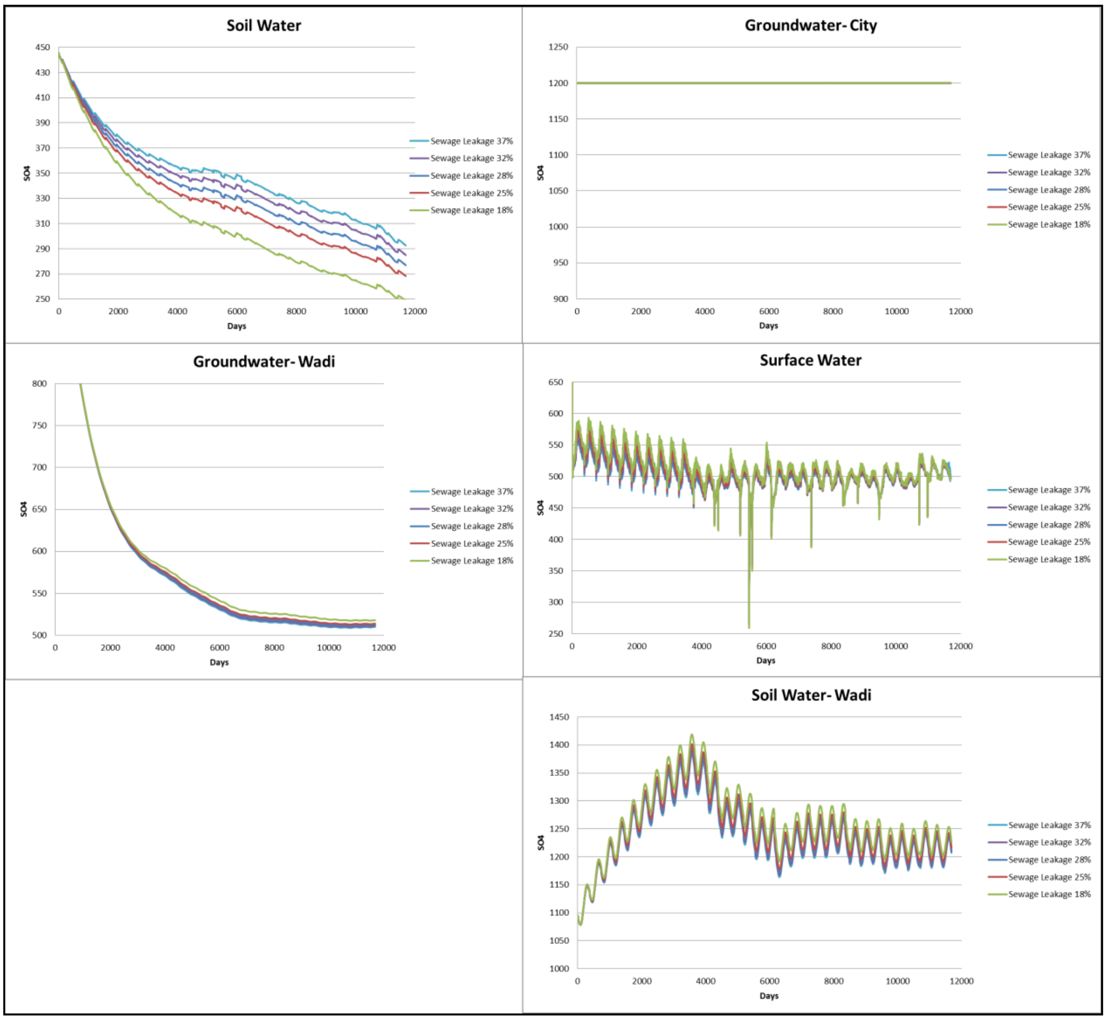


Figure 6-16 Sulphate concentration (mg/l) in waters in scenario 6 divided according to stock. Standard model leakage averages 37%

The effects on concentrations in the wadi surface waters and the wadi sediments are more limited, again as expected. Interestingly even a small change is seen in the Jubaila Aquifer, and this is in agreement with the observation that nitrate is present in the Jubalia groundwaters (Chapter 2).

## 6.6 Discussion

### 6.6.1 Introduction

This section will attempt to draw together the results presented above and in Chapters 4 and 5. First the hydrogeology is summaried (Section 6.6.2), then sustainability is considered (Section 6.6.3). Finally there is section on how good this type of modelling might be for these issues (Section 6.6.4).

### 6.6.2 Hydrogeology

The main flows in the system are summaried in Figure 6-4. Rain fall is not that important and subsequent sensitivity analysis (Section 6.5.2) indicated that it is not even that important for concentrations even though precipitation concentrations are much lower than any others in the system. The water system is completely dominated by humans activity. The recharge to deep aquifers (Jubaila and Riyadh) are mainly due to urban waters imported from the distant well fields and the desalination plants.

The sensitivity analysis of Sections 6.4.1 (hydraulic conductivity of the upper Jubaila Formation) and 6.4.2 (hydraulic conductivity of the upper part of the Arab

Formation) has confirmed which previous estimates of permeabilities are most likely to be correct. It and Chapter 5 has shown how modern humans water can get into the deep aquifers and explains why nitrate is seen in these groundwaters. Vertical hydraulic conductivity has been shown important in how the present system works.

The other sensitivity analyses show that the system is connected up, as Figure 6-4 also indicates. So when sewer leakage (Section 6.5.5) and domestic water leakage (Section 6.5.4) change most of the other water chemistry changes. Changing one part of the system has impacts elsewhere even though the aquifers are not directly connected.

The system takes a while to respond to change. For example the change in the wadi soil heads following the significant increase in rainfall between about 2000 and 4000 days (Figure 4- 13) and longer in the deeper Jubaila Aquifer (Figure 4- 11). And also as expected shallow soil aquifer water levels react more quick than deep aquifer water levels includes to seasonal variations.

### 6.6.3 Sustainability

#### ***6.6.3.1 <u>Introduction</u>***

Cannot cover all the area of sustainability and there are many things that could be done to add to the model or look at model outputs. Here will look at some of the results of the modelling: first a general statement about the system and sustainability; second likely effect of water demand; third effect of urban infrastructure decay; fourth effect of climate change; and fifth effect of management actions. (These headings are what was listed in Section 6.1.2). The discussion will use both the standard model results and the sensitivity analysis results.

#### 6.6.3.2 *Evidence from standard model on the present system's sustainability*

In general over the period modelled to December 2012 the system does not show steep trends in concentration or falling water levels. Exception to this is concentration in the city soil water which continues to fall through the modelled period. This is probably because the leakage from domestic supplies is increasing as the supply increases so more good quality water enters the aquifer. But it is also due to drop in leakage rate indicated by the decrease in the difference between the water supplied and the water treated declining. This latter could contain significant errors in measurement as both water supplied and treated are from field data. It would be good to collect chemical data from the field to see if the city soil water is getting less concentrated. In summary there are no obvious concentration issues of immediate concern (though of course there will always be spills and toxic chemicals from point sources but these are not concerned here).

There are certain issues that the model suggests: (i) increasing flows in the wadi stream with time as the imported water amount increases (and possibly more flooding)(Figure 4- 13); (ii) polluted urban waters getting to deep aquifers in significant amounts to changing concentrations (e.g. Figure 5- 3); (iii) possible increase in the wadi sediment soil water levels (Figure 4- 13); (iv) there are some high concentrations of $SO_4$ in places that would not be good for uses.

There needs more work to be done on other possible pollutants especially $NO_3$, but in general a conclusion of Section 2.9 is that the waters are toxic and hence $SO_4$ will behave like $NO_3$ and Cl in this system except in terms of precipitation (except if all waters are evaporated). Most times concentrations do not get to saturated with gypsum ($CaSO_4.2H_2O$) and this is less soluble than Cl and $NO_3$ salts. So $SO_4$ is probably good guide too to Cl and $NO_3$. One questions is why still toxic when there must be lots of organic matter from urban runoff, so may be some places there are differences between these ions.

#### *6.6.3.3 Effect of increasing water demand*

Water demand is increasing through the period modelled in the standard model. So the increase in flow rate in the wadi stream and possible increase in the wadi sediment water levels is due to increasing supply to the increasing demands. Concentrations were mainly stable but possibly slight increase in wadi stream concentration with time (Figure 5- 3). The exception is the concentrations in the city soil water where concentrations are still quickly falling with time at the end of the run as more and more domestic water leakage occurs.

In Section 6.5.3 the rate of water supply was varied from that did occur actually by amounts from -2% to -20%. This resulted in changes in concentration that were only small at most 25 mg/l. So though water imports to urban area are very important, changes in the rates by amounts up to even 20% make limited impact on the system. This is probably because both domestic leakage of good quality water and leakage of sewer water are both increased when supplies rise.

#### ***6.6.3.4 Effect of decay of urban infrastructure***

This issue could be looked at from point of sewers, domestic supply and efficiency of the sewage treatment works

In Section 6.5.4 the leakage rate from domestic supply was increased from 25% used in standard model to 35%. It found that there is a linear decrease in concentration in the city soil water where the piped water discharges to. The difference between 25% and 35% leakage in concentration terms was over 50 mg/l at the end of the modelled period but the difference was getting larger and the system still not reached a steady concentration. With greater water supply leakage there is a quicker fall in concentration in the city soil water as expected. The difference in the wadi stream water is about 30 mg/l at the end of the modelled period. This was passed on as about 25 mg/l into the wadi soil water and something less in the Jubaila Aquifer water.

#### ***6.6.3.5 Effect of climate change***

Climate change is looked at very simply here by considering effect of rain fall change on the system. Section 6.5.1 considered rain fall varying from -10% to +20%

of current values and showed the results of modelling the standard model period using rainfall changed by these amounts. Figure 6- 11 shows that there were very little changes in concentration. This of course does not mean that climate change will have no effect as temperature changes and wind speed and rainfall intensity may also change (affecting ET outputs (Figure 6- 4) and also demand possibly).

#### *6.6.3.6 Effect of management actions*

There is lots of ways the system could be managed but here is considered the effects of reduction in leakage from sewers and domestic supplies. These management options are often ones that are carried out to save water and reduce pollution. These actions has been looked at in Sections 6.5.4 and 6.5.5. It is noted that, as only the leakage rates have been changed but the total supply kept the same, the usage per person will have increased.

Reduction in domestic supply leakage from 25% in standard model to 15% causes rise in concentration in the city soil water by about 60 mg/l at the end of the modelling period though the differences are still increasing then. Drop in concentration is caused by less low concentration waters getting into the system. Because concentrations increase in the city soil water the wadi river also gets higher concentrations and higher concentrations are again then passed onto the wadi soil water and then to the Jubaila Aquifer. Jubaila Aquifer concentrations rise by 40 mg/l due to this.

In the city soil water, change in sewer leakage from standard model 37% to 18% causes just more than 40 mg/l change at the end of the modelling period but the concentration differences are still rising at this time. However, the difference is small and even smaller differences are present in the other waters.

Reduction of leakage for both domestic supplies and sewage will have an effect on concentrations. But in present system the concentration changes are not large against the total concentrations in the waters. Rain fall harvesting is unlikely to have much effect on quality as rain fall does not. Artificial recharge is not appropriate. Water reuse would have to be investigated by including the processes in the model so cannot be commented on here.

# CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Introduction

As stated in Chapter 1, the aim of the study has been "to determine whether system dynamics modelling is likely to be a useful way to determine whether urban waste water discharge to urban wadis is sustainable from a water quality point of view, and how it should be managed". The objectives were listed as:

1. develop a model for movement of water between the city and the wadi including all the water sources that feed the city;
2. develop a model of solute transfers using the model of water movement as a basis, by linking the mass concentration of solute with volumes of water as follows;
3. use the model, by the process of developing it and also by use of sensitivity analysis, to understand the nature of the links between the city and wadi water systems;
4. use the developed model to determine what effects management policies might have on water quality and quantity;
5. determine by experience in applying the SD approach to Riyadh what its advantages and disadvantages are in this sort of application.

In Section 7.2 to 7.5 the other objectives will be reviewed and findings discussed. The emphasis is not on the detail as this is covered earlier but on the broad conclusions. Section 7.6 summarises progress towards the aim. Section 7.7 gives some recommendations.

## 7.2 Objectives 1 and 2: Developing an SD model of the flow of water and solutes between the Riyadh aquifer and wadi systems

A flow and a solute transport model were developed for Riyadh (Chapters 4 and 5).

The flow model appears to give a believable simulation of water movement between the city and wadi Hanifah. Although a conventional calibration has not been possible there are quite a few features of the model that are not inconsistent with the real system, including groundwater levels and surface water flows.

In addition, the model is also consistent with the inputs, including the geometry, the amounts of water supplied, the amounts of water treated, the amounts of water dealt with by sewage trucks, the rainfall, the other meteorological data and the total irrigation abstraction rates.

The examination of the flow systems indicates that largely the flows are understandable and make hydrological sense. Though the model presented will not be the only model consistent with the data, it is a possible broad explanation of the system and is worth more investigation and subsequent testing in future.

The solute transfer model appears to be generally consistent with the field evidence and appears to make general sense. However, it does not produce the spatial or time variation that the real system does but this is largely because of the coarseness of the discretizing of the system. It would be useful to try out a range of other determinands especially Cl and $NO_3$ to see if the model is consistent with these. It would be useful to try out cations but in this case it would probably be necessary to add in ion exchange. An EC survey of the city waters would also help, also using specialist models to examine some of the assumptions of the model, e.g. Modflow, Phreeqc.

## 7.3 Objective 3: Developing an understanding of the hydrogeology of Riyadh including the nature of the links between the city and wadi water systems

A major use of the model has been to help think about the hydrogeology of Riyadh and develop further a conceptual model. The model has allowed broad quantitative checks to be done on flows and solutes. It has identified the main flows (Figure 6-4) and demonstrated how the various components of the system are linked. It has explained broadly why the concentrations and flows may be as they are, though there are probably other explanations also possible. It provides some indication of a resilience of the system.

It seems that the wadi system is largely a big vertical soil aquifer treatment facility with large scale artificial recharge.

The solute transfer model indicates a drop in concentration in the urban soil area and this needs to be investigated. Elsewhere there is no indication of rapidly rising concentrations of any determinand. The effects of rainwater and evapotranspiration clearly appear within the results of solute model, even if rainfall by itself directly does not cause recharge significantly.

## 7.4 Objective 4: Consideration of possible management policies

This has only been investigated using the examples of changing the leakage from water supply pipes and sewage pipes and changing the water supply rates but could in future be used to examine many more options. In the example cases looked at, the model has allowed the changes in concentration and flow to be assessed. The values of the concentrations, being averaged over the quite large water stores, will not be accurate estimates especially during times of change but should indicate relative mass movements. One area that should be looked at is the long term future of the recirculation of water in the wadi area. To get the most from the model for management purposes, it could be extended to include other management practices like water reuse. It could also be used to look at how a simpler model might be developed: a simpler model might then be used in other software to investigate optimisation against management criteria.

So in conclusion, more can be done in future with investigating the possible effects of management practices but in the present study the model has been shown able to simulate example management actions.

## 7.5 Objective 5: The use of SD modelling

The SD approach has allowed a model to be set up rather easily in a system with many components, many of different processes and process timescales. It has required that all aspects of the system are considered in some detail. The software has allowed rapid visualisation though processing using other (spreadsheet) software has also been needed at times.

However there are problems. The processes have to be simplified considerably to allow them to be represented, and more testing would have been good, i.e. testing against other software such as Modflow. An aspect of this is the lumping approach, especially when considering concentrations as much numerical dispersion can occur. This has not been investigated. Also with lumped approaches, not just SD modelling, one difficulty is what to 'calibrate' against as calibration targets are often at much smaller scales than the model stock represents.

Overall this approach is best thought of as an aid to conceptual model development and something that once developed could be updated as and when data become available to get a truly calibrated representation. It could also be used to identify sub-problems that could then be looked using other software.

## 7.6 Achievement of Aim

The overall aim of the study was "to determine whether system dynamics modelling is likely to be a useful way to determine whether urban waste water discharge to urban wadis is sustainable from a water quality point of view, and how it should be managed".

In spite of the difficulties and limited data, a good model has been built by SD to predict the future behaviour of the water system in the city of Riyadh and Wadi Hanifah. The hydrogeological investigations and “sustainability scenarios” show how the water and solute systems may interact and change over future time. Reduction of leakage from both domestic supplies and sewage systems will have an effect on concentrations. However, in the present system, the concentration changes are not large compared with the total concentrations in the waters. Water reuse would have to be investigated by including additional processes in the model, so further comment cannot be made here.

Overall, the project showed that SD approach is a useful way for developing conceptual models in complex interacting systems such as is the case with urban discharges to urban wadis. Though accuracy will be less good than more standard numerical models, SD models have the advantage of flexibility to include processes which cannot easily be included in, for example, Modflow. SD models are therefore recommended for use in conceptual model development as a link between purely qualitative conceptual models and a full, rigorous numerical representation. Used in this way they are likely to provide justification for simplifications that have to be made for implementing more accurate but less flexible numerical models like Modflow.

The wadi Hanifa system appears potentially sustainable, but more work is needed, as highlighted in the following recommendations (Section 7.7), in order to prove the case and also investigate all the possible management methods and how best the system could be managed. SD could be used as a basis for this, but may be also backed up by sub-system modelling using more specialist software for answering specific questions raised by the SD model.

## 7.7 Recommendations

The following are recommended:

1. examine role of precipitation in controlling solute concentrations;
2. look at other solutes including Cl and $NO_3$;
3. develop sorption and decay reactions and then look at organic pollutants;
4. use more specialist models to examine some of the assumptions of the model, e.g. Modflow, phreeqc;
5. examine the issues of numerical dispersion of solute masses and what they mean;
6. consider calibration methods and whether they can be appropriately done when using lumped representations and point observations;
7. suggest a set of monitoring that would be of most use for calibrating the model better in future;
8. add socio-economic aspects to the model;
9. add water re-use processes to the model to allow tracking of for example grey water;
10. use the model to try and obtain a better estimate of the hydraulic conductivity of the upper Jubaila and Arab Formations;
11. use model to explore ‘water futures’ (e.g. Rodgers et al., 2012);
12. use model to examine various meteorological regimes including into future;

13. use model to explore many more management options, effects of climate change and infrastructure decay;
14. develop a simplified version of the model system for use in management optimisation;

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# APPENDICE

# Appendix A:

# Model Input Parameters

## Flow Model parameters

| Parameters | Code name | Units |
|---|---|---|
| Evapotranspiration from Soil water in Hanifah Catchment area | ***AET*** | $m^3$/day |
| Riyadh width- east side of Aquifer | ***Aquifer_width*** | m |
| Aquitard base (Sulaiy Aquitard) | ***Aquitard_base*** | m |
| Aquitard Thickness | ***Aquitard_Thickness*** | m |
| Base of upper part of Jubaila formation | ***base_of_J1*** | m |
| Catchment Area of non-urban area of wadi Hanifah | ***Catchment_Area_of_Hanifah*** | $m^2$ |
| Volume of runoff water run from upstream of drainages | ***Catchment_Runoff*** | $m^3$/day |
| Non-urban wadi area mean slop | ***Catchment_Slop*** | - |
| Volume of runoff water run out City to East | ***City_Runoff*** | $m^3$/day |
| hydraulic conductivity of soil in City | ***City_Soil_K*** | m/day |
| Water Thickness in soil in city | ***City _Water_ Thickness*** | m |
| Consume Factor | ***Consume_Factor*** | - |
| Consumptive Use | ***Consumptive Use*** | $m^3$/day |
| Cross Section of surface water Drainage in urban wadi area | ***Cross_Sec_Area*** | m |
| Curve Number for calculate city Runoff | ***Curve Number*** | - |
| Curve Number for calculate Wadi Runoff | ***Curve Number 2*** | - |
| Curve Number for calculate Hanifah Catchment area Runoff | ***Curve Number 3*** | - |
| Water Supply from Desalinated water | ***Desalinated_water*** | $m^3$/day |
| Distance Between Drains | ***Dist_Between_Drains*** | m |
| Wadi Hanifah width at downstream (urban area) | ***Downstream width*** | m |
| Area of Drainage of surface water | ***Drainage_Area*** | $m^2$ |
| Depth of Drainage of surface water | ***Drainage_Depth*** | m |
| width of surface water stream | ***Drainge width*** | m |
| Diameter of pipe(hydraulic radius) | ***Eng_Hyd_Rad*** | m |
| Total gravity drainage network length | ***Eng_L*** | m |
| Volume of water flow in gravity drainage network | ***Engineering_Flow*** | $m^3$/day |
| Volume of Evapotranspiration City | ***ET*** | $m^3$/day |
| Volume of Evapotranspiration in non-urban wadi area | ***ET_CH*** | $m^3$/day |
| Evapotranspiration Coefficient in city | ***ET Coeff City*** | - |

| | | |
|---|---|---|
| Evapotranspiration Coefficient in wadi | ***ET Coeff H Catchment*** | - |
| Evapotranspiration Coefficient in wadi | ***ET_Coeff_Wadi*** | - |
| Evapotranspiration from surface water in non-urban wadi area | ***ET_HSW*** | $m^3$/day |
| Evapotranspiration in wadi area | ***ET_Wadi*** | $m^3$/day |
| Evapotranspiration in wadi area | ***ET Wadi WT*** | $m^3$/day |
| Evaporation from surface water | ***Evap*** | $m^3$/day |
| Extinction depth in city | ***Extinction_depth*** | m |
| Extinction depth in Wadi | ***Extinction_depth_in_Wadi*** | m |
| Volume of soil water flow in urban wadi area | ***Flow_in*** | $m^3$/day |
| Volume of soil water flow out urban wadi area | ***Flow_out*** | $m^3$/day |
| Percentage of irrigation water return from soil | ***Fract_Irr_from_Soil*** | % |
| Volume of groundwater in City area(Riyadh Aquifer) | ***Groundwater_City*** | $m^3$ |
| Volume of groundwater in Wadi area(Jubaila Aquifer) | ***Groundwater_Wadi*** | $m^3$ |
| Growth of Population | ***Growth*** | p/day |
| Growth rate | ***Growth_rate*** | % |
| Input flow to groundwater in Wadi area | ***GW_Input*** | $m^3$/day |
| Output flow from groundwater in Wadi area | ***GW_Out*** | $m^3$/day |
| Head of soil water in non-urban wadi area | ***h_Catchment*** | m |
| Head of soil water in city | ***h_city_water*** | m |
| Head at urban wadi Hanifah downstream | ***h downstream*** | m |
| Head of groundwater in City | ***h_GW*** | m |
| Head of groundwater in Wadi | ***h_GW_wadi*** | m |
| Head of groundwater for flow-in (Jubaila Aquifer) | ***H in*** | m |
| Head of groundwater for flow-out ( Jubaila Aquifer) | ***H out*** | m |
| Head of groundwater for flow-out ( Riyadh Aquifer) | ***H out 2*** | m |
| Head at urban wadi Hanifah upstream | ***h Upstream*** | m |
| Head of soil water in wadi | ***h_Wadi_Water*** | m |
| Head of soil surface water in wadi | ***h water Surface*** | m |
| Different between surface water level and wadi soil water level | ***h2 h1*** | m |
| Wadi Length in non-urban wadi area | ***Hanifah_catchment_length*** | m |
| Head of soil water in in non-urban area of wadi Hanifah | ***Hanifah_Hw*** | m |
| Soil thickness in in non-urban area of wadi Hanifah | ***Hanifah_soil_thickness*** | m |

| | | |
|---|---|---|
| Volume of soil water in non-urban area in wadi Hanifah | ***Hanifah_Soil_Water*** | $m^3$ |
| Lateral Flow of soil water from non-urban to urban wadi areas | ***Hanifah_Subsurface_Lateral_Flow*** | $m^3$/day |
| Volume of surface water in non-urban wadi area | ***Hanifah_Surface_Water*** | $m^3$ |
| Hydraulic Gradient (Riyadh Aquifer) | ***Hydraulic_Gradient_Aquifer*** | - |
| Hydraulic Gradient at input flow cross section | ***hydraulic_Input*** | - |
| Hydraulic Gradient at output flow cross section | ***hydraulic_output*** | - |
| Irrigation water in City | ***IRRI*** | $m^3$/day |
| Irrigation area Fraction | ***IRRI Area Fraction*** | % |
| Irrigation water in Wadi | ***IRRI_Wadi*** | $m^3$/day |
| Upper part of Jubaila formation(Aquitard) | ***J1_Thickness*** | - |
| HydraulicCondiuctiviy of upper part of Jubaila formation(Aquitard) | ***K_J1*** | m/day |
| Hydraulic Condiuctiviy (Riyadh Aquifer) | ***K_Riyadh_Aq*** | m/day |
| Hydraulic Condiuctiviy of Sulaiy Aquitard | ***K_Sulaiy_ Aquitard*** | m/day |
| Hydraulic Condiuctiviy of soil in wadi | ***K_Wadi*** | m/day |
| Hydraulic Condiuctiviy of lower part of Jubaila formation(Aquifer) | ***K Jubaila_J2*** | m/day |
| Water Supply network Leakage | ***Leakage*** | $m^3$/day |
| Water Supply network Leakage Rate | ***Leakage_rate*** | - |
| values for various channel surfaces(Manning's coefficient) | ***n*** | m |
| values for various channel surfaces (Manning's coefficient) | ***n2*** | m |
| Depth of gravity drainage network | ***Network_Depth*** | m |
| Numbers of streams in non-urban wadi area | ***Numbers_of_streams*** | - |
| Percolation from soil to groundwater (city area) | ***Percolation*** | $m^3$/day |
| Potential Evapotranspiration | ***PET*** | mm |
| Factor of Potential Evapotranspiration | ***PET Evap F*** | % |
| Population | ***Population*** | p |
| Porosity of soil in city | ***Porosity*** | % |
| Porosity of soil in wadi | ***Porosity Wadi*** | % |
| Volume of rain water in city area | ***PP*** | $m^3$ |
| Volume of rainfall water over Non-urban Wadi area | ***PP_CH*** | $m^3$ |
| Volume of rain water in wadi area | ***PP_Wadi*** | $m^3$ |
| Daily rain fall | ***Rain_fall*** | mm |
| Recharge to groundwater in wadi area | ***Recharge*** | $m^3$/day |

| | | |
|---|---|---|
| Riyadh Aquifer base elevation | ***Riyadh Aq Base*** | m |
| Volume of runoff water run in non-urban area of wadi Hanifah | ***Runoff_Hanifah*** | m |
| Potential maximum soil moisture retention (curve method) | ***S*** | - |
| Potential maximum soil moisture retention (curve method) | ***S 2*** | - |
| Potential maximum soil moisture retention (curve method) | ***S 3*** | - |
| Specific yield of Riyadh Aquifer | ***Specific_yield_of_Riyadh_Aq*** | - |
| Specific Storage , Jubaila Aquifer | ***Ss_of_Jubaila_J2*** | $m^{-1}$ |
| Channel Slope (Manning's Equation) | ***Sv*** | - |
| Sewage water Flow | ***Sewage_Flow*** | $m^3$/day |
| Sewage water Leakage | ***Sewage_Leakage*** | $m^3$/day |
| Sewage water flow in sewage network | ***Sewage_Net*** | $m^3$/day |
| Sewage network Depth | ***Sewage_Net_Depth*** | $m^3$/day |
| Volume of Sewage water in City | ***Sewage_Water*** | $m^2$ |
| Sewer Exfiltration Factor | ***Sewer_Exfiltration_Factor*** | m |
| Soil Depth in city | ***Soil_Depth*** | m/day |
| Soil Surface Area in city | ***Soil_Surface_Area*** | $m^2$ |
| Soil Surface Area in urban part of wadi | ***Soil_Surface_area_Wadi*** | $m^2$ |
| Soil Volume in city (alluvium layer) | ***Soil Volume*** | $m^3$ |
| Soil Volume in wadi (alluvium layer) | ***Soil Volume Wadi*** | $m^3$ |
| Volume of soil water in city | ***Soil_Water*** | $m^3$ |
| Volume of soil water in Wadi area | ***Soil_Water_Wadi*** | $m^3$ |
| Subsurface flow out from Riyadh Aquifer | ***Subsurface_Flow_To_South*** | $m^3$/day |
| Volume of water subsurface flow between Surface water and soil water (urban wadi area) | ***Subsurface_Flow_Wadi*** | $m^3$/day |
| Surface water flow out urban wadi | ***Surface_Out*** | $m^3$/day |
| Volume of Surface water run in urban wadi area | ***Surface_Water_Wadi*** | $m^3$ |
| hydraulic gradients between Surface water and soil water in wadi | ***SWGW i*** | - |
| Pirzometric_surface_of_Jubaila_Aq | ***Pirzometric_surface_of_Jubaila_Aq*** | m |
| Treated Water | ***Treated Water*** | $m^3$ |
| Sewage water transfer by trucks | ***Trucks_Water*** | $m^3$/day |
| Wadi Hanifah width at upstream (urban area) | ***Upstream width*** | m |

| | | |
|---|---|---|
| Use rate | ***Use_rate*** | - |
| Velocity of surface water | ***Velocity*** | m/day |
| Part of city area located at wadi Hanifah | ***Wadi area in City*** | $m^2$ |
| hydraulic conductivity of wadi bed | ***Wadi Bed K*** | m/day |
| Thickness of wadi bed | ***Wadi Bed Th*** | m |
| Volume of irrigation water return to groundwater | ***Wadi_Irr*** | $m^3$/day |
| Wadi Length in urban wadi area | ***Wadi_Length*** | m |
| Volume of runoff water run in urban area of wadi Hanifah | ***Wadi_Runoff*** | |
| Water Thickness in wadi soil | ***Wadi_water_Thickness*** | |
| Width of wadi Hanifah (urban area) | ***Wadi Width*** | m |
| Water Content of soil layer in city | ***Water Content*** | - |
| Water Content of soil layer in non-urban Hanifah wadi | ***Water content CH*** | - |
| Volume of Water Supply | ***Water Supply*** | $m^3$ |
| Water Thickness in Jubaila Aquifer | ***Water_Thickness__Jubaila_Aq*** | m |
| Water Thickness in Riyadh Aquifer | ***Water_Thickness__Riyadh_Aq*** | m |
| Water Supply from Groundwater | ***Wells_water*** | $m^3$/day |
| Width of cross section for input flow | ***Width_Input*** | m |
| Width of cross section for output flow | ***Width_output*** | m |
| Wetted surface measured to the stream | ***WP*** | - |
| vertical distance to calculate hydraulic gradients flow-in Jubaila Aquifer | ***X in*** | m |
| vertical distance to calculate hydraulic gradients flow-out Jubaila Aquifer | ***X out*** | m |
| vertical distance to calculate hydraulic gradients flow-out Riyadh Aquifer | ***X out 2*** | m |

## Solute Model parameters

| Parameters | Code name | Units |
|---|---|---|
| Mass of Solute in runoff flow from upstream of drainages | *Catchment Runoff1* | g/$m^3$ |
| Mass of Solute in runoff water run out City to East | *City Runoff 1* | g/$m^3$ |
| Mass of Solute in Consumptive Use water | *Consumptive Use 1* | g/$m^3$ |
| Mass of Solute in Desalinated water | *Desalinated water 1* | g/$m^3$ |
| Rate of dissolution in Hanifah soil water | *Diss Prec HSoil* | g/$m^3$ |
| Dissolution of Solute | *Dissolution* | g/$m^3$ |
| Mass of Solute in water flow in gravity drainage network | *Engineering flow 1* | g/$m^3$ |
| Factor of Sulphate concentration in Sewage water | *Factor SO4 Sewage* | - |
| Factor of Sulphate concentration in Surface water | *Factor SO4 Surface* | - |
| Mass of Solute in soil water flow in urban wadi area | *Flow in 1* | g/$m^3$ |
| Mass of Solute in soil water flow out urban wadi area | *Flow out1* | g/$m^3$ |
| Rate of dissolution | *g per m3 diss* | g/$m^3$ |
| Mass of Solute in groundwater in City area(Riyadh Aquifer) | *Groundwater City1* | g |
| Mass of Solute in groundwater in Wadi area(Jubaila Aquifer) | *Groundwater Wadi 1* | g |
| Mass of Solute Input flow to groundwater in Wadi area | *GW Input 1* | g/$m^3$ |
| Mass of Solute Output flow from groundwater in Wadi area | *GW Out 1* | g/$m^3$ |
| Mass of Solute in runoff water in wadi Hanifah (non-urban area) | *Hainfah Runoff1* | g/$m^3$ |
| Mass of Solute in soil water in non-urban area in wadi Hanifah | *Hanifah Soil water1* | g |
| Mass of Solute in Lateral Flow of soil water from non-urban to urban wadi areas | *Hanifah Subsurface Flow1* | g/$m^3$ |
| Mass of Solute in surface water in non-urban wadi area | *Hanifah Surface water1* | g |
| Mass of Solute in Irrigation water in City | *IRRI 1* | g/$m^3$ |
| Mass of Solute in Irrigation water in Wadi | *IRRI wadi 1* | g/$m^3$ |
| Mass of Solute in Water Supply network Leakage | *Leakage 1* | g/$m^3$ |
| Maximum of Solute concentration | *Max conc* | g/$m^3$ |
| Mass of Solute of Percolation from soil to groundwater (city area) | *Percolation 1* | g/$m^3$ |
| Dissolution in Percolation water | *Percolation dissolution* | g/$m^3$ |
| Volume of rain water in city area | *PP 1* | g/$m^3$ |
| Volume of rainfall water over Non-urban Wadi area | *PP CH 1* | g/$m^3$ |

| | | |
|---|---|---|
| Volume of rain water in wadi area | ***PP wadi 1*** | g/m$^3$ |
| Rate of Precipitation in soil water in wadi Hanifah (non-urban area) | ***Precip H Soil Water*** | g/m$^3$ |
| Rate of Precipitation in Hanifah surface water (non-urban area) | ***Precip H Surface Water*** | g/m$^3$ |
| Rate of Precipitation in soil water in city | ***Precip Soil water*** | g/m$^3$ |
| Rate of Precipitation in soil water in wadi (urban area) | ***Precip Soil Water Wadi*** | g/m$^3$ |
| Solute Precipitation in Hanifah surface water (non-urban area) | ***Precipitation H Surface water*** | g/m$^3$ |
| Solute Precipitation in soil water in wadi (urban area) | ***Precipitation Soil W*** | g/m$^3$ |
| Solute Precipitation in soil water in city | ***Precipitation Soil water*** | g/m$^3$ |
| Recharge to groundwater in wadi area | ***Recharge 1*** | g/m$^3$ |
| Change Factor of Solute in sewage water | ***Sewage Conc*** | g |
| Sewage water Flow | ***Sewage flow 1*** | g/m$^3$ |
| Sewage water Leakage | ***Sewage Leakage 1*** | g/m$^3$ |
| Sewage water flow in sewage network | ***sewage net 1*** | g/m$^3$ |
| Volume of Sewage water in City | ***Sewage water 1*** | g/m$^3$ |
| Concentration of sulphate in Desalinated water | ***$SO_4$ Desalinated*** | g/m$^3$ |
| Concentration of sulphate in groundwater in Riyadh Aquifer | ***$SO_4$ GW*** | g/m$^3$ |
| Concentration of sulphate in groundwater in Jubaila Aquifer(non-urban area) | ***$SO_4$ GW Upstream*** | g/m$^3$ |
| Concentration of sulphate in groundwater in Jubaila Aquifer | ***$SO_4$ GW wadi*** | g/m$^3$ |
| Concentration of sulphate in Hanifah soil water | ***$SO_4$ Hanifah*** | g/m$^3$ |
| Concentration of sulphate in rain water | ***$SO_4$ Rain*** | g/m$^3$ |
| Concentration of sulphate in wadi runoff water | ***$SO_4$ Runoff*** | g/m$^3$ |
| Concentration of sulphate in sewage water | ***$SO_4$ Sewage*** | g/m$^3$ |
| Concentration of sulphate in soil water in city | ***$SO_4$ Soil water*** | g/m$^3$ |
| Concentration of sulphate in water supply | ***$SO_4$ supply*** | g/m$^3$ |
| Concentration of sulphate in surface water | ***$SO_4$ Surface*** | g/m$^3$ |
| Concentration of sulphate in treated water | ***$SO_4$ Treated water*** | g/m$^3$ |
| Concentration of sulphate in soil water in wadi | ***$SO_4$ wadi*** | g/m$^3$ |
| Concentration of sulphate in water supply come from groundwater | ***$SO_4$ Wells*** | g/m$^3$ |
| Mass of Solute in soil water in city | ***Soil water 1*** | g |
| Mass of Solute in soil water in Wadi area | ***Soil water wadi 1*** | g |
| Solubility of Solute | ***Solubility*** | |

| | | |
|---|---|---|
| Mass of Solute in Subsurface flow out from Riyadh Aquifer | ***Subsurface flow 1*** | $g/m^3$ |
| Mass of Solute in subsurface flow water between Surface water and soil water (urban wadi area) | ***Subsurface flow wadi 1*** | $g/m^3$ |
| Mass of Solute in water flow surface water urban wadi area | ***Surface Flow 1*** | $g/m^3$ |
| Mass of Solute in Surface water flow out urban wadi | ***Surface Out 1*** | $g/m^3$ |
| Change Factor of Solute in surface water | ***Surface water Conc*** | $g/m^3$ |
| Mass of Solute in Surface water run in urban wadi area | ***Surface water Wadi 1*** | $g/m^3$ |
| Mass of Solute in Treated Water | ***Treated water 1*** | g |
| Mass of Solute in Sewage water transfer by trucks | ***Trucks water 1*** | $g/m^3$ |
| Mass of Solute in runoff water run in urban area of wadi Hanifah | ***Wadi Runoff 1*** | $g/m^3$ |
| Mass of Solute in Water Supply | ***Water Supply 1*** | g |
| Mass of Solute in Groundwater wells (water supply) | ***Wells water 1*** | $g/m^3$ |

# Appendix B:

# Model Code

## Flow & Solute transport Model Equations

Groundwater_City(t) = Groundwater_City(t - dt) + (Percolation - Subsurface_Flow_To_South) * dt

INIT Groundwater_City = 3.3e9{m^3}

INFLOWS:

Percolation = IF h_GW<=Aquitard_base THEN K_Sulaiy_Aquitard*((h_city_water-Aquitard_base)/Aquitard_Thickness)*Soil_Surface_Area{m^3/day} ELSE (K_Sulaiy_Aquitard*((h_city_water-h_GW)/Aquitard_Thickness)*Soil_Surface_Area){m^3/day}

OUTFLOWS:

Subsurface_Flow_To_South = Hydraulic_Gradient_Aquifer*K_Riyadh_Aq*Aquifer_width*Water_Thickness__Riyadh_Aq{m^3/day}

Groundwater_City1(t) = Groundwater_City1(t - dt) + (Percolation_1 + Percolation_dissolution - Subsurface_flow_1) * dt

INIT Groundwater_City1 = 3.96e12{g}

INFLOWS:

Percolation_1 = IF h_GW<=Aquitard_base THEN Percolation*$SO_4$_Soil_water {g/day} ELSE Percolation*$SO_4$_GW {g/day}

Percolation_dissolution = (Max_conc-$SO_4$_Soil_water)*Percolation

OUTFLOWS:

Subsurface_flow_1 = Subsurface_Flow_To_South*$SO_4$_GW {g/day}

Groundwater_Wadi(t) = Groundwater_Wadi(t - dt) + (Recharge + GW_Input + Wadi_Irr - IRRI_Wadi - GW_Out) * dt

INIT Groundwater_Wadi = 18e7{m^3}

INFLOWS:

Recharge = IF h_GW_wadi<=base_of_J1 THEN K_J1*((h_Wadi_Water-base_of_J1)/J1_Thickness)*Soil_Surface_area_Wadi{m^3/day} ELSE -(K_J1*((h_Wadi_Water-h_GW_wadi)/J1_Thickness)*Soil_Surface_area_Wadi){m^3/day}

GW_Input = hydraulic_Input*Width_Input*KJubaila_J2*Pirzometric_surface_of_Jubaila_Aq {m^3/day}

Wadi_Irr = Fract_Irr_from_Soil*IRRI_Wadi

OUTFLOWS:

IRRI_Wadi = GRAPH(TIME{m^3/day})

(0.00, 47640), ............(9861, 90000)

GW_Out = hydraulic_Output*KJubaila_J2*Width_Output*Pirzometric_surface_of_Jubaila_Aq {m^3/day}

Groundwater_Wadi_1(t) = Groundwater_Wadi_1(t - dt) + (Recharge_1 + GW_Input_1 + IRRI_from_Wadi - IRRI_wadi_1 - GW_Out_1) * dt

INIT Groundwater_Wadi_1 = 2.0e11{g}

INFLOWS:

Recharge_1 = IF h_Wadi_Water-h_GW_wadi>0 THEN Recharge*$SO_4$_wadi {g/day} ELSE Recharge*$SO_4$_GW_wadi {g/day}

GW_Input_1 = GW_Input*$SO_4$_GW__Upstream {g/day}

IRRI_from_Wadi = Fract_Irr_from_Soil*IRRI_wadi_1 {g/day}

OUTFLOWS:

IRRI_wadi_1 = IRRI_wadi*$SO_4$_GW_wadi {g/day}

GW_Out_1 = GW_Out*$SO_4$_GW_wadi {g/day}

Hanifah_Soil_Water(t) = Hanifah_Soil_Water(t - dt) + (PP_CH - Hanifah_Subsurface_Lateral_Flow - ET_CH - AET) * dt

INIT Hanifah_Soil_Water = 1.4e9{m^3}

INFLOWS:

PP_CH = ((Rain_fall/1000)*Catchment_Area_of_Hanifah)-Catchment_Runoff{m^3/day}

OUTFLOWS:

Hanifah_Subsurface_Lateral_Flow = IF Hanifah_Hw>0 THEN K_Wadi*(Wadi_Length*Hanifah_Hw)*(((Hanifah_Hw+20+660)-J1_Thickness-base_of_J1-Wadi_water_Thickness)/Hanifah_catchment_length) {m^3/day} ELSE 0 {m^3/day}

ET_CH = IF Hanifah_Hw>=(Hanifah_soil_thickness-Extinction_depth_in_Wadi) THEN (ET_Coeff_Wadi*(((1.16*PET)-0.37)/1000)*Catchment_Area_of_Hanifah)*((Extinction_depth_in_Wadi-(Hanifah_soil_thickness-Hanifah_Hw))/Extinction_depth_in_Wadi){m^3/day} ELSE 0{mˆ3/day}

AET = IF(PP_CH > 0) THEN (ET_Coeff_H_Catchment*(((1.16*PET)-0.37)/1000)*Catchment_Area_of_Hanifah-ET_CH) ELSE 0 {m/d}

Hanifah_Surface_Water(t) = Hanifah_Surface_Water(t - dt) + (Catchment_Runoff - Runoff_Hanifah - ET_HSW) * dt

INIT Hanifah_Surface_Water = 0.0 {m^3}

INFLOWS:

Catchment_Runoff = IF Rain_fall_inch>(0.2*S3) THEN (((Rain_fall_inch-(0.2*S3))^2/(Rain_fall_inch+0.8*S3))/39.37)*(Catchment_Area_of_Hanifah) {m^3/day} ELSE 0

OUTFLOWS:

Runoff_Hanifah = IF h_Catchment>0 THEN ((1/n2)*(h_Catchment^(2/3))*(Catchment_Slop^0.5))*(86400)*(Numbers_of_streams) {m^3/day} ELSE 0 {m^3/day}

ET_HSW = IF h_Catchment>0.0 THEN ET_Coeff_Wadi*(((1.16*PET)-0.37)/1000)*Catchment_Area_of_Hanifah{m^3/day} ELSE 0{mˆ3/day}

Hanifah_Surface_water1(t) = Hanifah_Surface_water1(t - dt) + (Catchment_Runoff1 - Hainfah_Runoff1 - Precipitation_H_Surface_water) * dt

INIT Hanifah_Surface_water1 = 0{g}

INFLOWS:

Catchment_Runoff1 = $SO_4$_Runoff*Catchment_Runoff{g/day}

OUTFLOWS:

Hainfah_Runoff1 = $SO_4$_Runoff*Runoff_Hanifah{g/day}

Precipitation_H_Surface_water = Hanifah_Surface_water1-Solubility*Hanifah_Surface_Water

Hanifah__Soil_water1(t) = Hanifah__Soil_water1(t - dt) + (PP_CH_1 + Diss_Prec_HSoil - Hanifah_Subsurface_Flow1) * dt

INIT Hanifah__Soil_water1 = 21e10{g}

INFLOWS:

PP_CH_1 = $SO_4$_Rain*PP_CH{g/day}

Diss_Prec_HSoil = Solubility*Hanifah_Soil_Water-Hanifah__Soil_water1

OUTFLOWS:

Hanifah_Subsurface_Flow1 =

Hanifah_Subsurface_Lateral_Flow*$SO_4$_Hanifah{g/day}

Population(t) = Population(t - dt) + (Growth) * dt

INIT Population = 2100000{p}

INFLOWS:

Growth = Population*Growth_rate{p/day}

Precip_H_Soil_Water(t) = Precip_H_Soil_Water(t - dt) + (-Diss_Prec_HSoil) * dt

INIT Precip_H_Soil_Water = 0

OUTFLOWS:

Diss_Prec_HSoil = Solubility*Hanifah_Soil_Water-Hanifah__Soil_water1

Precip_H_Surface_Water(t) = Precip_H_Surface_Water(t - dt) +

(Precipitation_H_Surface_water) * dt

INIT Precip_H_Surface_Water = 0

INFLOWS:

Precipitation_H_Surface_water = Hanifah_Surface_water1-

Solubility*Hanifah_Surface_Water

Precip_Soil_water(t) = Precip_Soil_water(t - dt) + (Precipitation_Soil_water) * dt

INIT Precip_Soil_water = 0

INFLOWS:

Precipitation_Soil_water = Soil_water_1-Solubility*Soil_Water

Precip_Soil_Water_Wadi(t) = Precip_Soil_Water_Wadi(t - dt) +

(Precipitation_Soil_W) * dt

INIT Precip_Soil_Water_Wadi = 0

INFLOWS:

Precipitation_Soil_W = Soil_water_wadi_1-Solubility*Soil_Water_Wadi

Sewage_Water(t) = Sewage_Water(t - dt) + (Sewage_Flow - Sewage_Leakage - Trucks_Water - Sewage_Net) * dt

INIT Sewage_Water = 430000{m^3}

INFLOWS:

Sewage_Flow = (1-Consume_Factor)*Population*Use_rate{m^3/day}

OUTFLOWS:

Sewage_Leakage = IF (Soil_Depth-City_Water_Thickness)>= Sewage_Net_Depth THEN (Sewage_Flow-Sewage_Net-Trucks_Water) {m^3/day} ELSE -(Sewage_Net_Depth-Soil_Depth+City_Water_Thickness)*Soil_Surface_Area*Sewer_Exfiltration_Factor {m^3/day}

Trucks_Water = GRAPH(TIME{m^3/day})

(1.00, 36987), ........, (9861, 80497)

Sewage_Net = GRAPH(TIME{m^3/day})

(1.00, 370240), ..........,(9861, 805778)

Sewage_water_1(t) = Sewage_water_1(t - dt) + (Sewage_flow_1 + Sewage_Conc - sewage_net_1 - Trucks_water_1 - Sewage_Leakage_1) * dt

INIT Sewage_water_1 = 3.44e8{g}

INFLOWS:

Sewage_flow_1 = Sewage_flow*$SO_4$_supply {g/day}

Sewage_Conc = Sewage_flow_1*Factor_$SO_4$_Sewage{g/day}

OUTFLOWS:

sewage_net_1 = sewage_net*$SO_4$_Sewage {g/m^3}

Trucks_water_1 = Trucks_water*$SO_4$_Sewage {g/m^3}

Sewage_Leakage_1 = IF (Soil_Depth-City_Water_Thickness)>= 3.0 THEN Sewage_Leakage*$SO_4$_Sewage {g/day} ELSE Sewage_Leakage*$SO_4$_Soil_water {g/day}

Soil_Water(t) = Soil_Water(t - dt) + (Leakage + PP + Sewage_Leakage + IRRI - ET - Percolation - Engineering_Flow - City_Runoff) * dt

INIT Soil_Water = 1.1e9{m^3}

INFLOWS:

Leakage = (Wells_water+Desalinated_water)*Leakage_rate{m^3/day}

PP = (Rain_fall/1000)*Soil_Surface_Area{m^3/day}

Sewage_Leakage = IF (Soil_Depth-City_Water_Thickness)>= Sewage_Net_Depth THEN (Sewage_Flow-Sewage_Net-Trucks_Water) {m^3/day} ELSE -(Sewage_Net_Depth-Soil_Depth+City_Water_Thickness)*Soil_Surface_Area*Sewer_Exfiltration_Factor {m^3/day}

IRRI = GRAPH(TIME{m^3/day})

(1.00, 57535), ......, (9861, 125218)

OUTFLOWS:

ET = IF City_Water_Thickness >=(Soil_Depth-Extinction_depth) THEN (ET_Coeff_City*(((1.16*PET)-0.37)/1000)*Soil_Surface_Area)*((Extinction_depth-(Soil_Depth-City_Water_Thickness))/Extinction_depth){m^3/day} ELSE PP/(PP+0.00000001)*(ET_Coeff_City*(((1.16*PET)-0.37)/1000)*Soil_Surface_Area){m^3/day}

Percolation = IF h_GW<=Aquitard_base THEN K_Sulaiy_Aquitard*((h_city_water-Aquitard_base)/Aquitard_Thickness)*Soil_Surface_Area{m^3/day} ELSE

(K_Sulaiy_Aquitard*((h_city_water-

h_GW)/Aquitard_Thickness)*Soil_Surface_Area){m^3/day}

Engineering_Flow = IF (Soil_Depth-City_Water_Thickness)<= Network_Depth

THEN Eng_Hyd_Rad*3.142*Eng_L*City_Soil_K*(Network_Depth-(Soil_Depth-

City_Water_Thickness))/Dist_Between_Drains

ELSE 0{mˆ3/day}

City_Runoff = IF Rain_fall_inch>(0.2*S) THEN (((Rain_fall_inch-

(0.2*S))^2/(Rain_fall_inch+0.8*S))/39.37)*Sulaiy_Area {m^3/day} ELSE 0

Soil_water_1(t) = Soil_water_1(t - dt) + (Leakage_1 + Sewage_Leakage_1 + IRRI_1

+ PP_1 + Dissolution - Engineering_flow_1 - Percolation_1 - City_Runoff_1 -

Precipitation_Soil_water) * dt

INIT Soil_water_1 = 4.9e11{g}

INFLOWS:

Leakage_1 = Leakage*$SO_4$_supply*DT{g/day}

Sewage_Leakage_1 = IF (Soil_Depth-City_Water_Thickness)>= 3.0 THEN

Sewage_Leakage*$SO_4$_Sewage {g/day} ELSE Sewage_Leakage*$SO_4$_Soil_water

{g/day}

IRRI_1 = GRAPH(IRRI*$SO_4$_Treated_water {g/m^3})

(1.00, 147766), ........,(30.0, 165787)

PP_1 = PP*$SO_4$_Rain {g/day}

Dissolution = PP*DT*g_per_m3_diss

OUTFLOWS:

Engineering_flow_1 = Engineering_Flow*$SO_4$_Soil_water{g/day}

Percolation_1 = IF h_GW<=Aquitard_base THEN Percolation*$SO_4$_Soil_water

{g/day} ELSE Percolation*$SO_4$_GW {g/day}

City_Runoff_1 = $SO_4$_Soil_water*City_Runoff {g/day}

Precipitation_Soil_water = Soil_water_1-Solubility*Soil_Water

Soil_Water_Wadi(t) = Soil_Water_Wadi(t - dt) + (PP_Wadi +

Hanifah_Subsurface_Lateral_Flow + IRRI_Wadi + Subsurface_Flow_Wadi +

Flow_in - ET_Wadi - Recharge - Flow_out - Wadi_Irr) * dt

INIT Soil_Water_Wadi = 1.3e8{m^3}

INFLOWS:

PP_Wadi = (Rain_fall/1000)*Soil_Surface_area_Wadi-Wadi_Runoff-

(0.2*S_2){m^3/day}

Hanifah_Subsurface_Lateral_Flow = IF Hanifah_Hw>0 THEN

K_Wadi*(Wadi_Length*Hanifah_Hw)*(((Hanifah_Hw+20+660)-J1_Thickness-

base_of_J1-Wadi_water_Thickness)/Hanifah_catchment_length) {m^3/day} ELSE 0

{m^3/day}

IRRI_Wadi = GRAPH(TIME{m^3/day})

(0.00, 47640), .............,(9861, 90000)

Subsurface_Flow_Wadi = Wadi_Bed_K*WP*Wadi_Length*SWGW_i{m^3/day}

Flow_in = K_Wadi*(Wadi_water_Thickness*Upstream_width)*((h_Upstream-

h_downstream)/Wadi_Length){m^3/day}

OUTFLOWS:

ET_Wadi = ET_Wadi_WT{mˆ3/day}

Recharge = IF h_GW_wadi<=base_of_J1 THEN K_J1*((h_Wadi_Water-

base_of_J1)/J1_Thickness)*Soil_Surface_area_Wadi{m^3/day} ELSE -

(K_J1*((h_Wadi_Water-

h_GW_wadi)/J1_Thickness)*Soil_Surface_area_Wadi){m^3/day}

Flow_out =

K_Wadi*(Wadi_water_Thickness*Downstream_width)*((h_Wadi_Water-

h_downstream)/Wadi_Length){m^3/day}

Wadi_Irr = Fract_Irr_from_Soil*IRRI_Wadi

Soil_water_wadi_1(t) = Soil_water_wadi_1(t - dt) + (Subsurface_flow_wadi_1 +

PP_wadi_1 + IRRI_wadi_1 + Hanifah_Subsurface_Flow1 + Flow_in_1 -

Recharge_1 - Flow_out1 - Precipitation_Soil_W - IRRI_from_Wadi) * dt

INIT Soil_water_wadi_1 = 0.7e11{g}

INFLOWS:

Subsurface_flow_wadi_1 = IF Subsurface_flow_wadi >0.0 THEN

Subsurface_Flow_Wadi*$SO_4$_Surface {g/day}

ELSE -Subsurface_Flow_Wadi*$SO_4$_wadi {g/day}

PP_wadi_1 = PP_Wadi*$SO_4$_Rain {g/day}

IRRI_wadi_1 = IRRI_wadi*$SO_4$_GW_wadi {g/day}

Hanifah_Subsurface_Flow1 =

Hanifah_Subsurface_Lateral_Flow*$SO_4$_Hanifah{g/day}

Flow_in_1 = Flow_in*$SO_4$_wadi{g/day}

OUTFLOWS:

Recharge_1 = IF  h_Wadi_Water-h_GW_wadi>0 THEN  Recharge*$SO_4$_wadi

{g/day} ELSE  Recharge*$SO_4$_GW_wadi {g/day}

Flow_out1 = Flow_out*$SO_4$_wadi{g/day}

Precipitation_Soil_W = Soil_water_wadi_1-Solubility*Soil_Water_Wadi

IRRI_from_Wadi = Fract_Irr_from_Soil*IRRI_wadi_1 {g/day}

Surface_Water_Wadi(t) = Surface_Water_Wadi(t - dt) + (Engineering_Flow + Surface_Flow + Wadi_Runoff + Runoff_Hanifah - Subsurface_Flow_Wadi - Surface_Out - Evap) * dt

INIT Surface_Water_Wadi = 250000{m^3}

INFLOWS:

Engineering_Flow = IF (Soil_Depth-City_Water_Thickness)<= Network_Depth THEN Eng_Hyd_Rad*3.142*Eng_L*City_Soil_K*(Network_Depth-(Soil_Depth-City_Water_Thickness))/Dist_Between_Drains

ELSE 0{mˆ3/day}

Surface_Flow = Sewage_Net+Trucks_Water-IRRI{m^3/day}

Wadi_Runoff = IF Rain_fall_inch>(0.2*S_2)  THEN (((Rain_fall_inch-(0.2*S_2))^2/(Rain_fall_inch+0.8*S_2))/39.37)*(Soil_Surface_area_Wadi+Wadi_area_in_City) {m^3/day} ELSE 0

Runoff_Hanifah = IF h_Catchment>0  THEN ((1/n2)*(h_Catchment^(2/3))*(Catchment_Slop^0.5))*(86400)*(Numbers_of_streams) {m^3/day} ELSE 0 {m^3/day}

OUTFLOWS:

Subsurface_Flow_Wadi = Wadi_Bed_K*WP*Wadi_Length*SWGW_i{m^3/day}

Surface_Out = IF (Surface_Water_Wadi - Factor*(Drainage_Area*Drainge_Depth)) < (Velocity*Cross_Sec_Area*DT) THEN  (Surface_Water_Wadi - Factor*(Drainage_Area*Drainge_Depth)) ELSE (Velocity*Cross_Sec_Area*DT) {mˆ3/day}

Evap = PET/1000*PET_Evap_F*(WP-2*h_water_Surface)*Wadi_Length

Surface_water_Wadi_1(t) = Surface_water_Wadi_1(t - dt) + (Engineering_flow_1 + Surface_Flow_1 + Wadi_Runoff_1 + Hainfah_Runoff1 + Surface_water_Conc - Surface_Out_1 - Subsurface_flow_wadi_1) * dt

INIT Surface_water_Wadi_1 = 2e8{g}

INFLOWS:

Engineering_flow_1 = Engineering_Flow*$SO_4$_Soil_water{g/day}

Surface_Flow_1 = Surface_Flow*$SO_4$_Treated_water{g/day}

Wadi_Runoff_1 = $SO_4$_Runoff*Wadi_Runoff{g/day}

Hainfah_Runoff1 = $SO_4$_Runoff*Runoff_Hanifah{g/day}

Surface_water_Conc = Subsurface_flow_wadi_1*Factor_$SO_4$_Surface{g/day}

OUTFLOWS:

Surface_Out_1 = (Surface_Out*$SO_4$_Surface){g/day}

Subsurface_flow_wadi_1 = IF Subsurface_flow_wadi >0.0 THEN

Subsurface_Flow_Wadi*$SO_4$_Surface {g/day}

ELSE -Subsurface_Flow_Wadi*$SO_4$_wadi {g/day}

Treated_Water(t) = Treated_Water(t - dt) + (Trucks_Water + Sewage_Net - Surface_Flow - IRRI) * dt

INIT Treated_Water = 400000{m^3}

INFLOWS:

Trucks_Water = GRAPH(TIME{m^3/day})

(1.00, 36987), ............, (11686, 80497)

Sewage_Net = GRAPH(TIME{m^3/day})

(1.00, 370240), ........., (11686, 805778)

OUTFLOWS:

Surface_Flow = Sewage_Net+Trucks_Water-IRRI{m^3/day}

IRRI = GRAPH(TIME{m^3/day})

(1.00, 57535), ..........., (11686.00, 125218)

Treated_water_1(t) = Treated_water_1(t - dt) + (sewage_net_1 + Trucks_water_1 - IRRI_1 - Surface_Flow_1) * dt

INIT Treated_water_1 = 3.2e8{g}

INFLOWS:

sewage_net_1 = sewage_net*$SO_4$_Sewage {g/m^3}

Trucks_water_1 = Trucks_water*$SO_4$_Sewage {g/m^3}

OUTFLOWS:

IRRI_1 = GRAPH(IRRI*$SO_4$_Treated_water {g/m^3})

(1.00, 147766), ....,( 11686.00, 165787)

Surface_Flow_1 = Surface_Flow*$SO_4$_Treated_water{g/day}

Water_Supply(t) = Water_Supply(t - dt) + (Wells_water + Desalinated_water - Consumptive_Use - Sewage_Flow - Leakage) * dt

INIT Water_Supply = 740000{m^3}

INFLOWS:

Wells_water = GRAPH(TIME{mˆ3/day})

(1.00, 361079), ...., (11686, 584821)

Desalinated_water = GRAPH(TIME{mˆ3/day})

(1.00, 622857),......., (11686, 899850)

OUTFLOWS:

Consumptive_Use = Consume_Factor*Population*Use_rate{m^3/day}

Sewage_Flow = (1-Consume_Factor)*Population*Use_rate{m^3/day}

Leakage = (Wells_water+Desalinated_water)*Leakage_rate{m^3/day}

Water_Supply_1(t) = Water_Supply_1(t - dt) + (Desalinated_water_1 + Wells_water_1 - Leakage_1 - Sewage_flow_1 - Consumptive_Use_1) * dt

INIT Water_Supply_1 = 1.85e8{g}

INFLOWS:

Desalinated_water_1 = Desalinated_water*$SO_4$_Desalinated*DT {g/day}

Wells_water_1 = Wells_water*$SO_4$_Wells*DT {g/day}

OUTFLOWS:

Leakage_1 = Leakage*$SO_4$_supply*DT{g/day}

Sewage_flow_1 = Sewage_flow*$SO_4$_supply {g/day}

Consumptive_Use_1 = Consumptive_Use*$SO_4$_supply {g/day}

Aquifer_width = 43000{m}

Aquitard_base = 605{m}

Aquitard_Thickness = 50{m}

base_of_J1 = 580{m}

Catchment_Area_of_Hanifah = 3.3e9{m^2}

Catchment_Slop = 0.0044

check1 = Soil_Depth-City_Water_Thickness

Check2 = Sewage_Flow-Sewage_Net-Trucks_Water

City_Soil_K = 75 {m/day}

City_Water_Thickness = (Soil_Water/(Soil_Surface_Area*Porosity)){m}

Consume_Factor = 0.05

Cross_Sec_Area = IF Surface_Water_Wadi>(Drainage_Area*Drainge_Depth)

THEN

(Wadi_Width*h_water_Surface){mˆ2}

ELSE (Drainge_width*h_water_Surface){mˆ2}

Curve_Number = 89

Curve_Number_2 = 70

Curve_Number_3 = 70

Dist_Between_Drains = 50 {m}

Downstream_width = 475{m}

Drainage_Area = 287500{m^2}

Drainge_Depth = 1.5{m}

Drainge_width = 11.5{m}

Eng_Hyd_Rad = 0.475{m}

Eng_L = 300000{m}

ET_Coeff_City = 0.82

ET_Coeff_H_Catchment = 0.85

ET_Coeff_Wadi = 0.85

ET_Wadi_WT = IF Wadi_water_Thickness >=(Soil_Depth_Wadi-Extinction_depth_in_Wadi) THEN (ET_Coeff_Wadi*(((1.16*PET)-0.37)/1000)*Soil_Surface_area_Wadi)*((Extinction_depth_in_Wadi-(Soil_Depth_Wadi-Wadi_water_Thickness))/Extinction_depth_in_Wadi) ELSE (1-IRRI_Area_Fraction)*PP_Wadi/(PP_Wadi+0.00000001)*(ET_Coeff_Wadi*(((1.16*PET)-0.37)/1000)*Soil_Surface_area_Wadi)+IRRI_Area_Fraction*(ET_Coeff_Wadi*(((1.16*PET)-0.37)/1000)*Soil_Surface_area_Wadi) {m^3/day}

Extinction_depth = 4{m}

Extinction_depth_in_Wadi = 2{m}

Factor = 0.2

Factor_$SO_4$_Sewage = 1.5

Factor_SO$_4$_Surface = 0

Fract_Irr_from_Soil = 0.73

Growth_rate = 0.000114

g_per_m3_diss = 200

h2_h1 = Wadi_water_Thickness-(Soil_Depth_Wadi+h_water_Surface-Drainge_Depth){m}

Hanifah_catchment_length = 35000{m}

Hanifah_Hw = Hanifah_Soil_Water/(Catchment_Area_of_Hanifah*Porosity_Wadi){m}

Hanifah_soil_thickness = 5{m}

Hydraulic_Gradient_Aquifer = (Water_Thickness__Riyadh_Aq-H_out_2)/X_out_2

hydraulic_Input = (H_in-Water_Thickness__Jubaila_Aq)/X_in

hydraulic_Output = (Water_Thickness__Jubaila_Aq-H_out)/X_out

h_Catchment = (Hanifah_Surface_Water/Catchment_Area_of_Hanifah){m}

h_city_water = Aquitard_base+Aquitard_Thickness+City_Water_Thickness{m}

h_downstream = 550+Wadi_water_Thickness{m}

h_GW = Water_Thickness__Riyadh_Aq+Riyadh_Aq_Base{m}

h_GW_wadi = Water_Thickness__Jubaila_Aq+524{m}

H_in = 46{m}

H_out = 14{m}

H_out_2 = 65{m}

h_Upstream = 610+Wadi_water_Thickness{m}

h_Wadi_Water = J1_Thickness+Wadi_water_Thickness+base_of_J1{m}

h_water_Surface = IF Surface_Water_Wadi> (Drainage_Area*Drainge_Depth) THEN Drainge_Depth+((Surface_Water_Wadi-

(Drainage_Area*Drainge_Depth))/Soil_Surface_area_Wadi) {m} ELSE

Surface_Water_Wadi/Drainage_Area{m}

IRRI_Area_Fraction = 0.4

IS_1_if_ET_from_WT = IF Wadi_water_Thickness >=(Soil_Depth_Wadi-

Extinction_depth_in_Wadi) THEN 1 ELSE 0

J1_Thickness = 30{m}

KJubaila_J2 = 40{m/day}

K_J1 = 0.001{m/day}

K_Riyadh_Aq = 70{m/day}

K_Sulaiy_Aquitard = 0.001{mlday}

K_Wadi = 10{m/day}

Leakage_rate = 0.25

Max_conc = 1200

n = 0.05

n2 = 0.03

Network_Depth = 5{m}

Numbers_of_streams = 196

PET = GRAPH(time{mm/day})

(1.00, 4.40), ......., (9861, 2.16)

PET_Evap_F = 0.7

Piezometric_surface__of_Jubaila_Aq =

Groundwater_Wadi/(Soil_Surface_area_Wadi*Ss_of_Jubaila_J2*Thickness_of_Jub

aila_Aq){m}

Porosity = 0.34

Porosity_Wadi = 0.2

R = Cross_Sec_Area/WP{m}

Rain_fall = GRAPH(TIME{mm/day})

(1.00, 0.00), ......, (9861, 0.00)

Rain_fall_inch = Rain_fall*0.03937{inch/day}

Riyadh_Aq_Base = 527{m}

S = (1000/Curve_Number)-10

S3 = (1000/Curve_Number_3)-10

Sewage_Net_Depth = 3{m}

Sewer_Exfiltration_Factor = 0.1{/day}

$SO_4$_Desalinated = 93 {g/m^3}

$SO_4$_GW = Groundwater_City1/Groundwater_City{g/m^3}

$SO_4$_GW_wadi = Groundwater_Wadi_1/Groundwater_Wadi {g/m^3}

$SO_4$_GW__Upstream = 100 {g/m^3}

$SO_4$_Hanifah = IF Hanifah_Soil_Water>0 THEN

Hanifah__Soil_water1/Hanifah_Soil_Water{g/m^3} ELSE 0 {g/m^3}

$SO_4$_Rain = 15 {g/m^3}

$SO_4$_Runoff = 203{g/m^3}

$SO_4$_Sewage = (Sewage_water_1/Sewage_water) {g/m^3}

$SO_4$_Soil_water = Soil_water_1/Soil_water {g/m^3}

$SO_4$_supply = Water_Supply_1/Water_Supply{g/m^3}

$SO_4$_Surface = (Surface_water_Wadi_1/Surface_Water_Wadi){g/m^3}

$SO_4$_Treated_water = Treated_water_1/Treated_water {g/m^3}

$SO_4$_wadi = Soil_water_wadi_1/Soil_Water_Wadi {g/m^3}

$SO_4$_Wells = 400 {g/m^3}

Soil_Depth = 25{m}

Soil_Depth_Wadi = 50{m}

Soil_Surface_Area = 1.55e8{m^2}

Soil_Surface_area_Wadi = 25e6{m^2}

Soil_Volume = Soil_Surface_Area*Soil_Depth{m^3}

Soil_Volume_Wadi = Soil_Surface_area_Wadi*Soil_Depth_Wadi{m^3}

Solubility = 1500{g/m3}

Specific_yield_of_Riyadh_Aq = 0.13

Ss_Jubaila_Aquifer = 0.0013

Sulaiy_Area = 1.725e8{m^2}

SWGW_i = IF(ABS(h2_h1)>h_water_Surface+Wadi_Bed_Th) THEN

(h_water_Surface+Wadi_Bed_Th)/Wadi_Bed_Th ELSE (-h2_h1/Wadi_Bed_Th){1}

S_2 = (1000/Curve_Number_2)-10

S_v = 0.0034

Thickness_of_Jubaila_Aq = 56{m}

Upstream_width = 325{m}

Use_rate = (Wells_water+Desalinated_water-Leakage)/Population{m^3/p}

Velocity = ((1/n)*(R^(2/3))*(S_v^0.5))*(86400) {m/day}

Wadi_area_in_City = 5.43e8{m^2}

Wadi_Bed_K = 0.01{m/d}

Wadi_Bed_Th = 1{m}

Wadi_Length = 25000 {m}

Wadi_water_Thickness =

Soil_Water_Wadi/(Soil_Surface_area_Wadi*Porosity_Wadi){m}

Wadi_Width = 150{m}

Water_Content = Soil_Water/(Soil_Volume*Porosity)

Water_content_CH = Hanifah_Soil_Water/(Catchment_Area_of_Hanifah*5)

Water_Thickness__Riyadh_Aq =

Groundwater_City/(Soil_Surface_Area*Specific_yield_of_Riyadh_Aq){m}

Width_Input = 25000{m}

Width_Output = 25000{m}

WP = IF Surface_Water_Wadi> (Drainage_Area*Drainge_Depth) THEN

Wadi_Width+(2*h_water_Surface){m}

ELSE Drainge_width+(2*h_water_Surface){m}

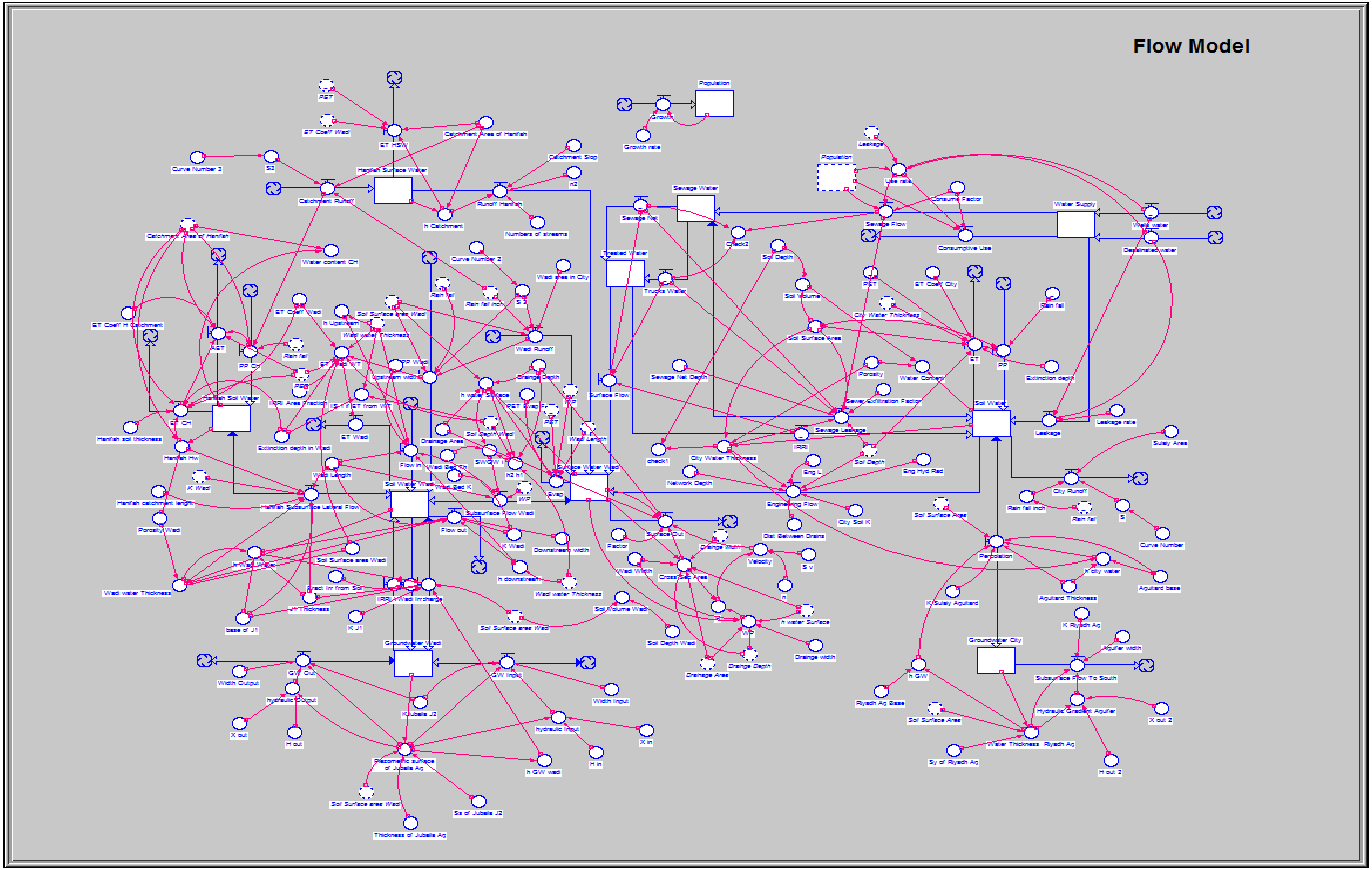
X_in = 6000{m}

X_out = 4000{m}

X_out_2 = 5000{m}

## Manning's n for Closed Conduits Flowing Partly Full (Chow, 1959).

| Type of Conduit and Description | Minimum | Normal | Maximum |
|---|---|---|---|
| **1. Brass, smooth:** | 0.009 | 0.010 | 0.013 |
| **2. Steel:** | | | |
| Lockbar and welded | 0.010 | 0.012 | 0.014 |
| Riveted and spiral | 0.013 | 0.016 | 0.017 |
| **3. Cast Iron:** | | | |
| Coated | 0.010 | 0.013 | 0.014 |
| Uncoated | 0.011 | 0.014 | 0.016 |
| **4. Wrought Iron:** | | | |
| Black | 0.012 | 0.014 | 0.015 |
| Galvanized | 0.013 | 0.016 | 0.017 |
| **5. Corrugated Metal:** | | | |
| Subdrain | 0.017 | 0.019 | 0.021 |
| Stormdrain | 0.021 | 0.024 | 0.030 |
| **6. Cement:** | | | |
| Neat Surface | 0.010 | 0.011 | 0.013 |
| Mortar | 0.011 | 0.013 | 0.015 |
| **7. Concrete:** | | | |
| Culvert, straight and free of debris | 0.010 | 0.011 | 0.013 |
| Culvert with bends, connections, and some debris | 0.011 | 0.013 | 0.014 |
| Finished | 0.011 | 0.012 | 0.014 |
| Sewer with manholes, inlet, etc., straight | 0.013 | 0.015 | 0.017 |
| Unfinished, steel form | 0.012 | 0.013 | 0.014 |
| Unfinished, smooth wood form | 0.012 | 0.014 | 0.016 |
| Unfinished, rough wood form | 0.015 | 0.017 | 0.020 |
| **8. Wood:** | | | |
| Stave | 0.010 | 0.012 | 0.014 |
| Laminated, treated | 0.015 | 0.017 | 0.020 |
| **9. Clay:** | | | |
| Common drainage tile | 0.011 | 0.013 | 0.017 |
| Vitrified sewer | 0.011 | 0.014 | 0.017 |
| Vitrified sewer with manholes, inlet, etc. | 0.013 | 0.015 | 0.017 |
| Vitrified Subdrain with open joint | 0.014 | 0.016 | 0.018 |
| **10. Brickwork:** | | | |
| Glazed | 0.011 | 0.013 | 0.015 |
| Lined with cement mortar | 0.012 | 0.015 | 0.017 |
| Sanitary sewers coated with sewage slime with bends and connections | 0.012 | 0.013 | 0.016 |
| Paved invert, sewer, smooth bottom | 0.016 | 0.019 | 0.020 |
| Rubble masonry, cemented | 0.018 | 0.025 | 0.030 |


Flow Model