M.Sc. Thesis

GROUNDWATER RECHARGE OF LAHORE CITY BY PONDING IN RIVER RAVI

Advisor

PROF. DR. MUHAMMAD ASHIQ KHARAL

Submitted By

Abaid Ullah

(2015-MS-WRE-05)

CENTRE OF EXCELLENCE IN WATER RESOURCES ENGINEERING

University of Engineering and Technology,

Lahore, Pakistan

2019

ABSTRACT

Groundwater plays an important role for domestic, agriculture, urban and in industrial purposes for the city of Lahore. Due to continuous increase in population and people moving towards the urbanized areas causes the extra groundwater extraction cause depletion in aquifer. To enhance groundwater recharge and control of groundwater depletion a dam is proposed at 3 mile Upstream of Mohlanwall and 5 mile downstream of motorway bridge. The height of the proposed dam is 10 ft against which a back watering of 12.5 mile was simulated using HEC-RAS.

HEC-RAS model was used to check the backwater effect in river Ravi due to dam structure. Model was calibrated using manning roughness values between 0.015-0.025 for the main channel, left over bank (LOB) and right over bank (ROB).

Recharge rate of the river Ravi was calculated by Zhukovsky's method against a maximum discharge of 18000 cusec observed in last two decades and found out that River Ravi has a recharging capacity of about 6978783 ft^3 /year. The slope of the River was found to line 1.4ft/mile which was from the longitudinal section of River Ravi. Visual MODFLOW was run to check the effect of river stage on the groundwater level. Pumping data of about 3200 tube wells were used for modelling and R^2 value of about 0.9 was observed during calibration period. A groundwater level of about 20-40ft was observed in the surrounding areas of River Ravi and about 3ft depletion rate in groundwater level was found under normal circumstances. After the proposed dam the extra recharge capacity 24666069 ft^3 /year of River Ravi was calculated.

A rise of 3-6 ft. was simulated in the areas close to the proposed site with a coverage area of 36.33 $mile^2$ on the left side of the river towards Lahore site. It is recommended to install more piezometric tube wells to check the groundwater levels situation and to maintain water levels more recharging options should also be considered.

TABLE OF CONTENTS

ABSTRACT..i

TABLE OF CONTENTS..ii

LIST OF FIGURES vi

LIST OF TABLES xiii

1 INTRODUCTION..1

1.1 General 1

1.2 Climate and Geography..2

1.3 Problem Statement 3

1.4 Study Area...3

1.5 Study Objectives 4

1.6 Limitations of Study..4

1.7 Utilization of Research...4

2 LITERATURE REVIEW..5

2.1 Sources of Water 5

2.1.1 Surface Water Resources 5

2.1.2 Groundwater Resources...6

2.1.3 Groundwater Recharge Techniques...7

2.2 Model Background...7

2.2.1 HEC-RAS 7

2.2.2 Groundwater Visual MODFLOW 8

2.3 HEC-RAS Modelling 9

2.4 Groundwater Modelling 13

3 DATA COLLECTION AND ANALYSIS 20

3.1 Data Collection 20

3.2 Makesens Analysis 20

3.3 Trend Analysis 20

3.3.1 Discharge Trend 20

3.3.2 Rainfall Analysis 22

4 METHODOLOGY 24

4.1 HEC-RAS Model 24

4.1.1 HEC-RAS Geometry Input 24

4.1.2 Flow Data Input 26

4.1.3 Boundary Condition 26

4.2 HEC-RAS Unsteady Flow 27

4.2.1 Boundary Conditon 27

4.3 Unsteady Flow with dam 28

4.4 VISUAL MODLFOW 30

4.4.1 Model Settings 31

4.4.2 Flow Settings 32

4.4.3 Defining Model Domain 33

4.4.4 Import Surface Elevation 34

4.4.5 Adding Pumping Wells 35

4.4.6 Adding Observation Wells 36

4.4.7 Conductivity Data 37

4.4.8 Importing Initial Heads 38

4.4.9 General Head Boundary 39

4.4.10 Constant Head Boundary 40

4.4.11 River Head Boundary 40

5 RESULTS AND DISCUSSIONS 42

5.1 Flow Calculation 42

5.1.1 Flow Duration Curve 42

5.1.2 Frequency Analysis 45

5.2 Recharge Calculation for River Ravi 45

5.3 HEC-RAS Results 46

5.3.1 Steady flow analysis 46

5.4 Model Calibration 48

5.5 Unsteady Flow Analysis without installation of dam 49

5.6 Unsteady flow with Maximum flow conditon and dam 50

5.7 Visual MODFLOW 52

5.8 Groundwater Situation after Rising the River Stage 55

5.9 Groundwater Level Interpolation in ArcMap 58

6 CONCLUSIONS AND RECOMMENDATIONS 65

6.1 Conclusions 65

6.2 Recommendations 65

7 REFERENCES 67

Annexure A 72

Annexure B: 77

Annexure C 81

Annexure D 90

Annexure E 106

LIST OF FIGURES

Figure 1.1: Land use map of Lahore District showing River Ravi and proposed dam site 1

Figure 3.1: Annual Average Daily flow for the year 2000-2014 of River Ravi 21

Figure 3.2: Average annual dialy rainfall for year 2000-2014 22

Figure 4.1: X-Section of the river Ravi with terrain for river Ravi study area 25

Figure 4.2: River Ravi X-Section at 4500ft D/S of Indian Boarder 25

Figure 4.3: Steady flow boundary condition for River Ravi 26

Figure 4.4: Avg. flow hydrograph for river Ravi 27

Figure 4.5: Unsteady flow boundary condition for river Ravi 28

Figure 4.6: Proposed broad crested dam design and Elevation: 29

Figure 4.7: Proposed dam section in HEC-RAS 29

Figure 4.8: Visual MODFLOW Modelling Process flow chart for the study 31

Figure 4.9: Model setting for the groundwater model of study area 32

Figure 4.10: Flow setting for model input of study area 33

Figure 4.11: Defining model domain for study area in Visual Modflow 34

Figure 4.12: Importing surface elevation of the study area 35

Figure 4.13: Importing pumping wells data for study area 36

Figure 4.14: Importing observation wells for study area 37

Figure 4.15: Conductivity map of the study area 38

Figure 4.16: Boundary conditions in study area 39

Figure 4.17: Constant head boundary condition for study area 40

Figure 4.18: River ravi boundary condition for the study area 41

Figure 5.1: Avg. Flow Duration Curve of River Ravi for Peak months in year (2001-2013) 42

Figure 5.2: Average daily discharge in river Ravi for (2000-2014) 43

Figure 5.3: Max daily flow in monthly basis of river Ravi (2000-2014)..................43

Figure 5.4: River Ravi discharge available 90% of the time for (2000-2014) 44

Figure 5.5: Minimum discharge throughout the year (2000-2014) 44

Figure 5.6: Velocity profile in river Ravi for steady flow condition 47

Figure 5.7: Water Surface Profile of river Ravi for steady flow 47

Figure 5.8: Water Surface Profile at max flow available 49

Figure 5.9: Water Surface Profile for the River Ravi 50

Figure 5.10: River Stage and Flow graph at D/S 50

Figure 5.11: Water Surface Profile for the River Ravi after installation of DAM 51

Figure 5.12: Maximum water surface profile with dam installed.............................51

Figure 5.13: Rating Curve for D/S after installation of dam in river Ravi 52

Figure 5.14: Groundwater contours for the year 2014..53

Figure 5.15: Model Calibration for year 2003-2010...53

Figure 5.16: Model Validation for year 2014 54

Figure 5.17: Groundwater contour for year 2017 situation 54

Figure 5.18: Contour 2020 with no changes in River stage.......................................55

Figure 5.19 : Groundwater contour after 1 year of changing the rive Stage 56

Figure 5.20: Contour after 3 years changing river stage (2020) 57

Figure 5.21: Simulated Head Vs. Time in different Location of Lahore city............57

Figure 5.22: Study Area map including proposed dam site.......................................58

Figure 5.23: Observed GW level (ft.) map of Lahore city for year 2003 59

Figure 5.24: Observed GW level (ft.) map of Lahore city for year 2017 59

Figure 5.25: Simulated GW level (ft.) map of Lahore city for year 2003 60

Figure 5.26: Simulated GW level (ft.) map of Lahore city for year 2017 60

Figure 5.27: Simulated GW level (ft.) map of Lahore city after installation of DAM in year 2018......62

Figure 5.28: Simulated GW level (ft.) map of Lahore city after installation of DAM in year 2019......62

Figure 5.29: Simulated GW level (ft.) map of......62

Lahore city after installation of DAM in year 2020......62

Figure 5.30: water level difference map of Lahore for year 2019......64

Figure 5.29: water level difference......64

map of Lahore for year 2018......64

Figure 5.30: water level difference map of......64

Lahore for year 2020......64

Figure B.1: Annual average daily discharge in cusec trend (2003-2014)......78

Figure B.2: Winter average daily discharge in cusec trend (2003-2014)......78

Figure B.3: Summer average daily discharge in cusec trend (2003-2014)......78

Figure B.4: Spring average daily discharge in cusec trend (2003-2014)......79

Figure B.5: Flow duration curve November - April (2003-2014)......79

Figure B.6: Flow duration curve May - October (2003-2014)......79

Figure B.7: Minimum and Q90 flood in river Ravi discharge in cusec (2003-2014)80

Figure B.8: Minimum flow in river Ravi discharge in cusec (2003-2014)......80

Figure B.8: Mean flow in river Ravi discharge in cusec (2003-2014)......80

Figure C.1: Ravi Section at RD 81500......82

Figure C.2: Ravi Section at RD 79000......82

Figure C.3: Ravi Section at RD 77000......82

Figure C.4: Ravi Section at RD 75000......83

Figure C.5: Ravi Section at RD 73000......83

Figure C.6: Ravi Section at RD 67000 83

Figure C.7: Ravi Section at RD 64000 84

Figure C.8: Ravi Section at RD 61000 84

Figure C.9: Ravi Section at RD 55000 84

Figure C.10: Ravi Section at RD 52000 85

Figure C.11: Ravi section at RD 49000...85

Figure C.12: Ravi Section at RD 46000 85

Figure C.13: Ravi Section at RD 42000 86

Figure C.14: Ravi Section at RD 39000 86

Figure C.15: Ravi Section at RD 37000 86

Figure C.16: Ravi Section at RD 35000 87

Figure C.17: Ravi Section at RD 31000 87

Figure C.18: Ravi Section at RD 28000 87

Figure C.19: Ravi Section at RD 25000 88

Figure C.20: Ravi Section at RD 22000 88

Figure C.21: Ravi Section at RD 16000 88

Figure C.22: Ravi Section at RD 13000 89

Figure C.23: Ravi Section at RD 7000 89

Figure C.24: Ravi Section at RD 500 89

Figure D.1: Ravi Section at RD 4000 91

Figure D.2: Ravi Section at RD 8000 91

Figure D.3: Ravi Section at RD 11000 91

Figure D.4: Ravi Section at RD 14000 92

Figure D.5: Ravi Section at RD 21000 92

Figure D.6: Ravi Section at RD 24000 92

Figure D.7: Ravi Section at RD 27000 93

Figure D.8: Ravi Section at RD 30500 93

Figure D.9: Ravi Section at RD 33000 93

Figure D.10: Ravi Section at RD 36000 94

Figure D.11: Ravi Section at RD 39000 94

Figure D.12: Ravi Section at RD 41500 94

Figure D.13: Ravi Section at RD 44000 95

Figure D.14: Ravi Section at RD 47000 95

Figure D.15: Ravi Section at RD 50500 95

Figure D.16: Ravi Section at RD 53000 96

Figure D.17: Ravi Section at RD 55500 96

Figure D.18: Ravi Section at RD 58000 96

Figure D.19: Ravi Section at RD 60500 97

Figure D.20: Ravi Section at RD 63000 97

Figure D.21: Ravi Section at RD 66000 97

Figure D.22: Ravi Section at RD 69000 98

Figure D.23: Ravi Section at RD 72000 98

Figure D.24: Ravi Section at RD 75000 98

Figure D.25: Ravi Section at RD80500 99

Figure D.26: Ravi Section at RD 83000 99

Figure D.27: Ravi Section at RD 86000 99

Figure D.28: Ravi Section at RD 89000 100

Figure D.29: Ravi Section at RD 92000 100

Figure D.30: Ravi Section at RD 95000 100

Figure D.31: Ravi Section at RD 98000 101

Figure D.32: Ravi Section at RD 111000 101

Figure D.33: Ravi Section at RD 114000 101

Figure D.34: Ravi Section at RD 117000 102

Figure D.35: Ravi Section at RD 123000 102

Figure D.36: Ravi Section at Rd 126000 102

Figure D.37: Ravi Section at RD 129000 103

Figure D.38: Ravi Section at Rd 132000 103

Figure D.39: Ravi Section at RD 135000 103

Figure D.40: Ravi Section at RD 138000 104

Figure D.41: Ravi Section at RD 141000 104

Figure D.42: Ravi Section at RD 144000 104

Figure D.43: Ravi Section at RD 147000 105

Figure D.44: Ravi Section at RD 154000 105

Figure D.45: Ravi Section at RD 156500 105

Figure E.1: Observed WL (ft.) map of Lahore city in year 2003 107

Figure E.2: Observed WL (ft.) map of Lahore city in year 2004 107

Figure E.3: Observed WL (ft.) map of Lahore city in year 2005 107

Figure E.4: Observed WL (ft.) map of Lahore city in year 2006 107

Figure E.5: Observed WL (ft.) map of Lahore city in year 2007 107

Figure E.8: Observed WL (ft.) map of Lahore city in year 2010 107

Figure E.6: Observed WL (ft.) map of Lahore city in year 2008 107

Figure E.9: Observed WL (ft.) map of Lahore city in year 2011 107

Figure E.10: Observed WL (ft.) map of Lahore city in year 2012 107

Figure E.11: Observed WL (ft.) map of Lahore city in year 2013 107

Figure E.12: Observed WL (ft.) map of Lahore city in year 2014 107

Figure E.13: Observed WL (ft.) map of Lahore city in year 2015 107

Figure E.14: Observed WL (ft.) map of Lahore city in year 2016 107

Figure E.15: Observed WL (ft.) map of Lahore city in year 2017 107

Figure E.16: Observed WL (ft.) map of Lahore city in year 2018 107

Figure E.17: Simulated WL (ft.) map of Lahore city in year 2003 107

Figure E.18: Simulated WL (ft.) map of Lahore city in year 2004 107

Figure E.19: Simulated WL (ft.) map of Lahore city in year 2005 107

Figure E.20: Simulated WL (ft.) map of Lahore city in year 2006 107

Figure E.21: Simulated WL (ft.) map of Lahore city in year 2007 107

Figure E.22: Simulated WL (ft.) map of Lahore city in year 2008 107

Figure E.23: Simulated WL (ft.) map of Lahore city in year 2009 107

Figure E.24: Simulated WL (ft.) map of Lahore city in year 2010 107

Figure E.25: Simulated WL (ft.) map of Lahore city in year 2011 107

Figure E.26: Simulated WL (ft.) map of Lahore city in year 2012 107

Figure E.27: Simulated WL (ft.) map of Lahore city in year 2013 107

Figure E.28: Simulated WL (ft.) map of Lahore city in year 2014 107

Figure E.29: Simulated WL (ft.) map of Lahore city in year 2015 107

Figure E.30: Simulated WL (ft.) map of Lahore city in year 2016 107

Figure E.31: Simulated WL (ft.) map of Lahore city in year 2017 107

Figure E.32: Simulated WL (ft.) map of Lahore city in year 2018 107

Figure E.33: Simulated WL (ft.) map of Lahore city in year 2019 107

Figure E.34: Simulated WL (ft.) map of Lahore city in year 2020 107

LIST OF TABLES

Table 3.1: Daily average discharge of river Ravi estimated by Sen's method........... 21

Table 3.3: Mann Kendall trend of Rainfall for Lahore city 23

Table 4.1: Visual MODFLOW Packages 30

Table 5.1: Frequency Analysis of Discharge data of River Ravi............................... 45

Table 5.2: Recharge Calculation for River Ravi 46

Table 5.3: HEC-RAS Model Calibration.. 48

Table 5.4: Variation of observed water levels before installation of DAM in Lahore city (2003-2017)... 60

Table 5.5: Variation of simulated water levels before installation of DAM in Lahore city (2003-2017)... 61

Table 5.6: Variation of simulated water levels after installation of dam in Lahore city (2017-2018)... 63

Table 5.7: Variation of simulated water levels after installation of dam in Lahore city (2019-2020)... 63

Table A.1: Observation Wells Data 73

CHAPTER I

INTRODUCTION

1.1 General

Lahore is the capital of Punjab province and the second largest and metropolitan city in Pakistan. It is located on the world map with geographical coordinates as 31° 32′ 58″ N and 74° 20′ 36″ E. With its proximity to Kasur district in the South and Sheikhupura in the North-west, the district area is 1,772 km^2 and its urban area comprises largely of converted agricultural lands (Figure 1.1). Urban area of Lahore has expanded almost double in the last 12 to 15 years. According to the 1998 census, there were nearly 6.32 million people; a population density of 3,566 persons/Km^2. Urban population consisted of 82.4% of the total. Lahore is the second largest financial hub of Pakistan and has industrial areas including Kot Lakhpat and the new Sundar Industrial Estate (near Raiwind). Thus, rapid urbanization of the area, including the industrial establishments, is posing many key challenges, and at the same time, opportunities in the new millennium. Out of these challenges, sustaining the water and sanitation demands of the residents is an emerging issue. (Lahore master planning, 2016)

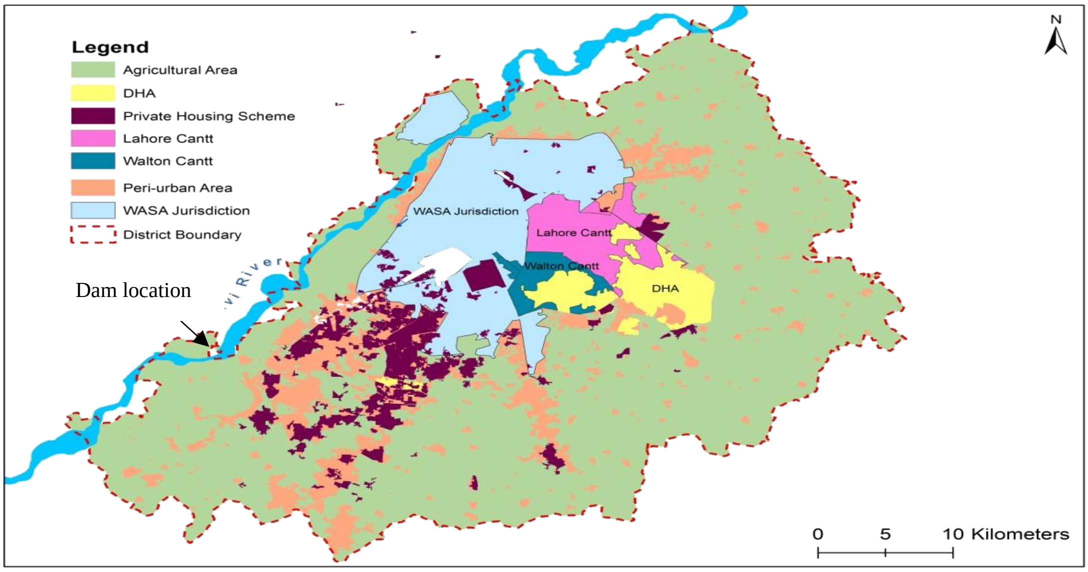

Figure 1.1: Land use map of Lahore District showing River Ravi and proposed dam site

1.2 Climate and Geography

The climate of the region is characterized by large seasonal variations in temperature and rainfall. Mean annual rainfall is 712 mm and reference crop evapotranspiration (ETO) is 1,649 mm. Mean annual temperature is about 24.3 ℃ ranging from 33.9 ℃ in June to 12.8 ℃ in January (Pakistan Meteorological Department, 2006). The hottest month is June, where average highs routinely exceed 40 °C, highest temperature observed is 48.3°C, recorded on May 30, 1944, and the lowest recorded is –1°C, observed on January 13, 1967. The wettest month is July, with heavy rainfalls and evening thunderstorms with the possibility of cloudbursts. (Lahore master planning, 2016)

The Lahore District forms the part of the Bari Doab – inter-fluvial lands between the Ravi in the North West and the Sutlej River to the south. The area is underlain by a significant thickness of alluvial deposits, up to 1200 ft in depth, proven by the investigations carried out by Water and Soils Investigation Division (WASID), during the period 1961-62 (WAPDA, 1980). The recharge sources are Ravi River (occasional flows, nowadays) on the North West and BRBD Canal on the East. Discharging boundaries are Sukh-Beas drainage channel on the south and again the Ravi River in the west. However, these discharging boundaries only function in the form of surface runoff during heavy rainfalls; no groundwater discharge is possible due to excessive groundwater depletion in the area. The general altitude of the area is 682 to 699 ft, above mean sea level (amsl). The area slopes towards the south and south-west, at an average gradient of one in 3000. The upper most part of the upper Bari Doab is now Indian Territory, after partition, but being the integral part to the Lower and Central Bari Doab provides natural route for the regional groundwater flow.

1.3 Problem Statement

Due to Rapid population growth, intensive migration of people to Lahore and the establishment of several industries has increased water demand by manifolds. Mushrooming private housing societies, particularly on the periphery of cities, along with industrial activities has caused two-fold stress on the underlying groundwater reservoir, i.e. increased groundwater pumping for domestic and industrial activities and reduced groundwater recharge from agricultural fields and rainfall due to most urban areas being covered by buildings and roads.

Despite a reduction in Ravi flows due to upstream water use by India the main recharge (82 per cent) to groundwater is contributed by the river. The rainfall and canal system contribute only 12 percent whereas the return flow from irrigation fields is about 6. percent. This shows the importance of Ravi flows in sustaining the Lahore aquifer

WASA supplies drinking water to more than 6 million people by means of 484 tube wells. These tube wells are located in different area and their depth varies between 490 to 650 ft. Over time water, demand has increased from 180 litres per capita per day (lpcd) in 1967 to 274 lpcd in 2013. (WASA Report, 2013)

Due to these reasons, it is necessary that such methods and techniques are to be adopted that could minimize the ground water depletion and enhance groundwater recharge. The Ravi river is a major source of groundwater recharge, which ultimately increase the groundwater recharge capacity of the Lahore city

1.4 Study Area

The study area of the present research was from Ravi siphon to katcha kahna near Chung Lahore. The length of the reach is nearly 38 mile, and cross section varies at different locations. The area adjacent to the Ravi River is urban and mostly populated. Therefore, it considered that if the dam was constructed in that area and if the high flow comes in moon soon season what will happen to the adjacent area and how the effect of dam will be spread in that area. Study area with proposed dam location is showed in Figure 1.1

1.5 Study Objectives

- To evaluate the availability of the groundwater recharge capacity from river Ravi without and with dam.
- To determine the water surface profile in case of high flow floods in River Ravi.
- To determine the groundwater recharge capacity and variability in water level of Lahore city by the river by using VISUAL MODFLOW model.

1.6 Limitations of Study

The research only deals with the ground water recharge of the Lahore city and the effect of dam construction in Lahore city in case of the high flow flood. The source of water in river Ravi may be discussed, so that it can be understood that how much discharge is flowing in river Ravi and what contribution is from rainfall, and drainage system of Lahore. It will only deal with the ground water recharge through the river Ravi and not from any other source. The study did not include the effect of recharge on the adjacent cities like Sheikhupura because proposed dam and its backwater effect is not recharging to the Sheikhupura city. Water quality will not be discussed in this study.

1.7 Utilization of Research

This research will help to identify the groundwater potential of Lahore city from the River Ravi and what is the current condition of groundwater levels, and then from this study methods can be devised that help to reduce the groundwater depletion in Lahore city. This research would be helpful to check the current situation of Lahore district and how the groundwater levels is going to vary in the future, so the Irrigation & Agriculture departments can work on the planning to limit the groundwater use for future.

CHAPTER II

LITERATURE REVIEW

2.1 Sources of Water

2.1.1 Surface Water Resources

The main source of surface water in Pakistan are Rivers. In the Indus Water Treaty 1960, water rights of three eastern rivers (Ravi, Beas and Sutlej) were given to the India and three Western Rivers (Indus, Jehlum and Chenab) were given to Pakistan. Indus River and its Tributaries on an average brings 190 Billion cubic meter (BCM) of water annually. This include 179 BCM from the western River and 11 BCM from Eastern Rivers whose water rights is to India.

Currently, 93 percent of total water withdrawal (176.7 BCM) was distributed for the Agricultural use, 4 percent (7.6 BCM) is for domestic use and the remaining 3 percent (5.7 BCM) is for industrial use (Bakshi and Trivedi, 2011)

The flow In River Ravi mainly comes from Marala-Ravi link Canal and five flash streams, which flow, into Rive Ravi within Pakistan. In recent years, the flow of River Ravi declined due to climate change and construction of the irrigation and Hydropower diversion structure by the India. The Thein Dam constructed by India in 2000 impact the flow hydrology of the river Ravi that has reduced groundwater recharge significantly in and around the Lahore city.

The average flow in Ravi during 1922-1961 was 1300 million cubic meter per day MCM/day which was reduced to 800 MCM/day in 1985-1995, and further declined to its lowest level of 175 MCM/day in 2000-2009. However, peak flows of more than 260 MCM/day was also observed during this period (Basharat and Rizvi, 2011).

`

During the monsoon of 2010, a highest discharge of only 75-100 MCM/day was reported in River Ravi in spite of heavy monsoon on the regional scale (Khalid et al., 2013). This means that even in future the floods passing along the Lahore will be only from Ravi tributaries downstream of the Thein Dam or the flood that is more than the reservoir capacity of the Thein Dam. Therefore, except flood events from during an extraordinary rainy season, no regular flow of considerable amounts are expected except for M-R link canal releases from Marala Barrage.

2.1.2 Groundwater Resources

Most of the groundwater resources of Pakistan exist in the Indus Plain, extending from Himalayan foothills to Arabian Sea, and are stored in alluvial deposits. The Plain is about 1,600 Km long and covers an area of 21 Mha and is blessed with extensive unconfined aquifer, which is fast becoming the supplemental source of water for irrigation. The aquifer has been built due to direct recharge from natural precipitation, river flow, and the continued seepage from the conveyance-system of canals, distributaries, watercourses and application-losses in the irrigated lands during the last 90 years (Khalid et al., 2013).

The Lahore aquifer was composed of unconsolidated alluvial soil of up to 400 m in thickness. At present, the maximum observed water Table depth in Lahore city was 40 m and in the area of Raiwind was about 12 m (Basharat and Rizvi, 2011).

In 1960, the groundwater Table depth of Lahore city was 4.6 m. More use of the groundwater Table depth has headed to lowering of the water Table about 0.5 m for the last 30 years. In 1987 the depth of water Table ranging from 8-20 m, which has reduced further to 51 m in 2011. (Khalid et al., 2013)

WASA supplies water to the 6 million people by mean of 484 tube wells in Lahore city with a groundwater depth of 200-400m (WASA 2013).

2.1.3 Groundwater Recharge Techniques

Groundwater recharge techniques can be classified into Direct Methods and Indirect Method. Direct methods include Surface methods and Subsurface methods. In surface methods flooding, recharging basins, stream modification, and surface irrigation are included while in subsurface groundwater, recharging techniques include injection wells (recharging wells), gravity head recharging wells, and recharging pits. (Debu 2016)

Indirect method for groundwater recharge includes collector wells, infiltration gallery, and groundwater conservation structure development for the indirect groundwater recharge. (Debu 2016)

For the current study, the selected method for the groundwater recharge was ponding in river and a groundwater model in Visual MODFLOW was developed to evaluate the effect on groundwater recharge with different scenarios.

2.2 Model Background

2.2.1 HEC-RAS

HEC-RAS is a model developed by the hydraulic engineering centre of US Army Corps of Engineering. HEC-RAS is an integrated system of software. It is comprised of the graphical user interface (GUI), separate analysis component, data management capabilities and graphics. It is used for the analysis of the river system.

HEC-RAS contains the following different components of river analysis system.

- Steady flow water surface profile computation;
- One dimensional and two-dimensional unsteady flow simulation;

- Water quality analysis; and
- Quasi unsteady or fully unsteady sedimentation analysis.

HEC-RAS is designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and constructed channels, overbank, levee protected areas etc.

For two-dimensional unsteady flow analysis, HEC-RAS uses Navies-Stokes equation, which describe the motion of fluids in two dimensions. While in the context of channel and flood modelling, further simplification could be done.

Now in HEC RAS model RAS Mapper is also available which help us to georeferenced our cross section more easily because we can add a terrain of the study area in the back of our model (HEC-RAS User Manual, 2016).

2.2.2 Groundwater Visual MODFLOW

The Visual MODFLOW software (2011.1 ver.6.0.159), was developed by Schlumberger Water Services (SWS), Canada, has been used for this study. The Visual MODFLOW is the most complete and easy-to-use modelling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. This fully-integrated package combines MODFLOW, MODFLOWSURFACT, MODPATH, Zone Budget, MT3Dxx/RT3D, MGO, and WinPEST with the most intuitive and powerful graphical interface available.

The model input parameters and results can be visualized in 2D (cross-section and plan view) or 3D at any time during the development of the model, or the displaying of the results. For complete three-dimensional groundwater flow and contaminant transport modelling, Visual MODFLOW is one of the best software packages. The main interface for Visual MODFLOW has much of the same user-friendly look and feel as the previous versions of Visual MODFLOW. Some of the more significant upgrade features in the latest version of Visual MODFLOW are described below.

The logical menu structure and easy-to-use graphical tools allow users to:

- easily dimension the model domain and select units;
- conveniently assign model properties and boundary conditions;
- run the model simulations;
- calibrate the model using manual or automated techniques;
- optimize the pumping well rates and locations; and
- visualize the results using 2D or 3D graphics.

The main interface for Visual MODFLOW has much of the same user-friendly look and feel as the previous versions of Visual MODFLOW, but what's "under the hood" has been dramatically improved to give you more powerful tools for entering, modifying, analyzing, and presenting your groundwater modeling data (VMOD help)

A number of scientists and scholars used mathematical modelling in different area of groundwater like planning, development and managing groundwater studies. In this chapter, the studies done by the different researchers were reviewed and main findings were summarized.

2.3 HEC-RAS Modelling

Different Researcher used HEC-RAS model for the water surface profile computation and flood inundation for different scenario. Some of these researches are reviewed below for understanding the HEC-RAS modelling.

Bashir et al, (2010) studied hydrological modelling and flood hazard mapping for Nullah lai using HEC RAS and HEC GeoRAS. GIS model with hydrologic modelling was used to estimate of flood zone of Nullah lai, Rawalpindi. Topographic survey of fine resolution was used to create DEM. Interpolation method was used to obtain elevation data at unknown locations. Inundation area estimated at the discharge value of 3000 m^3/sec is 3.4 km^2 out of which 2.96 km^2 is occupied under the inundation depth from 1 to 5 meters. Maximum flood depth of 20 m was observed at this discharge for the study area. Output values of flood depth and flood area obtained by HEC-RAS was closed to the Survey done by Japan International Cooperation Agency (JICA).

Masood et al, (2011) developed a HEC-RAS model for the flood inundation of eastern Dhaka by using DEM from Shuttle Radar Topography Mission and hydrologic data for 30 years (1972-2004) is used for the study. The DEM was modified to cover the topography of the area because of high land filling by the developer. The model was run for the flood of a 100-year return period for the flood inundation of the eastern Dhaka. Simulation results shows a maximum depth of 7.55 m and south-eastern part of the study is flooded more than 50%. A flood Hazard map and Risk analysis map of the area was developed using ArcGIS considering depth of flow and vulnerability to people and property. These maps are helpful for the future management of floods.

Hagizadeh et al, (2012) studied the Neka's River Basin, Malaysia for the flood analysis using HEC RAS and HEC GeoRAS and water surface profile was developed for the Downstream of Neka's River. Hydraulic studies during the flood season of 1986-1999 and 2002-2004 was used to calibrate the model. 200 X-Section of the rivers was used for the model input. Model was calibrated by adjusting the roughness coefficient. The peak flood was well simulated at Nika's River Basin with mean square error of 10.7 cm compared to observation. Simulations of peak flood stages and hydrographs' evaluations are congruent with studies and observations, with the former showing mean square errors of 4.8 – 10 cm. The coupled HEC-RAS and HEC GeoRAS shows good results.

Siddique et al, (2011) compared the water level estimates from hydrodynamic hydrologic modelling and satellite altimetry for a complex environment. For hydrodynamic modelling he used 1D calibrated, HEC-RAS model for the rivers in Bangladesh, for the model input gaged stream flow; water level data and river geometry were input. On the other hand, Envisat mission was selected for satellite-based water level elevation data. Results showed that the valued obtained from satellite data is 0.2 m and 1.9 m higher than the values estimated by using HEC RAS in monsoon and Dry conditions respectively. Envisat satellite was found to be disagreed with most of the small and medium river in mountainous and flashy flood basins.

Sarhadi et al, (2012) studied flood inundation mapping of ungauged rivers at Halilrud basin and Jiroft city in south-eastern Iran. Land used and the channel morphology was extracted using GIS techniques. HEC GeoRAS pre-processing files was created in GIS, which is then imported to HEC RAS. Discharge at different return periods was calculated using frequency analysis and used in the flow inundation computation in HEC RAS which was then exported to GIS for better visualization satellite imagery was used to find out the extent of the model in real time. Previous floods data was used for the model performance evaluation in predicting flood inundation. Then map was prepared to check the vulnerable area form the extracted images from the satellite and flood inundation extent to find out the critical areas.

Baky et al, (2012) studied flood flows for the crop production and risk management with HEC RAS and GIS in the Agricultural area of Shariatpur, Dhaka. He prepared inundation maps of the area by using hydrodynamic models of HEC-RAS and HEC GeoRAS in Arc GIS. Optimal flood depth for the crop was estimated out using statistical analysis and finally water above the optimal depth was calculated using GIS techniques. This study also proposed two equation for the estimation of MAWA discharge depending on 2 upstream stations. This equation helped to find out the amount of water required to release from MAWA to the study Area for obtaining the optimal flood depth for crop production.

Francisco et al, (2015) studied water surface profiles developed in river flows. The HEC-RAS model usually computes the water surface profile. They studied 13 different discharge prediction methods for the computation of water surface profile for compound channels where both momentum and energy equation was applied, based on his results they developed a new theory for the computation of water surface profile in rapidly varied flow. It was found that the interaction of main channel and flood plain is compulsory for the discharge prediction as well as velocity correction coefficient and water surface profile in case of gradually varied flow. It was also found that the results of momentum equation are better than the energy equation.

Vladimir et al, (2015) studied the flood Hazard mapping for Mert River, Samsun, Turkey using GIS and HEC-RAS model. During the 2012 flood a large loss was observed so flood risks maps for the study area was developed using the model for future management of floods. The x- section is digitized and extracted using GIS and then HEC-RAS model was run on peak flow of 10, 25, 50 and 100 year to determine the effect of peak flow in different return period. Then flood maps were developed in GIS considering the Vulnerability and Risks at flood peaks of 10, 25, 50 and 100 year return period.

Weicia et al, (2015) studied threat assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalaya's. He used HEC RAS 2D modelling for the failure of moraine dam Cirenmaco and estimate' glacial lake outburst flood in downstream due to dam failure. He finds out that HEC-RAS produce reasonable depth and extent of flood and can use for the modelling of complex glacial lake outburst floods effectively. He finds out that HEC-RAS glacial Lake Outburst floods results can be used for the implantation of disaster management techniques.

Punys et al, (2015) studied hydro kinematic resource assessment in a lowland river in lithunia. For this study, hydrologic and hydraulic modelling methods were applied. HEC-RAS with HEC GeoRAS was used for the hydraulic computation. High Resolution DTM was embedded in study for extraction of cross section. Model was calibrated by adjusting the manning n values after computation of slope and stream discharge was measured. After model calibration model was simulated at mean annual, bankful, at low discharge is run and velocity, depth, and cross-sectional area was computed for the river cross sections.

Wicktoria et al, (2016) used HEC-RAS for modelling the flood capacity of a Polish Carpathian river. He compared the results with constrained channel and a free channel condition. For model input, he used 10 pair of river x-section adjacent to constrained and freely developed channel with channel slope and roughness for the Hydraulic modelling of the river using HEC-RAS 1D steady state analysis. The sections developed with freely cross section usually shows the lower water depth and larger width at a particular discharge. They also showed low velocity and bed shear stress. While the cross sections with constrained channel show different results for low frequency high flood. He found that only low frequency high magnitude can be carried out with low shear stress on wide channel x-section.

2.4 Groundwater Modelling

Fouepe et al, (2009) conducted a study for the groundwater modelling in the upper Anga'a River Watershed, Yaonde, Cameroon. MODFLOW software was used for modelling the flow and particle-tracking model for shallow unconfined aquifer for the Anga'a River watershed. The model grid was created of 106 x 68 columns and rows with two layers each of 50 m depth consisting unconfined and semi-confined aquifer. Lateral inflow and outflows were simulated by constant head boundary condition. Riverhead and Lake Levels in the model were simulated using River Package in MODFLOW. A steady state groundwater model was calibrated using 18 observation wells record for the year 2008. Computed contour show that the River Base flow was a part of the groundwater regime in the area. Results showed that the base flow is an important factor for modelling the groundwater in Anga'a River Watershed, and groundwater flows was controlled by the topography of the area.

Ahmed et al, (2009) used Visual MODFLOW, Pro 4.1 to evaluate water balance and study the flow system Yamuna–Krishni interfluve. The horizontal flows, seepage losses from unlined canals, recharge from rainfall and irrigation return flows were applied using different boundary packages available in the VISUAL MODFLOW. The river aquifer interaction was simulated using the river boundary package. Hydraulic conductivity values were applied to specific zones and these ranged from 9.8 to 26.6 m per day. Pumping rates of 500, 1000, 1500, 2000 and 2500 m^3/day were applied to appropriate areas of the model to simulate areas of stress. The zone budget of the area shows a water balance deficit for the period from 2006 to 2007. The total recharge to the study area was 160.21 million m^3 (MCM). The sensitivity analysis showed that the model was the most sensitive to hydraulic conductivity and recharge parameters.

Vijai et al, (2011) developed a conceptual model of groundwater for the Pali Area, India using VISULA MODFLOW. GIS was used for preparing out the hydrological, hydrogeological and geological data. The model was developed on spatial bases using GIS tool and not taking the average values for the whole area. Boundary conditions for the model was analysed and studied using GIS and a map created to import for the conceptual modelling showing various boundary condition in the area. GMS (groundwater modelling system) is used with the GIS for the preparing the 3D visualization of the study area. Groundwater recharge values were used on spatial bases for the whole area for the better results.

Senthilkumar et al, (2011) developed a model using MODFLOW and GMS version 3.1 for finding the impact of square on the groundwater stream for the Palar River catchment, Tamilnadu, Southern India. Groundwater requirements of the atomic center were increasing and in order to fulfil the requirements of the atomic plant an underground barrier across the Palar river was proposed to increase the recharge to groundwater. The groundwater model utilized as a part of his study to check that groundwater levels might increase by about 0.1 to 0.3 m broadening out a separation of about 1.5 to 2 km from the upstream side of the control, while on the downstream side, the groundwater head was lower by about 0.1 to 0.2 m. He finds out that the model also required that with the subsurface control set up the supplemental groundwater crucial component of essentially 13,600-m^3/day may be met with least lessen in adjacent groundwater head.

Fethi et al, (2012) developed a groundwater flow model in Zeramdine- Beni Hassen Mioclene Aquifer system (east central Tunisia). The model was developed to validate the groundwater properties deduced from geological, geophysics and hydrodynamic studies were done in the region using the MODFLOW 2000 and GIS. A 3D model was developed for ZBH aquifer using previous data. The model was calibrated and validated for the year 1980-2007. The results showed that aquifer shows susceptibility to change in infiltration and hydraulic conductivity values. The model results showed a good agreement with the observed data. The model could be used further for the area similar to ZBH aquifer characteristics and showed a good result in arid to semi-arid region.

Hussein et al, (2013) developed a numerical model using VISUAL MODFLOW for the Baoyang irrigation area and aquifer is considered a single layer. Model was run to check the sustainability of groundwater and to develop a suitable plan for the future groundwater use. Conceptual model was built by using Aquifer properties, pumping and observation data and model was run for 2006-2009 for calibration and validation, and then model was extrapolated to check the effect of groundwater level for future prediction up to year 2048.Model was calibrated using Parameter estimation Package (PEST) and water balance for the area is checked to find out the difference between the water entering and leaving the system. It was found that model results are very close to that of observed values of the observation wells and the model results showed that there is a slight fall in groundwater level for the Baoyang irrigation area.

Mohanty et al, (2013) developed groundwater flow model for khatajudi surua inter basin of Odisha, India. MODFLOW was used for the modelling; model was calibrated using weekly data of water level for (Feb 2004 to May 2006) and validated for the 1 year (June 2006- May 2007). 18 Observation wells were used for the calibration purpose. Calibration of the groundwater model was done by hit and trial method. Combined with automatic PEST with a mean RMSE of 0.62 and NSE value of 0.915. The inputs for the Artificial neutral network were rainfall, ET, River stage, pumping rates and groundwater levels of these wells in previous time. It was found that ANN provide better results in the study area then the numerical model of short time period over the area.

Mirudhula (2014) developed a groundwater model using VISUAL MODFLOW to check the impact of Lined / Unlined Canal on groundwater recharge for the Bhavani Basin. Groundwater recharge was calculated using groundwater flow modelling using visual mudflow. Three major natural sources of groundwater recharge were considered for the study consisting of rainfall infiltration, seepage from canals and return flow from irrigation. Zone budget of the area was carried out to study the effect on groundwater recharge form lined/unlined canals. Results shows that unlined canal recharge 20% more to groundwater then the lined canal.

Pradeep et al, (2014) developed a steady state finite model using VISUAL MODFLOW to quantify groundwater in Choutuppal Mandal, Nalgonda (Dt) AP. Used groundwater well data from 19 wells and found that the groundwater model gave good results because computed values have a good fitness. The groundwater budget was calculated using zone budget for the entire watershed using the groundwater flow model. It was determined that groundwater enters from Borrollagudem and leaves at Aregudem and Katrevu through Choutuppal. The output indicated that there was a very little amount of storage. This necessitates immediate arrangement for recharge of groundwater by all possible means to save the groundwater for future usage.

Vladimir et al, (2015) developed a groundwater model for the Kratal Agriculture Area to assess the artificial recharge through the infiltration pools near the Kratal river. The aim was to reduce the groundwater shortage. Outcomes showed that maximum recharge from the infiltration pool can be exceed to 1000 m^3/day, in response to an infiltration rate of 0.2 m/day. The radius of the infiltration pool should not exceed from 500 m for better efficiency. A spatial-distribution groundwater-flow model such as MODFLOW could provide reliable information for the planning of artificial groundwater recharge from infiltration pools under complex hydrogeological and intensive farming conditions.

Hong et al, (2015) studied the effect of rainfall intensity on groundwater recharge by using a 3D groundwater finite difference model in MODFLOW. A 3D finite difference groundwater model was calibrated and validated using MODFLOW and simulated rainfall was input to check the effect of the rainfall. Groundwater recharge coefficient was calculated using PES-ASP Package of MODFLOW. The value of groundwater recharge coefficient was reduced from 0.439 to 0.076 for increasing the rainfall intensity from 45 mm/hr to 120 mm/hr respectively. He concluded that rainfall intensity has great effect on groundwater regime, water shed management and river flows.

Maheswaran et al, (2016) developed groundwater model for Ganga River Basin. He used Visual MODFLOW covering an area of 1 million km^2 and run as transient model. The model domain was selected of 2500x2500m consisting of 500x500 rows and columns respectively. The study includes historical groundwater data from the concerned departments of the India and incorporate major tributaries of River Ganga as geo hydrological data was obtained from central groundwater board India. Model was run for 4.5 year and was calibrated using parameter Estimation (PEST) simulations. Analysis of stream network with zone budget helped to decide that the stream is gaining or losing in the study area. The study was helpful to facilitate development of detailed impact scenarios for groundwater contribution in the area.

Ambe et al, (2017) studied recharge through rainfall in north region of Cameron. He used water balance model GROWA for the assessment of recharge in north Cameron. For the input parameter of the GROWA, a world soil map of a scale 1: 3000,000 was used. The model results showed a good agreement between the computed values in model and observed values of recharge in the study area. It was found that GROWA model present good results for the computation of reliable recharge values for rainfall even the input parameters were extracted from a small-scale international soil map. The model would give more accurate results if high-resolution soil data is available for the calculation of groundwater recharge.

Alemu et al, (2017) used wetspa model to study the temporal and spatial variation in recharge of Geba Basin, Northern Ethiopia. The model was developed with covering an area of 4249 Km^{2-} and incorporate elevation, soil and land use data, hydro meteorological and river discharge data. He simulated wetspa for 4 years on daily basis (Jan 1, 2000- Dec 18, 2003). The model showed a good agreement between observed and simulated stream flow hydrographs. The water balance results showed a good value for both calibrated and validated period. He found that mean annual recharge is mostly dependent on rainfall amount followed by soil and land cover of the area. He computed that 21% of the geba basin has recharge more than 120 mm and 1% of the area has recharge less than 5 mm.

In previous studies different researches used different models for the groundwater recharge computation. The best model that was recommended by most researchers was Visual MODFLOW for the groundwater computation. In my study a dam is proposed at 3mile U/S of the Mohlanwall in River Ravi and then the effect of the proposed dam is studied in HEC-RAS & Visual MODFLOW for backwater effect and recharge computation for the Lahore city.

CHAPTER III

DATA COLLECTION AND ANALYSIS

3.1 Data Collection

- River Ravi X-section from Ravi Siphon to Head Balloki was collected from River Survey Division of Irrigation Department Lahore.
- Flow data for the river Ravi at Ravi Siphon and Shahdra gauge station was collected from the Chakbandi Division, Irrigation Department Lahore.
- Tube wells discharge and location data was obtained from WASA Lahore and Mott McDonald Pakistan (MMP) Consulting firm.
- Terrain Data of Lahore was obtained from Mott McDonald Pakistan; and
- Hydraulic conductivity data was extracted from the map developed by NESPAK for the past Lahore groundwater study.

3.2 Makesens Analysis

Mann Kendall test and Sens slope method were used to carry out the trend analysis and slope of the given data on yearly basis. Mann Kendal method gives the trend line for the data that how much the data deviate from its mean value and Sens method was used to check the slope of data.

Mann Kendall test requires minimum four values to study / analyse the non-parametric trend of the data. The confidence interval for Sens slope method was used to check the linear trend between the data. it requires a minimum of 10 values for the trend analysis.

3.3 Trend Analysis

3.3.1 Discharge Trend

Discharge trend was analysed using Makesens analysis for a period of 15-year data of discharge 2000-2014, Makesens gives trend of annual based daily data. Graphs were drawn for different time periods such as January to December, summer, winter season separately to determine that how the flow is available in river Ravi. The discharge yearly trend is shown in **Figure 3.1** and remaining are shown in Annexure B.

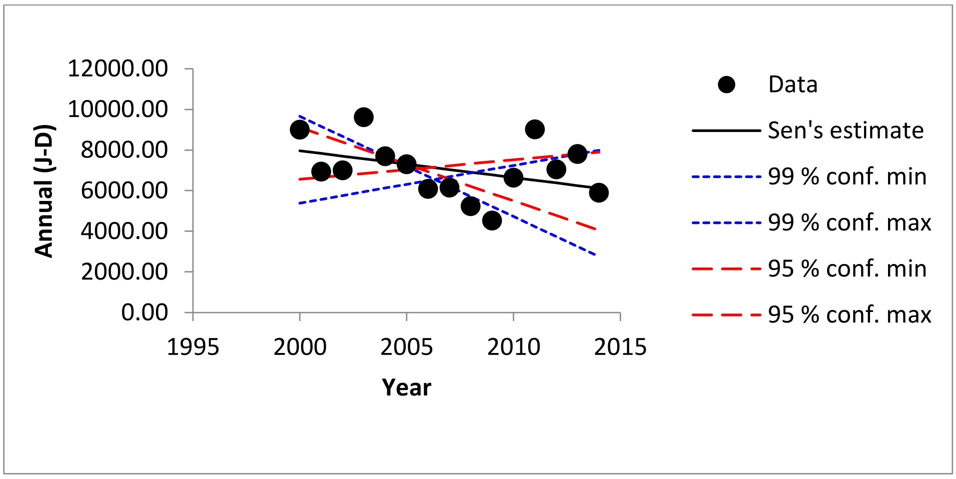

Figure 3.1: Annual Average Daily flow for the year 2000-2014 of River Ravi

The Sen’s estimate for discharge values and for 99% confidence interval wa observed by using sen’s estimate and a discharge data for the 15 year was used for this purpose the average difference between the actual daily discharge and sen’s estimate is almost 1200 cusec as shown in **Table 3.1**.

Table 3.1: Daily average discharge of river Ravi estimated by Sen's method

Year	**Data Cusic**	**Sen's estimate**	**99 % confidence min**	**99 % confidence max**	**95 % confidence min**	**95 % confidence max**	**Residual**
2000	9006.81	7960.82	9657.37	5384.67	9112.59	6562.68	1045.99
2001	6934.76	7829.06	9164.43	5570.36	8750.94	6657.76	-894.30
2002	7000.61	7697.30	8671.48	5756.06	8389.29	6752.83	-696.69
2003	9620.11	7565.55	8178.53	5941.75	8027.64	6847.91	2054.56
2004	7685.59	7433.79	7685.59	6127.44	7665.99	6942.99	251.80
2005	7304.34	7302.03	7192.64	6313.13	7304.34	7038.06	2.30
2006	6079.99	7170.27	6699.69	6498.83	6942.69	7133.14	1090.28
2007	6144.21	7038.52	6206.75	6684.52	6581.04	7228.21	-894.30
2008	5235.48	6906.76	5713.80	6870.21	6219.38	7323.29	1671.28
2009	4528.73	6775.00	5220.85	7055.90	5857.73	7418.37	2246.27
2010	6643.24	6643.24	4727.91	7241.60	5496.08	7513.44	0.00
2011	9019.40	6511.49	4234.96	7427.29	5134.43	7608.52	2507.91
2012	7045.65	6379.73	3742.01	7612.98	4772.78	7703.60	665.92
2013	7798.67	6247.97	3249.07	7798.67	4411.13	7798.67	1550.70
2014	5900.33	6116.21	2756.12	7984.37	4049.48	7893.75	-215.88

`

3.3.2 Rainfall Analysis

The rainfall analysis by Sen's estimated was done and the average daily rainfall on annual basis is between 1-3mm for the year between 2000-2014, and the graphs for 99% confidence interval as well as 95% confidence interval is shown in **Figure 3.2**

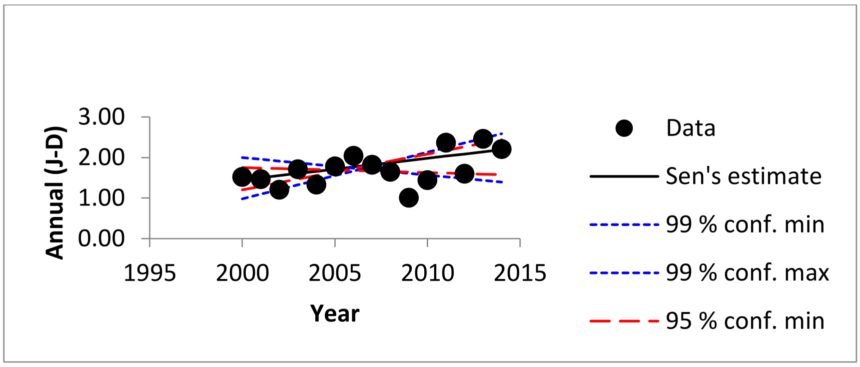

Figure 3.2: Average annual dialy rainfall for year 2000-2014

The detailed values for rainfall calculated using sen's analysis is shown in **Table 3.2** which shows that sen's estimated rainfall value is almost near to the average daily rainfall of the Lahore. 95% confidence interval was calculted by sen's method also which is accurate 95% for the given data.

Table 3.2: Average daily rainfall of Lahore city estimated by Sen's method

Year	Data mm	Sen's estimate	99 % confidence min	99 % confidence max	95 % confidence min	95 % confidence max	Residual
2000	1.52	1.45	2.00	0.98	1.75	1.20	0.07
2001	1.47	1.50	1.95	1.09	1.74	1.29	-0.03
2002	1.21	1.55	1.91	1.21	1.73	1.38	-0.34
2003	1.72	1.61	1.87	1.32	1.72	1.47	0.11
2004	1.34	1.66	1.82	1.44	1.70	1.56	-0.32
2005	1.79	1.71	1.78	1.55	1.69	1.64	0.07
2006	2.04	1.77	1.74	1.67	1.68	1.73	0.28
2007	1.82	1.82	1.70	1.78	1.67	1.82	0.00
2008	1.65	1.87	1.65	1.90	1.65	1.91	-0.22
2009	1.01	1.93	1.61	2.01	1.64	2.00	-0.91
2010	1.44	1.98	1.57	2.13	1.63	2.08	-0.54
2011	2.37	2.03	1.52	2.24	1.62	2.17	0.34
2012	1.60	2.09	1.48	2.36	1.60	2.26	-0.48
2013	2.46	2.14	1.44	2.47	1.59	2.35	0.32
2014	2.21	2.19	1.39	2.59	1.58	2.44	0.02

Significancy of the rainfall data was checked by mann kendall test. Mann kendall uses z test for significacy for different scenario, for annual daily trend and summer season the rainfall trend significally increase while for the autom the trend was also significant change but for the months of winter and summer the trend is not significant for the daily rainfall of the Lahore ciyt as shown in **Table 3.3.**

Table 3.3: Mann Kendall trend of Rainfall for Lahore city

TREND STATISTICS					
FI17 Virolahti 1987- 2000					
				Mann-Kendall trend	
Time series	**First year**	**Last Year**	**n**	**Test Z**	**Significance.**
Annual (J-D)	2000	2014	15	1.68	+
Winter (O-M)	2000	2014	15	0.20	
Summer (A-S)	2000	2014	15	1.78	+
Winter(D-F)	2000	2014	15	-0.10	
Spring (M-M)	2000	2014	15	-0.20	
Summer (J-A)	2000	2014	15	-0.10	
Autumn (S-N)	2000	2014	15	2.18	*

`

CHAPTER IV

METHODOLOGY

4.1 HEC-RAS Model

HEC-RAS model was run for the four Scenarios mentioned below on the selected reach of the River Ravi for the computation of water surface profile.

1. Steady state condition;
2. Unsteady state condition using average flow hydrograph for (2000-2014);
3. Unsteady state condition with dam and 90% flow within reach throughout the time (2000-2014); and
4. Unsteady state condition with dam and low flow condition (2000-2014).

4.1.1 HEC-RAS Geometry Input

Geometry data is the main input for the hydraulic model for water surface profile computation. HEC-RAS geometry data was obtained from Irrigation Department and was input manually in HEC-RAS model. X-sections obtained from River Survey Division, Irrigation Department was at the interval of 2000-3000 ft interval depending on the river pattern. A River Reach of 38 mile was drawn on the terrain for this study manually and then x-section is input manually as shown in **Figure 4.1**.

Terrain was plotted using HEC-RAS mapper and use a DEM of 1m obtained from Mott McDonald Pakistan (MMP). The value of manning's n was obtained from the literature and used as input in the model for its computation.

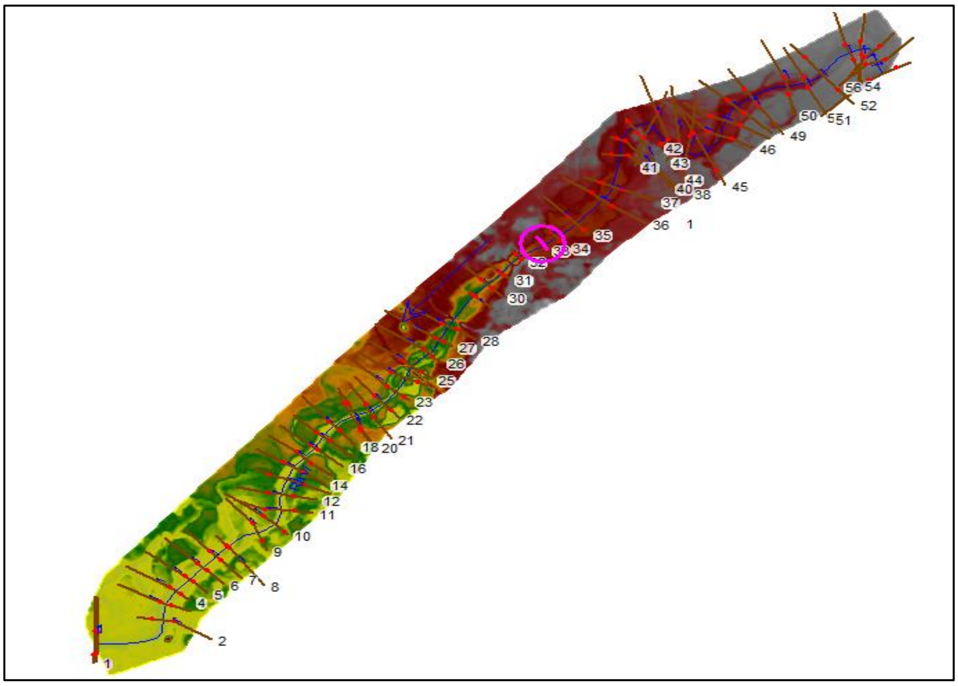

Figure 4.1: X-Section of the river Ravi with terrain for river Ravi study area

River Ravi x-sections were obtained from the Irrigation department and digitized in Excel. River Section at 4500 ft D/S of the Indian boarder is shown in Figure 4.2. River Ravi X- Section of reach from the Shahdra to head Balloki are given in the Annexures C & D respectively.

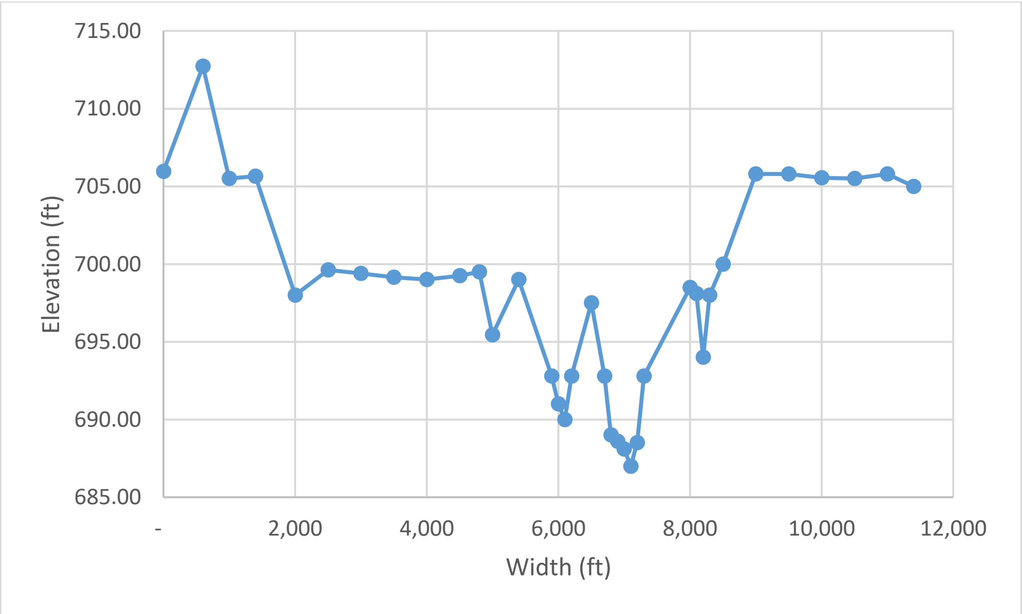

Figure 4.2: River Ravi X-Section at 4500ft D/S of Indian Boarder

`

4.1.2 Flow Data Input

Flow Data for the River Ravi from 1991-2014 was obtained from Irrigation Department.

The average daily flow of the River Ravi was 6967 cusecs for the year 2000-2014 at shahdra gauge station. The max flow of 314321 cusec was observed for the year 2010 due to peak flood.

Frequency analysis was done on the flow data to calculate the flow at different return period in River Ravi in case when the dam is to be installed on River Ravi for the Pondage that can help for the groundwater recharge.

4.1.3 Boundary Condition

Normal depth was used as boundary condition for steady flow analysis by inputting the slope of channel as input in the hydraulic model.

The model was simulated for the Steady state flow analysis for the calculation of the water surface srofile for the River Ravi. For steady state, boundary condition normal depth was used as a reference in downstream of the channel as shown in **Figure 4.3**.

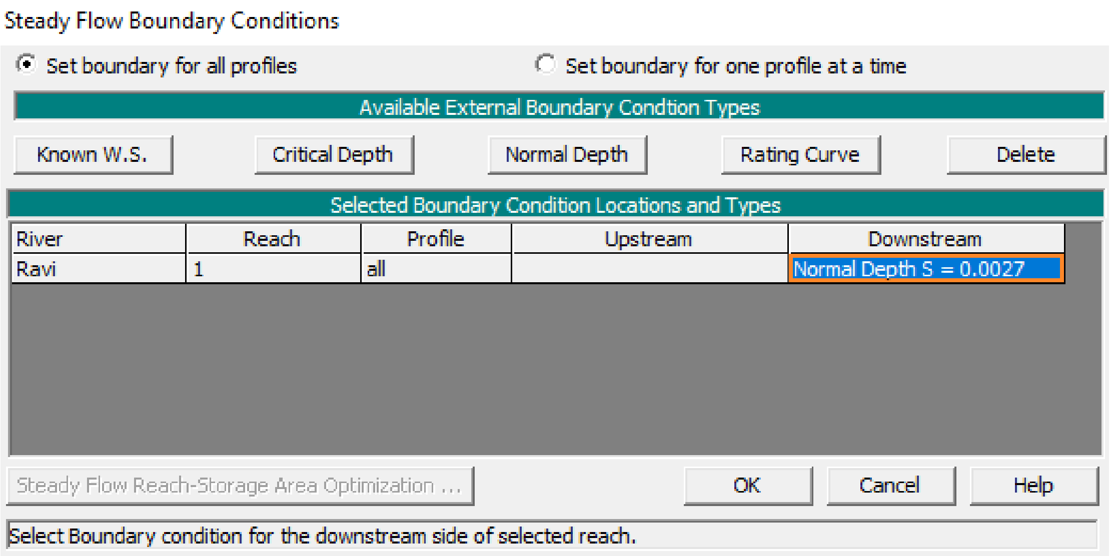

Figure 4.3: Steady flow boundary condition for River Ravi

4.2 HEC-RAS Unsteady Flow

HEC-RAS was run on the unsteady flow for the analysis of dam, for the unsteady flow the boundary conditions are changed. In upstream boundary condition flow Hydrograph and for downstream boundary condition Normal depth was used for the computation.

4.2.1 Boundary Conditon

The U/s boundary conditon for unsteady was used as flow hydrograph. The model was run for the unsteady flow computaion for the 90% available flow in the river as well as on the lowest flow in the river for computation.

Monthly flow hydrograph was developd for the easy computaion of the model and then input in the Bounndary conditon for the easy computioan. Flow hydrograph is shown in **Figure 4.4**.

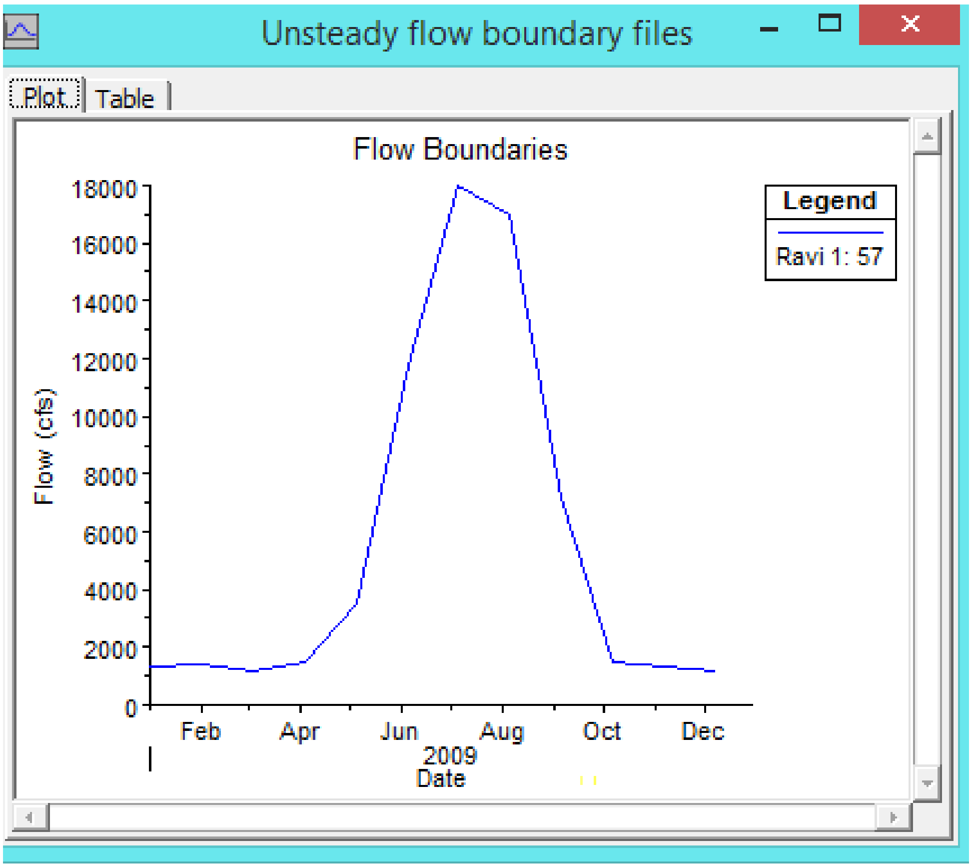

Figure 4.4: Avg. flow hydrograph for river Ravi

`

For unsteady flow, boundary condition was selected at U/S and D/S of the river channel. At U/S monthly flow hydrograph was used as input, while on D/S normal depth was used for which the slope of the channel was used to calculate normal depth. Boundary conditions for the unsteady flow are shown in **Figure 4.5**.

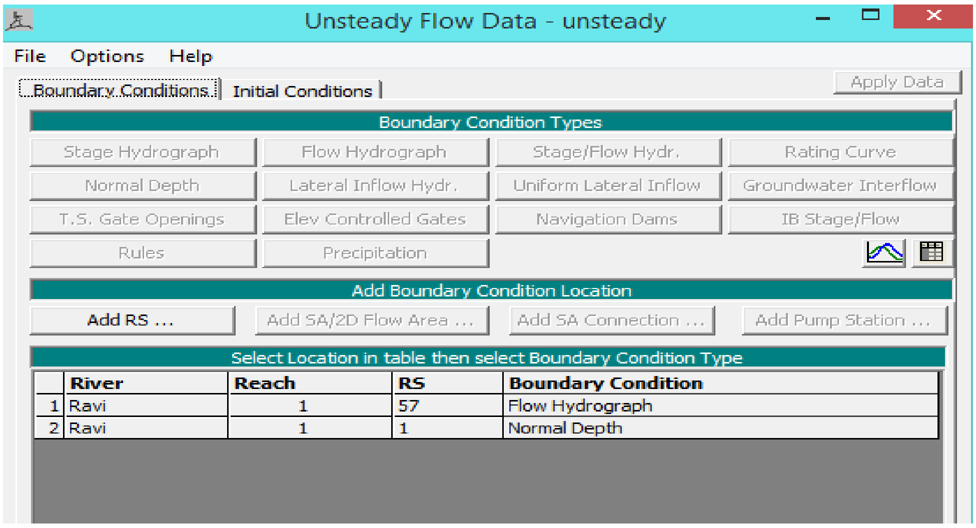

Figure 4.5: Unsteady flow boundary condition for river Ravi

4.3 Unsteady Flow with dam

HEC RAS model was run with dam installed in U/S of Mohlanwal site to check the effect of dam installed. The dam head was selected as 10ft and slope of the river was 0.00027 (1.4ft / mile). The water surface profile was computed on the basis of unsteady flow. Broad crested dam was designed with a dam coefficient of 2.6. as shown in **Figures 4.6** & **Figure 4.7** respectively.

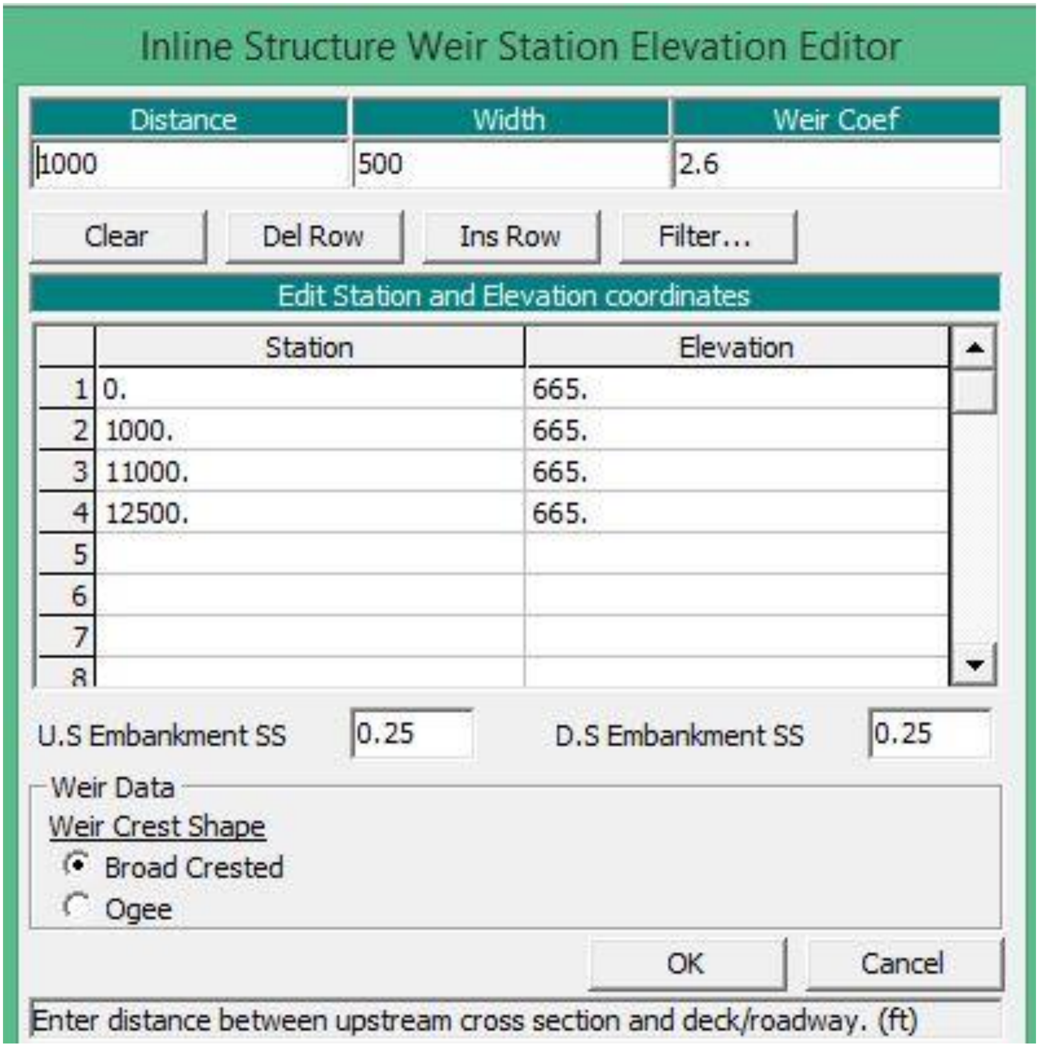

Figure 4.6: Proposed broad crested dam design and Elevation:

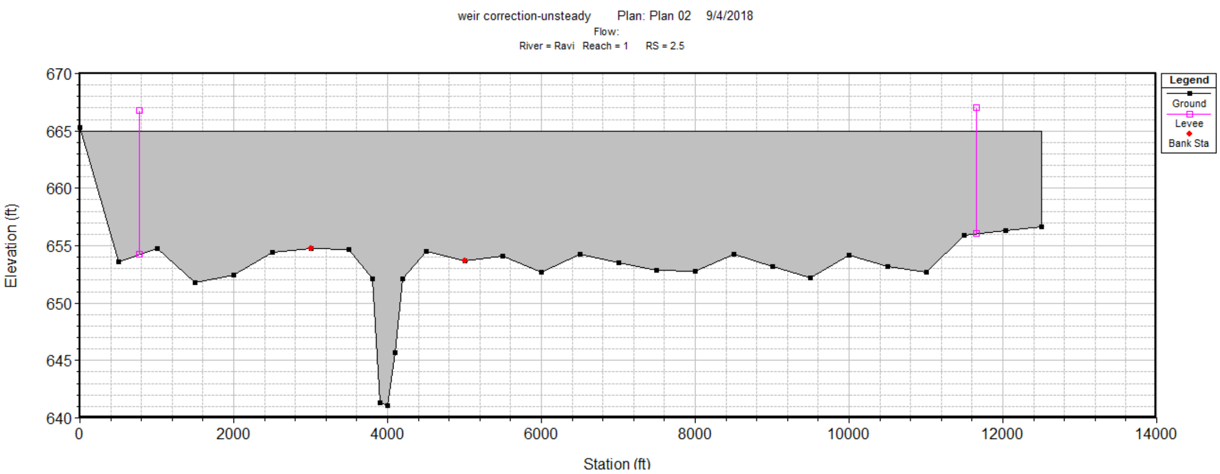

Figure 4.7: Proposed dam section in HEC-RAS

`

4.4 VISUAL MODLFOW

The Visual MODFLOW software (2011.1 ver.6.0.159), developed by Schlumberger Water Services (SWS), Canada, was used for the present study. The Visual MODFLOW is the most complete and easy-to-use modelling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations.

Visual MODFLOW was used to groundwater model for the Lahore Aquifer. The packages used for the groundwater model of Lahore city are shown in **Table 4.1**.

Table 4.1: Visual MODFLOW Packages

Name of Package	Abbreviations	Function
Basic	**BAS**	Specifies the grid, time step, etc.
Block-cantered flow	**BCF**	Calculates the terms in the finite-difference equations, which determine the flow between adjacent cells. It also computes the movement of water into and out of aquifer storage
Well	**WEL**	Flows from or to wells
River	**RIV**	Flows to or from rivers or main canals via bed seepage
General Head Boundary	**GHB**	Flows to or from the model area from adjacent areas of the aquifer
Constant Head Boundary	**CHD**	The constant head boundary condition is used to fix the head value in selected grid cells regardless of the system conditions in the surrounding grid cells
Alternate Solver Packages		
Strongly Implicit	**SIP**	Solves the finite-difference equations using the iterative SIP procedure
Slice-successive Over-relaxation	**SOR**	Solves the finite-difference equations using the iterative SOR procedure

`

Groundwater flow modelling is a complex process, which need many inputs, and required some pre-requisites for the computation of the groundwater level. The groundwater flow modelling process chart is shown in **Figure 4.8**.

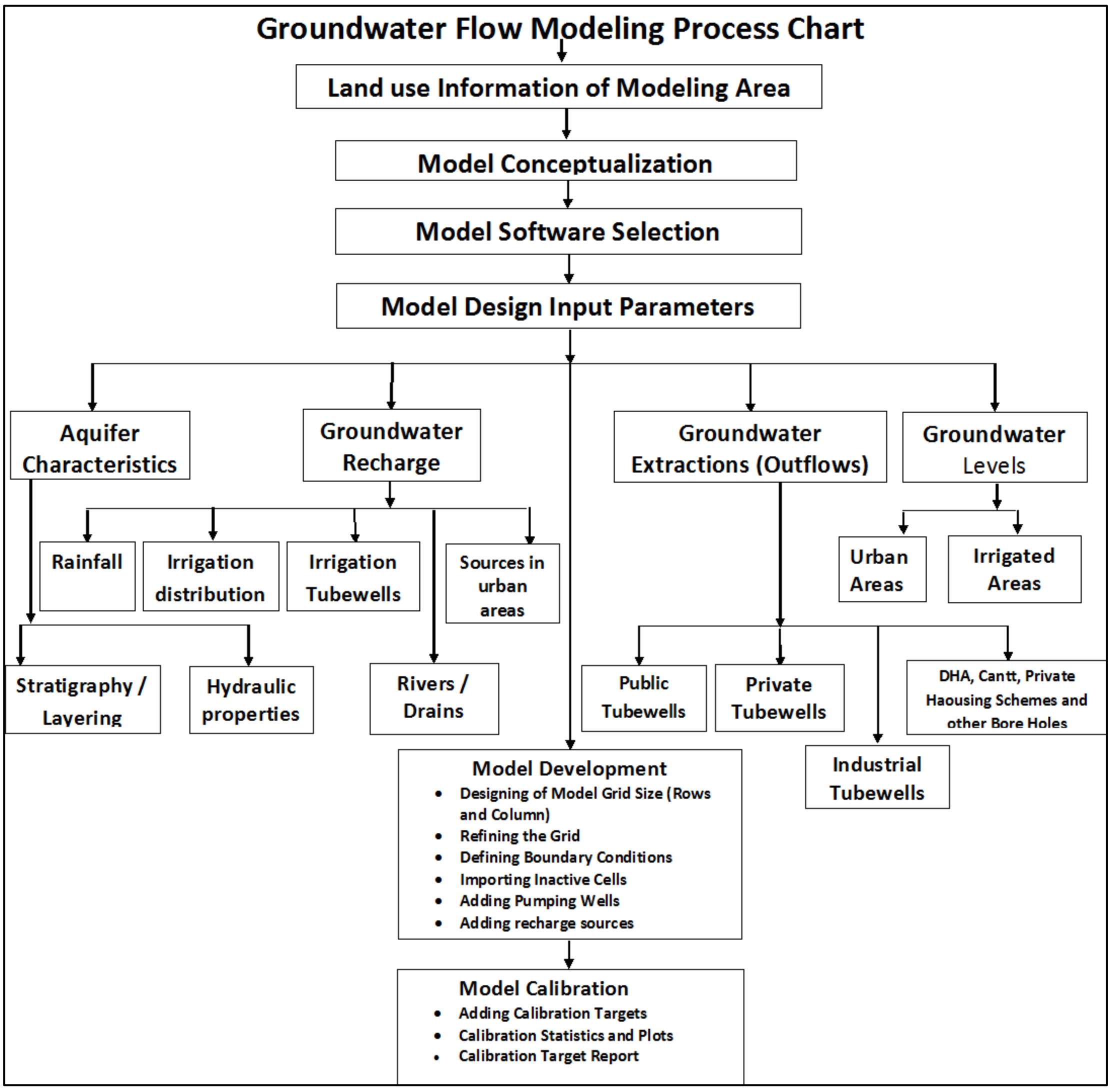

Figure 4.8: Visual MODFLOW Modelling Process flow chart for the study

4.4.1 Model Settings

After starting the model, first of all units for different parameters for the model and select the numeric model for the groundwater calculation are selected through the screen shown in **Figure 4.9**.

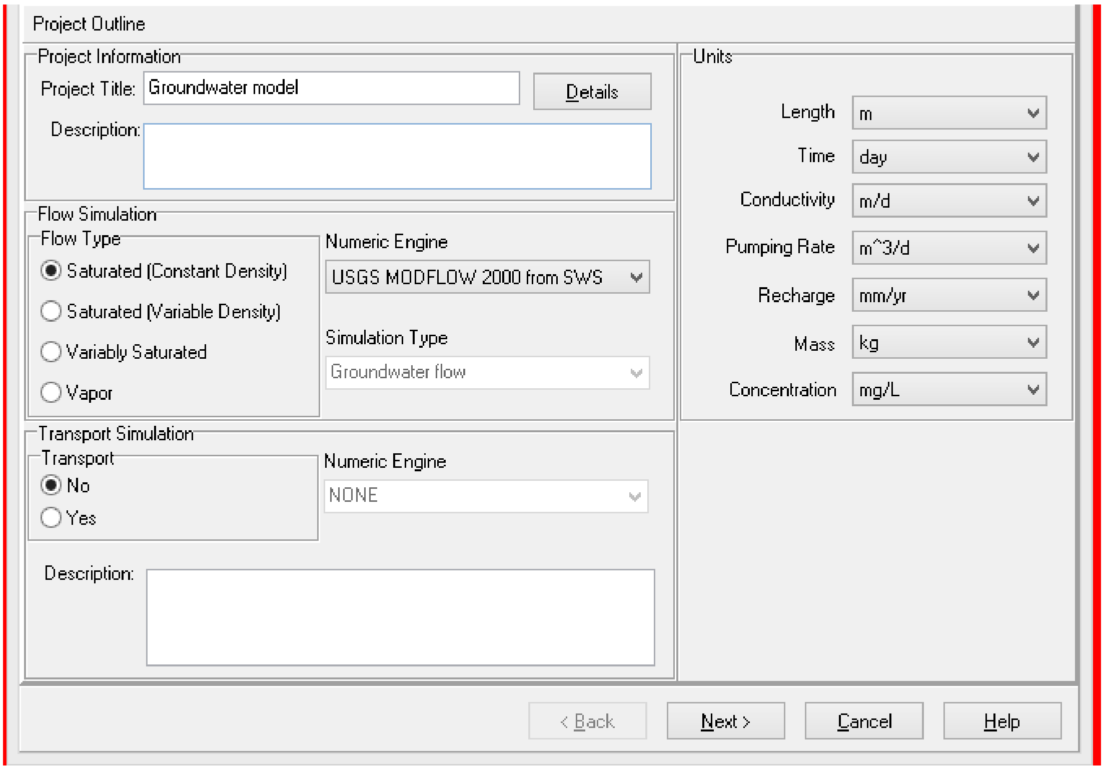

Figure 4.9: Model setting for the groundwater model of study area

4.4.2 Flow Settings

The next step for the model was to input the initial conditions to start the model, and define the simulation period for the model. Then it is selected whether model is to run steady state or transient condition. For this present study steady state analysis was selected for to make the computaion easy, because in transient condition variabillity of parameters over time is needed but in steady state parameteres remain constant for the whole period. The model was run for a period of 12 years and steady state condition. The remaining input parameters were assumed constant for the strarting of the model and after that they were be changed according to the study area characteristics, as shown in **Figure 4.10**.

`

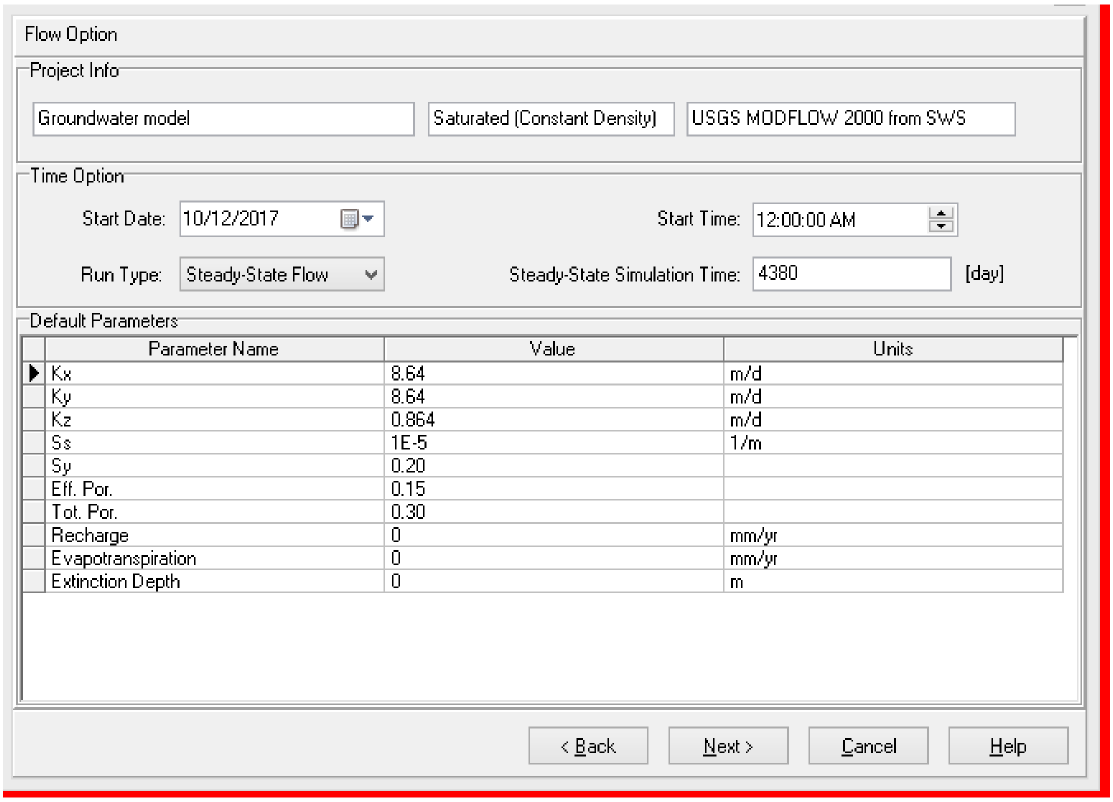

Figure 4.10: Flow setting for model input of study area

4.4.3 Defining Model Domain

The next step is to define the model area. This model was developed for the Lahore district containing an area of almost 1772 Km^2.Model consist of 221x151 columns and rows respectively. The background map of the study area could be imported also in the Visual MODFLOW. The map is helpful to define the boundary conditions for the model. The aquifer was considered a single layer with a thickness of almost 400 m. The image imported in the background of the model was georeferenced in UTM coordinate system.

A site map was georeferenced according to the model domain and world coordinate systems forming a uniform grid of 221x151 columns and rows, respectively as shown in **Figure 4.11**.

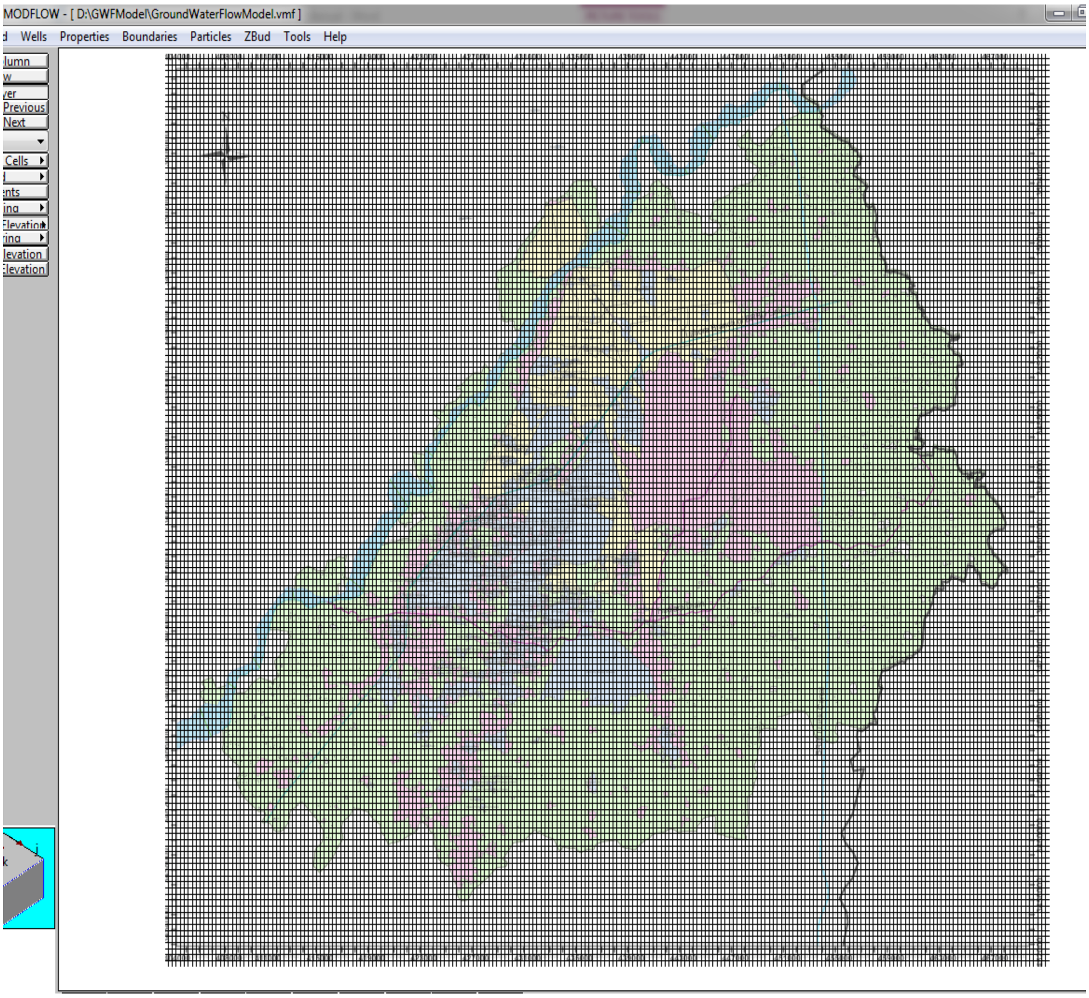

Figure 4.11: Defining model domain for study area in Visual Modflow

The grid could be refined according to the site condition in some points for the accuracy of model. The maximum number of rows and columns in VISUAL MODFLOW version used is 500x500.

4.4.4 Import Surface Elevation

Visual MODFLWO provides an improved set of tools for importing, creating, and editing and modifying layer elevation for the finite difference model grid. We can import data by using USGS DEM files to a specific number of grid cells. Visual MODFLOW supports importing of layer elevation files from a variety of data files including. The wells data, conductivity data and elevation data were imported from excel files and the interpolated using kriging method as shown in **Figure 4.12**.

- Points data (XYZ) ASCII files (.TXT, .ASC, .DAT);
- MS access database files (.MDB);
- MS excel files (.XLS);
- ESRI point files (.SHP);
- USGS DEM files (.DEM);
- Surfer grid files (.GRD); and
- ESRI grid files (.GRD).

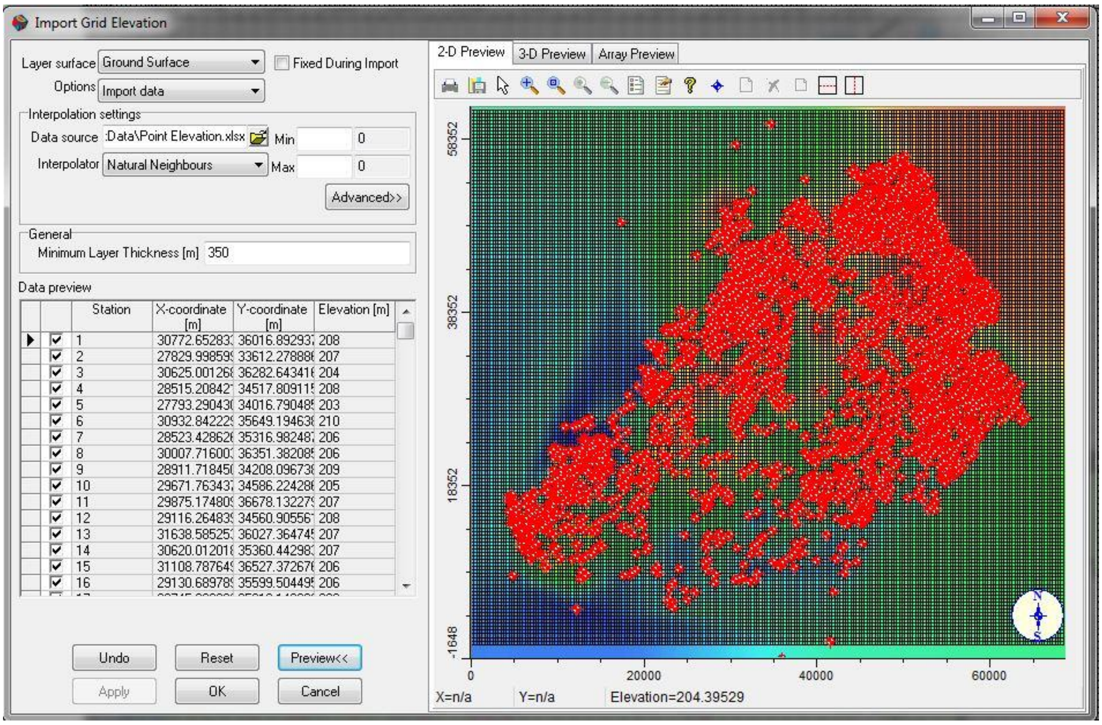

Figure 4.12: Importing surface elevation of the study area

4.4.5 Adding Pumping Wells

The pumping well data was obtained from WASA and MMP that was used for the model. About 484 WASA Tube wells and almost 2800 agricultural tube wells data was obtained and scheduling of these tube wells was done in Excel and then that excel sheet was imported in the model input. For agricultural tube wells the installed capacity is 1 Cusec, WASA, and non-WASA tube wells discharge capacity was varied 2-4 cusec and they run for an average 10-18 hr a day. This type of the Excel sheet was prepared for agricultural and WASA tube wells and then it was imported in the VISUAL MODFLOW as shown in **Figure 4.13**.

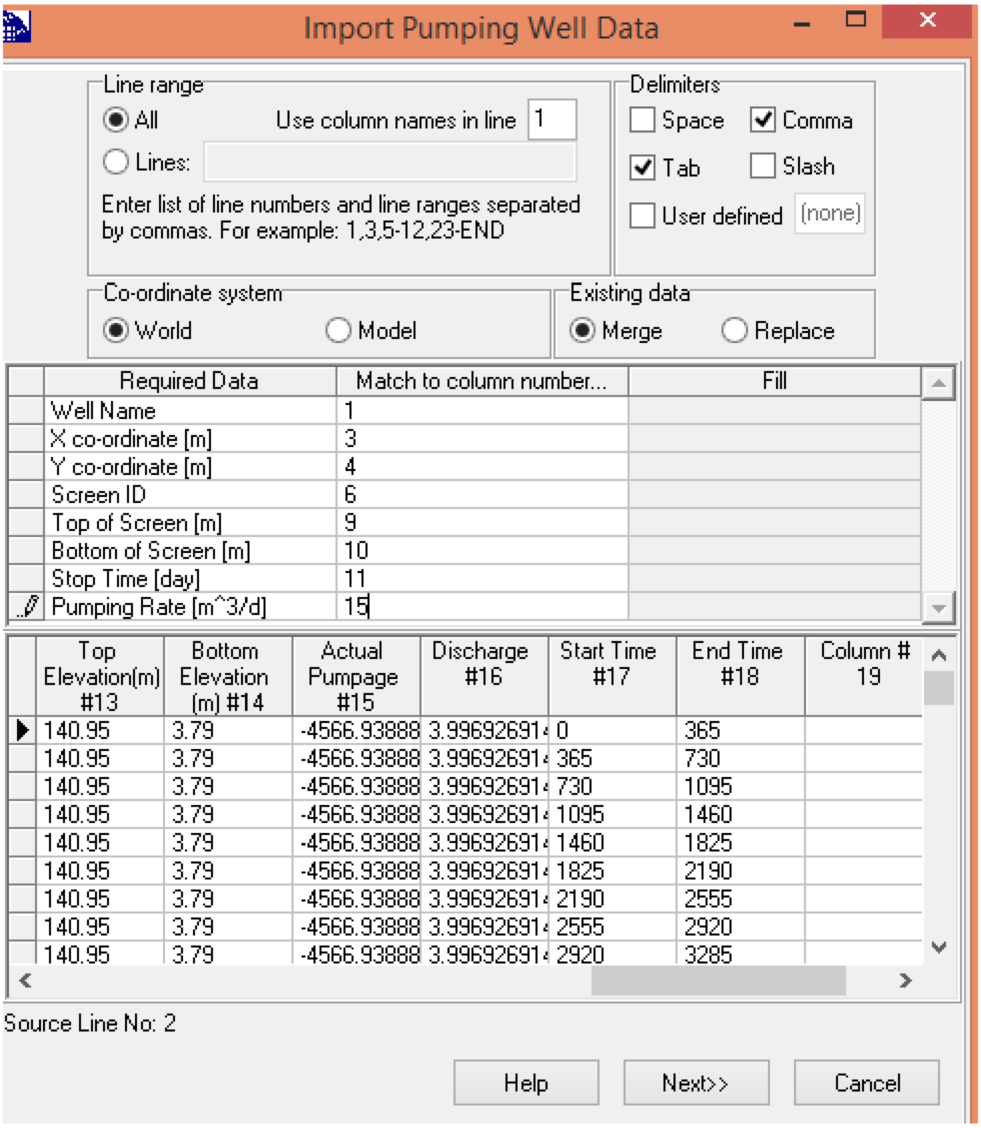

Figure 4.13: Importing pumping wells data for study area

4.4.6 Adding Observation Wells

Observation wells are required to calibrate the groundwater model so that the relationship between calibrated and observed head is obtained. To import the observation wells an excel file shown inn Annexure A was made and then imported in model. Thirteen observation wells were selected for the site and their excel file was prepared to import in the model as shown in **Figure 4.14**. These observation wells were used to calibrate the groundwater model of the study Area.

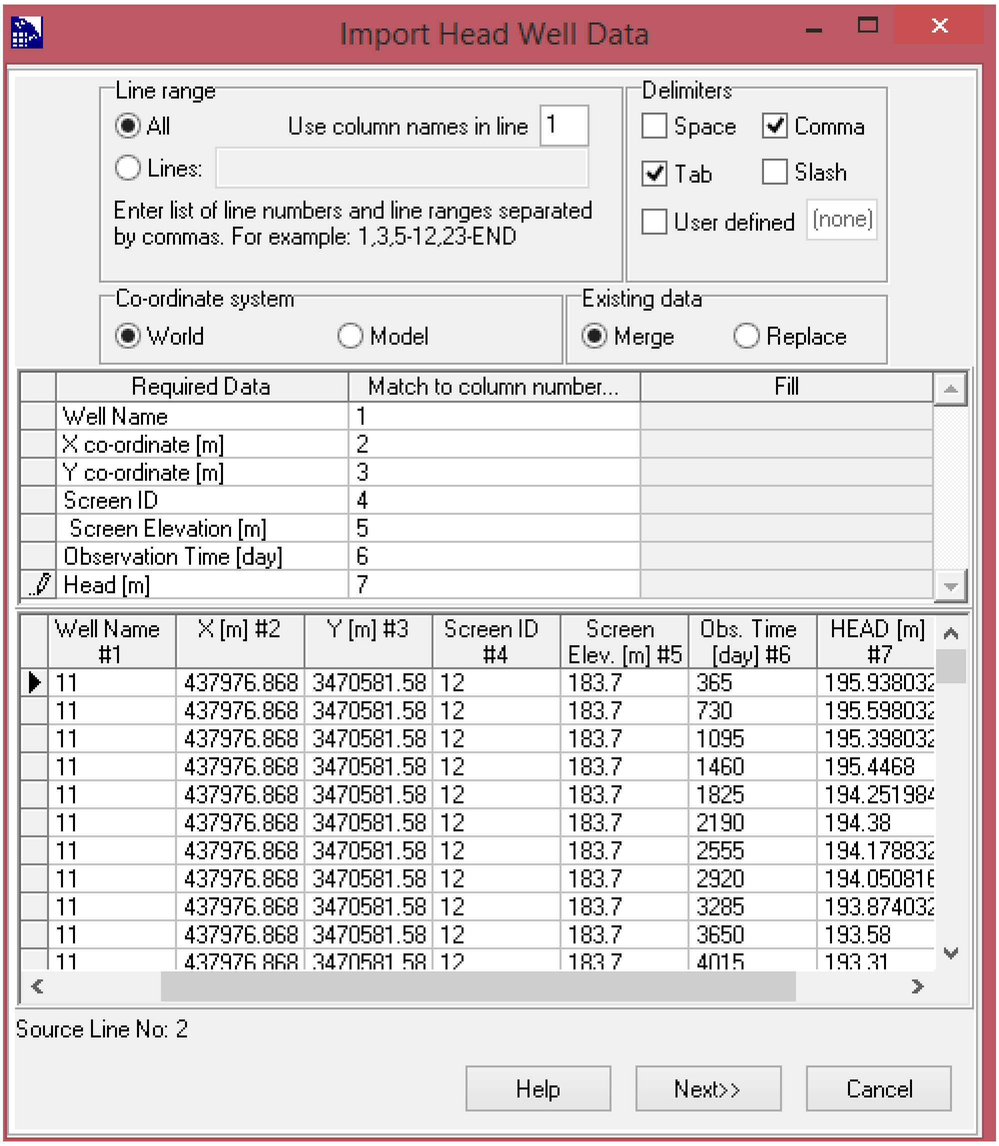

Figure 4.14: Importing observation wells for study area

4.4.7 Conductivity Data

The conductivity map of the Lahore city was obtained from the NESPAK past study in which NESPAK developed conductivity zones for Lahore city with respect to conductivity. A cluster of conductivity values were obtained from these zones and then imported to Visual MODFLOW. After doing interpolation in the model a conductivity map was developed for the study area. The cluster of the conductivity data was distributed with respect to latitude - longitude, and their conductivity values which improted to Visual MODFLOW and then, interpolated for the remainig area by using kriging method as shown in **Figure 4.15**.

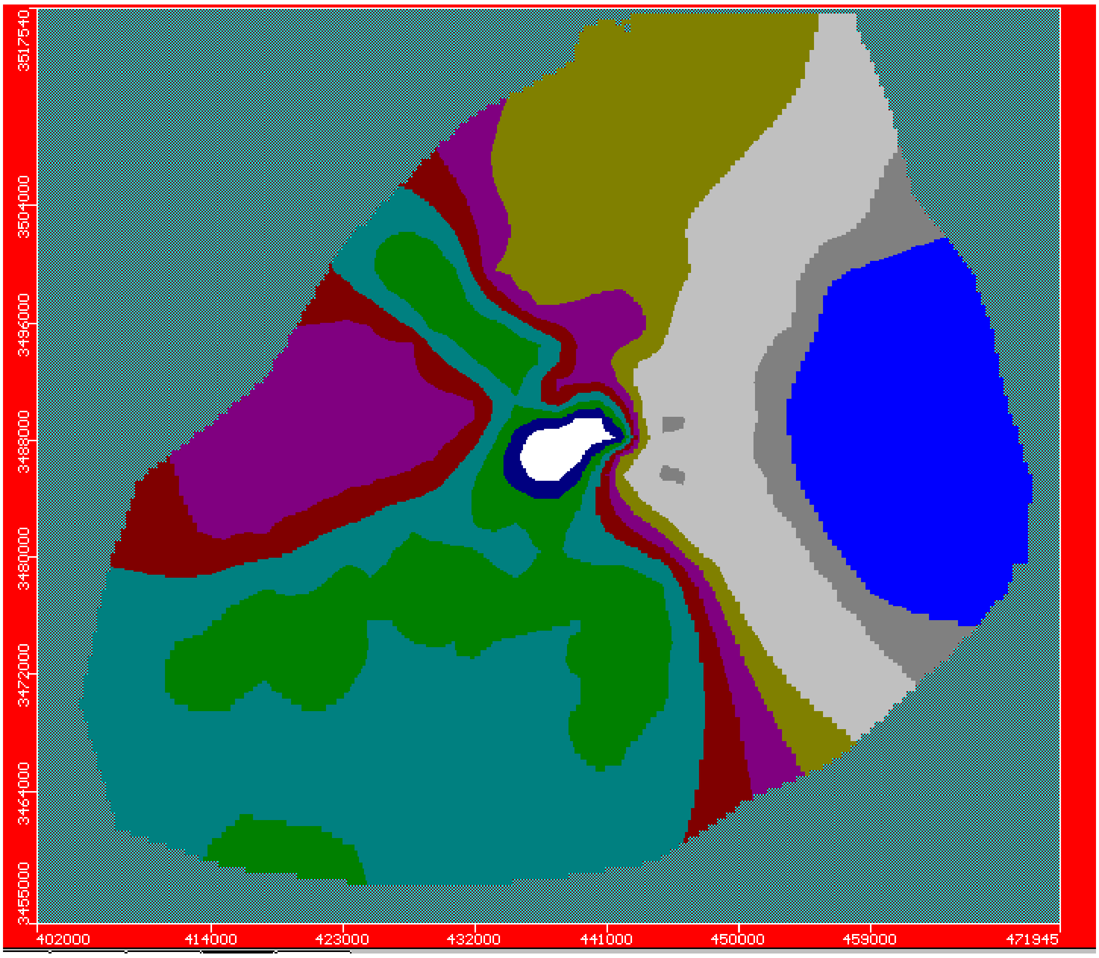

Figure 4.15: Conductivity map of the study area

4.4.8 Importing Initial Heads

Initial heads were observed from the observation wells. As observation wells record was collected for year 2001-2013. The heads obtained for the year 2001 were imported as initial head condition to run the model. The initial heads were imported and interpolated then to find out the initial head at remaining places as the initial head available were at the locations of observation wells only so remaining points were calculated with the help of kriging method with in the VISUAL MODFLOW model.

4.4.9 General Head Boundary

The function of the General-Head Boundary (GHB) Package is mathematically similar to that of the River, Drain, and ET Packages. Flow into or out of a cell from an external source is provided in proportion to the difference between the head in the cell and the reference head assigned to the external source. The application of this boundary condition is intended to be general, as indicated by its name, but the typical application of this boundary conditions is to represent heads in a model that are influenced by a large surface water body outside the model domain with a known water elevation. The purpose of using this boundary condition is to avoid unnecessarily extending the model domain outward to meet the element influencing the head in the model. As a result, the General Head boundary condition is usually assigned along the outside edges of the model domain. The boundary conditions for the study area is shown in **Figure 4.16**.

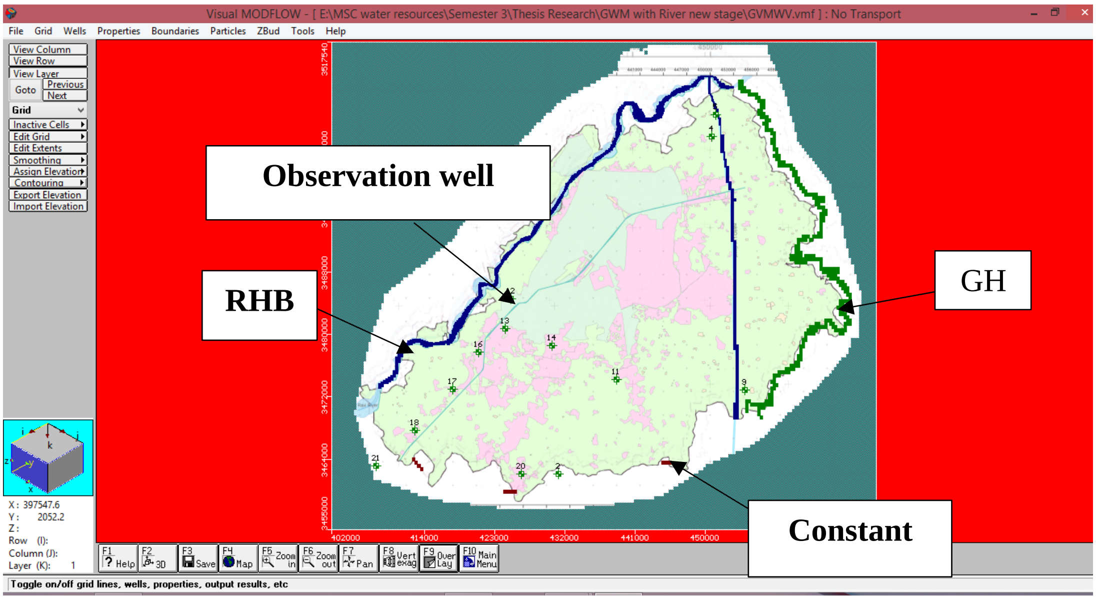

Figure 4.16: Boundary conditions in study area

4.4.10 Constant Head Boundary

Constant head boundary condition was assigned in the South East corner of the study area where head is fixed throughout the computation time as shown in **Figure 4.16**. The constant head boundary condition can be input as shown in **Figure 4.17**.

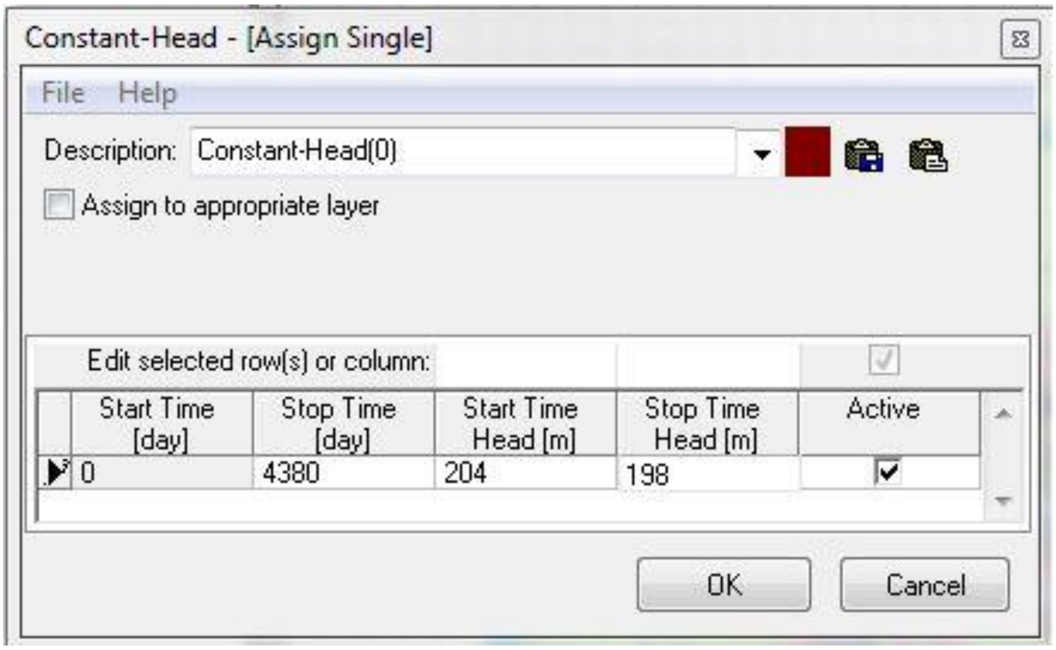

Figure 4.17: Constant head boundary condition for study area

4.4.11 River Head Boundary

River boundary condition was assigned in the study area for the River Ravi Reach and BRBD canal. Linear gradient method was selected to make the computation easier. It was assumed that river is flowing with a linear slope so a line was used for River input boundary condition where the input is required for the U/S and D/ S X-section of the River for the computation. Riverbed thickness of 1 m was used to make computation easier. The River data was input at starting point and ending point for linear gradient. River stage and river bottom were obtained from Ravi x-sections obtained from Irrigation Department. The input is shown in **Figure 4.18**.

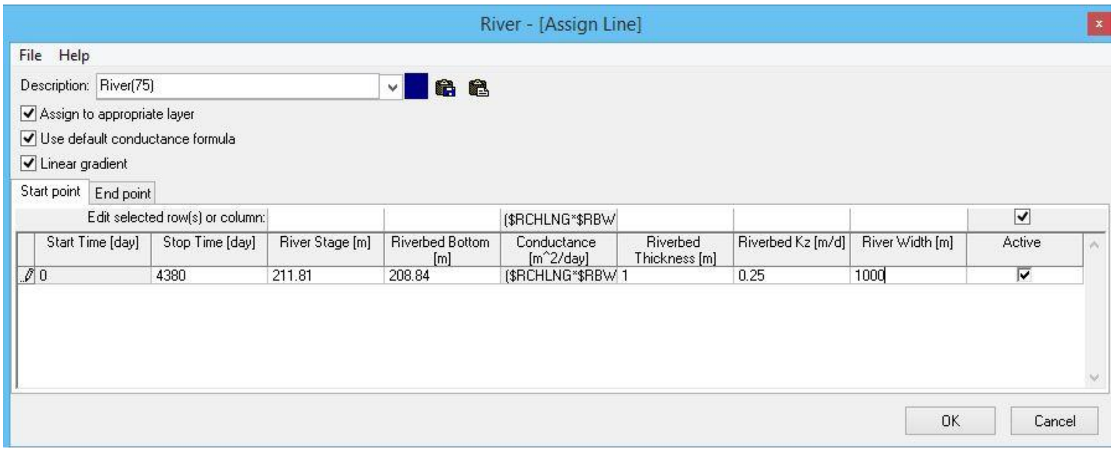

Figure 4.18: River ravi boundary condition for the study area

River Ravi condition was input and then model was run to check the effect of its stage under normal condition. After the proposed dam simulation, the River Ravi stage was changed to check the effect on the groundwater recharge and groundwater level contours were simulated.

CHAPTER V

RESULTS AND DISCUSSIONS

5.1 Flow Calculation

5.1.1 Flow Duration Curve

Flow duration curve on daily basis for the year 2001 to 2013 was plotted to check the amount of water available in River Ravi for the whole year. Flow duration curves for the summer season is shown below in **Figure 5.1**. which shows that a minimum discharge of 1754 cusec is available even if no water is coming from the link canal (MRL) for the whole summer season.

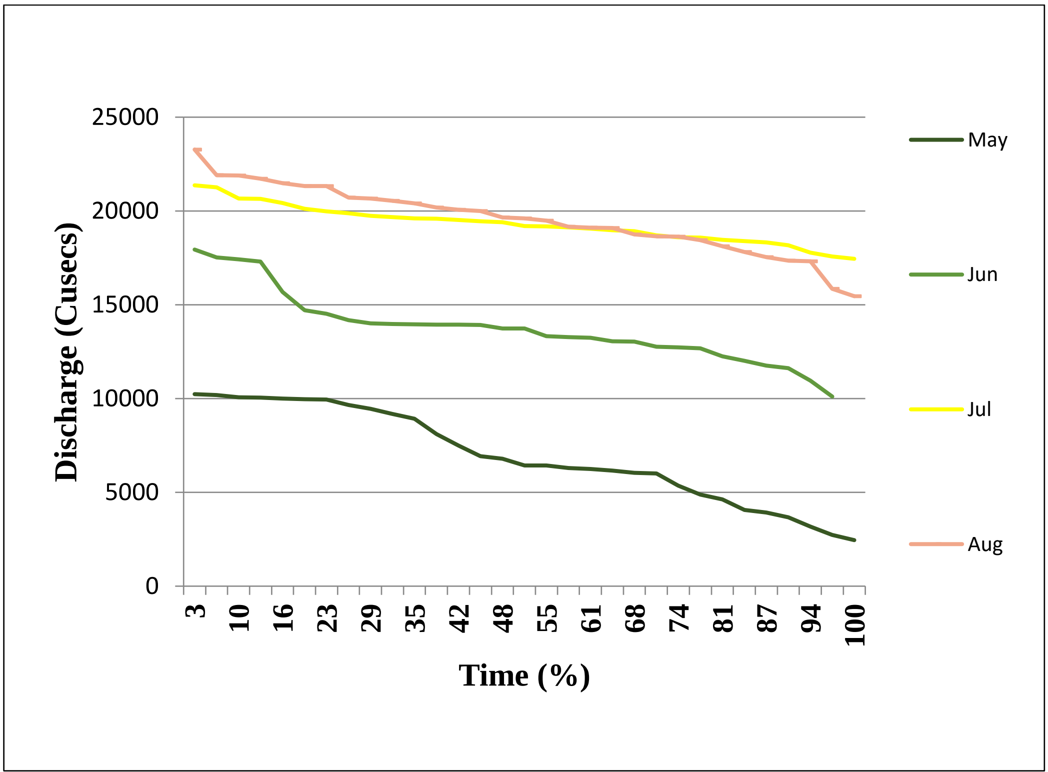

Figure 5.1: Avg. Flow Duration Curve of River Ravi for Peak months in year (2001-2013)

In addition, the graph shows the rise in discharge during the Jun-Sep, and then again reduces to a minimum value of 1754 cusec in December.

`

The average discharge for the year 2000-2014 on monthly basis is shown in Figure 5.2. The average flow in August is 22906 cusec and that for December is only 1754 cusec. This graph also shows the average flow available in the River Ravi for the whole year as shown in **Figure 5.2**.

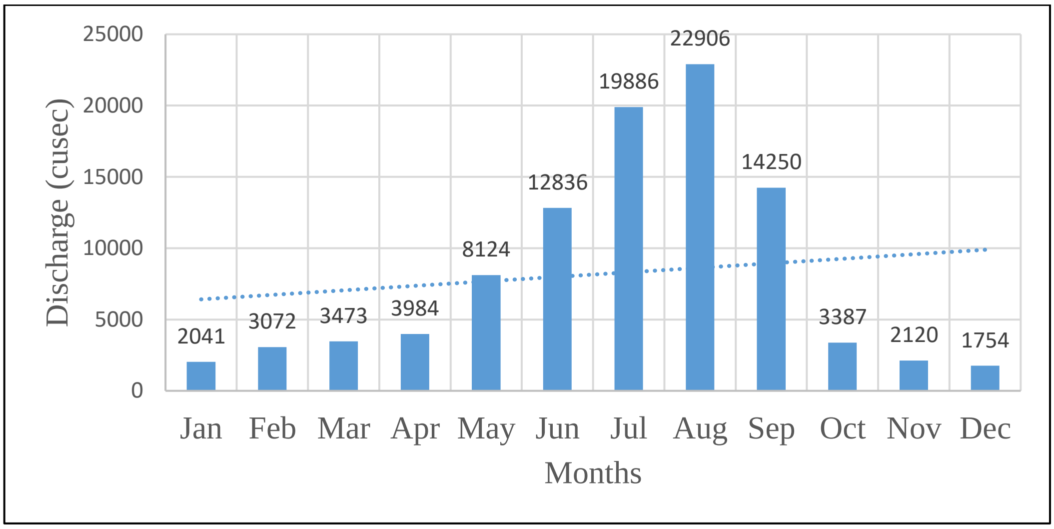

Figure 5.2: Average daily discharge in river Ravi for (2000-2014)

The flow analysis for the River Ravi was done and graphs for max, minimum and average discharge was ploteed for better visualization of available data. The max discharge on the river Ravi on monthly basis is 23274 cusec in August and that of december is 1472 cusec as shown in **Figure 5.3**.

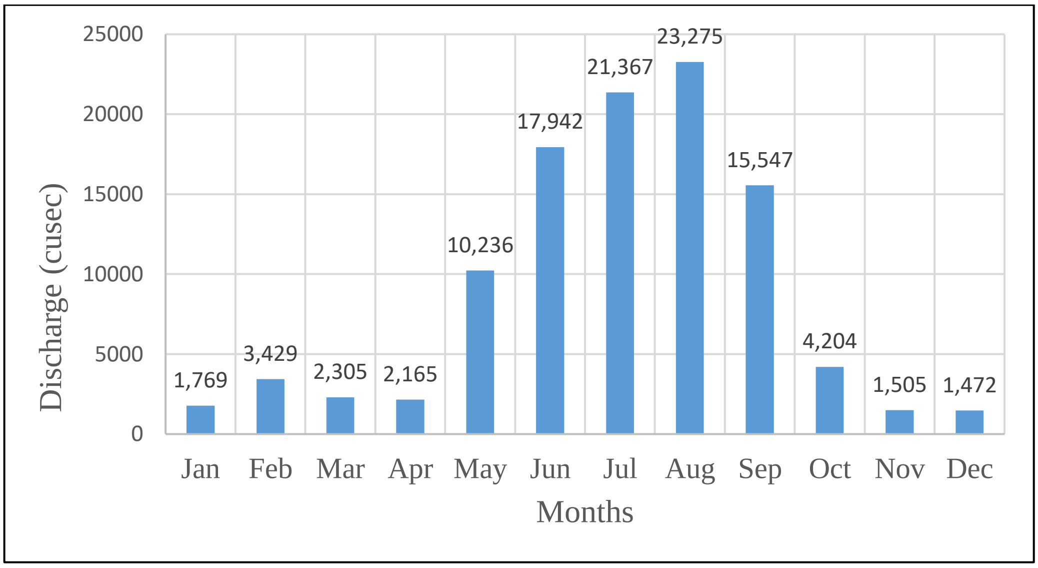

Figure 5.3: Max daily flow in monthly basis of river Ravi (2000-2014)

`

Flow analysis for the river ravi was done and discharge available in river ravi throughout the year was observed. Discharge at 90% of the time of whole year was calculated and it was found that a minimum value of 1200 cusec of water is availble in the river Ravi througout the year and a max discharge of 18000 cusec is available for the month of July in the river Ravi as shown in **Figure 5.4**.

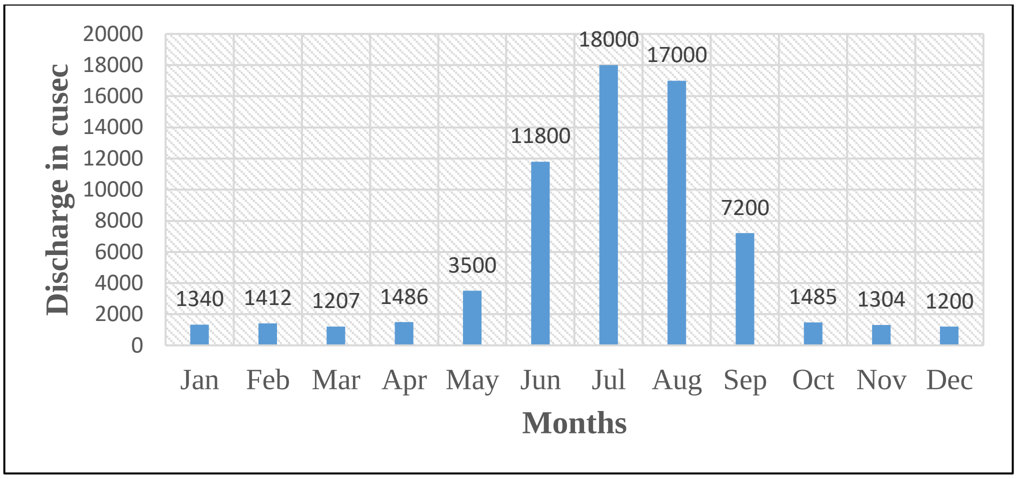

Figure 5.4: River Ravi discharge available 90% of the time for (2000-2014)

The minium discharge of the rive Ravi was also determined from the year 2000-2014. The dischare was determined for the Ravi Siphon and Shahadra. The minimum discharge of 200 cusec per day was observed for the month of December and similarly for moonsoon season a minimum discharge of 10000 cusec is observed in the month of July for the year 2000-2014 as shown in **Figure 5.5.**

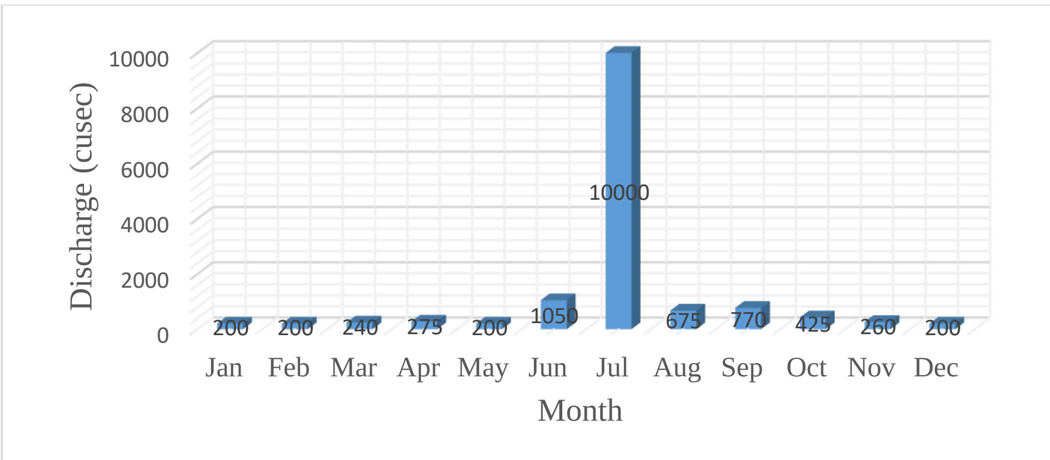

Figure 5.5: Minimum discharge throughout the year (2000-2014)

`

5.1.2 Frequency Analysis

Frequency analysis was used to calculate the peak discharge at different return period for the model input. The methods used for the frequency analysis was normal distribution, log normal distribution, extreme value type I, Frequency Factor, Log Pearson III and Gumbel Distribution. In Pakistan Gumbel, method is used mostly for the computation of the Probabilistic max flow or rainfall in different return period based on the structure designed. The Gumbel method shows a max discharge of 194902.31 cusec for a return period of 100-yr. while for the normal distribution it was 159676.12 cusec. As shown in **Table 5.1**.

Table 5.1: Frequency Analysis of Discharge data of River Ravi

Sr. No.	Time period	Normal Distribution	Log Normal Distribution	Extreme Value Type I	Frequency Factor	Log Pearson III	Gumbel
	Year	**Cusec**					
1	2	58473	47948	51328	51328	43888	51328
2	5	95072	79836	89765	89765	76321	89765
3	10	114221	104244	115214	115214	107723	115214
4	20	130031	129927	139626	139626	147623	139626
5	25	134635	138535	147369	147369	162688	147369
6	50	147819	166464	171224	171224	217878	171224
7	100	159676	196360	194902	194902	288490	194902
8	500	183673	274305	249619	249619	537702	249619
9	1000	192894	311906	273142	273142	696933	273142
10	10000	220235	456495	351244	351244	161089	351244

5.2 Recharge Calculation for River Ravi

Recharge from River Ravi was estimated on the basis of individual x-sectional area and seepage rate. Maximum discharge of 18000 cusic was observed in the period of 2000-2014 so that discharge is used to check the maximum river Ravi recharge capacity. The observed recharge in the River Ravi is about 6978784 ft^3 per annum, if the flow of

18000 cusec pass through the River Ravi. The recharge due to DAM structure was estimated as 24666069 ft^3/yr. as shown in **Table 5.2**.

Table 5.2: Recharge Calculation for River Ravi

Description	Units	River Ravi
Discharge	Cusec	18000
X-Sectional Area	sq. m	16843291.26
Velocity	ft/sec	0.037710916
Permeability	m/day	0.086
Seepage Rate	Cusec	569.66
Normal Recharge	Cubic ft	6978783
Recharge Due to DAM	Cubic ft	24666069

5.3 HEC-RAS Results

HEC RAS model was run to calculate the water surface profile for the flow condition in the river Ravi and to assess the effect of ponding in the river Ravi discharge and hydraulic characteristics. HEC-RAS model was run on three scenarios for river Ravi.

1- Steady flow analysis without installing dam

2- Unsteady flow analysis without installing dam at max flow

3- Unsteady flow analysis with dam installed and maximum flow in the year.

5.3.1 Steady flow analysis

Steady flow analysis was used for model calibration and then that model was used for unsteady analysis. For steady flow analysis, the velocity profile was drawn for the whole channel and it was found that max velocity in the channel is 6 ft/sec at 19 mile D/S of the Indian boarder and minimum velocity observed was 0.05ft/sec in the channel. The steady state analysis showed that flow in the channel is subcritical as shown in **Figure 5.6**.

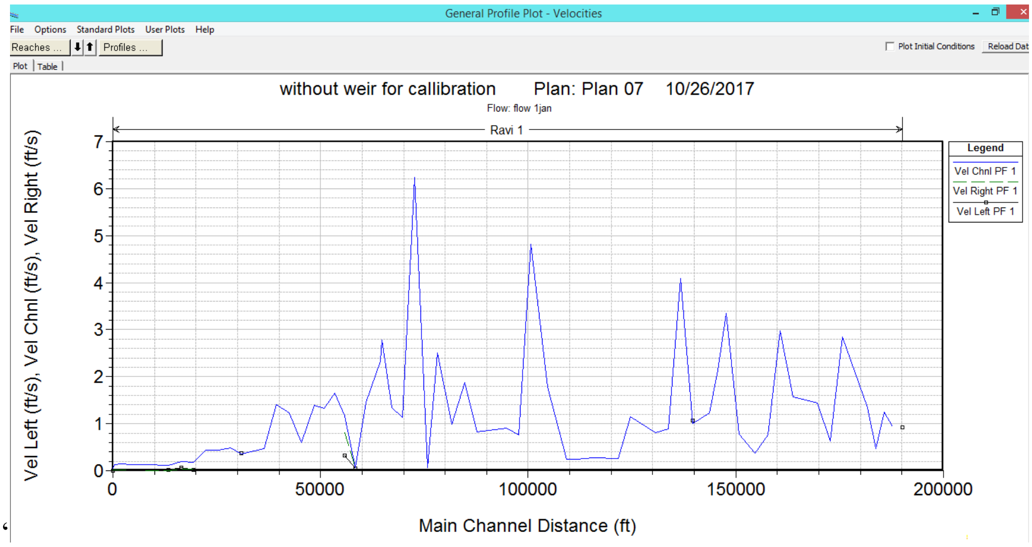

Figure 5.6: Velocity profile in river Ravi for steady flow condition

Water surface profile for the 38 mile reach of river Ravi was determined in HEC-RAS for the steady state conditions and run on the flow observed at 1 Jan 2014 at Shahdra station and then simulated the water surface profile for the channel. The flow for 1 Jan was assumed as base line for the callibratiion of HEC RAS model and water surface depth changed 37ft from U/S to D/S of the river channel as shown in **Figure 5.7**.

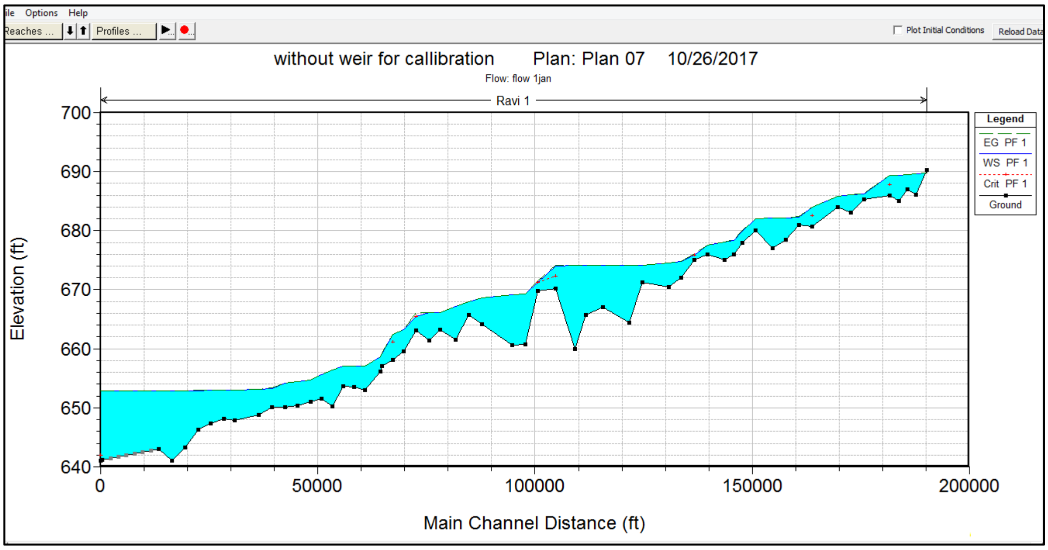

Figure 5.7: Water Surface Profile of river Ravi for steady flow

5.4 Model Calibration

HEC-RAS model was calibrated using steady state flow analysis for the study area reach. For calibration purpose, values of Manning roughness 'n' was changed between 0.015-0.025 for channel left over bank (LOB) and right over bank (ROB), while for the main channel the value of Manning's n was changed between 0.018- 0.03, and then flow was calculated at that section and simulated flow was compared for the better results. The value of Manning's n for main channel was 0.018 and for banks, a value of 0.015 was selected as these results at 99.78% accuracy as shown in **Table 5.3**.

Table 5.3: HEC-RAS Model Calibration

Manning's roughness coefficient "n"							
LOB	**Main**	**ROB**	**Flow Date**	**Observed WL**	**Simulated WL**	**Error**	**Accuracy**
0.025	0.030	0.025	1-01-09	672.6	674.66	0.305	99.69
0.027	0.031	0.027	1-01-09	672.6	674.77	0.322	99.68
0.023	0.029	0.023	1-01-09	672.6	674.62	0.299	99.70
0.030	0.032	0.030	1-01-09	672.6	674.74	0.322	99.68
0.020	0.022	0.020	1-01-09	672.6	674.29	0.250	99.75
0.018	0.020	0.018	1-01-09	672.6	674.18	0.234	99.76
0.015	0.018	0.150	1-01-09	672.6	674.04	0.214	99.78

5.5 Unsteady Flow Analysis without installation of dam

When hec ras model was run for the unsteady conditon and water surface profile was computed. The maximum flow observed in the whole year was 18000 cusec and against that flow a water depth of 5-18 ft was observed in the River Ravi reach as shown in **Figure 5.8**.

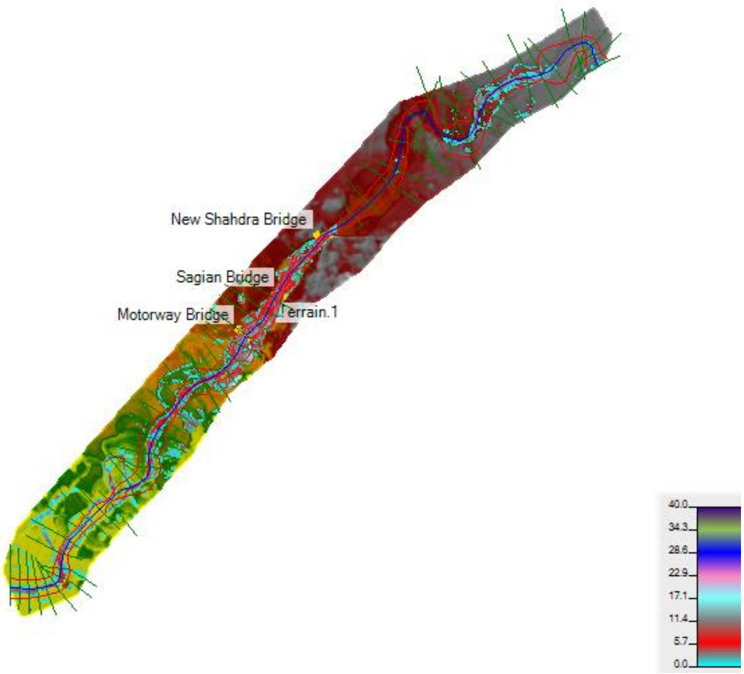

Figure 5.8: Water Surface Profile at max flow available

The river stage and discharge curve was calculated in HEC- RAS for every x-section in the river channel and it was found that the maximum river flow of 18000 in 5 July and the water depth of 18 ft was calculated.The max water surface elevation of 697 ft was observed at the flow of 18000 cusec. The water surface profile is shown in **Figure 5.9**

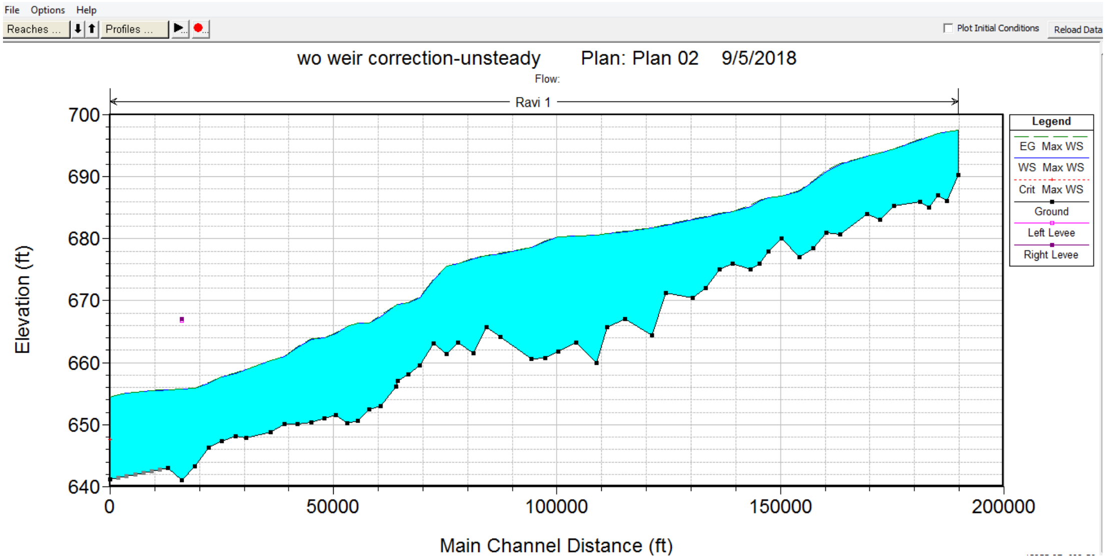

Figure 5.9: Water Surface Profile for the River Ravi

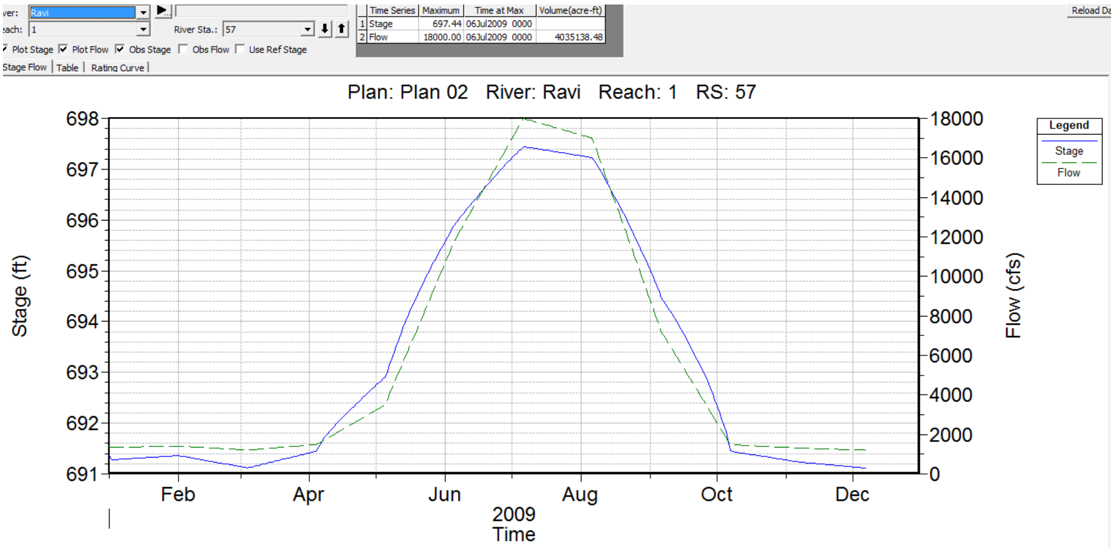

Figure 5.10: River Stage and Flow graph at D/S

The rating curve at the dam site is observed and found that the at flow less than 1200 cusec the stage is increased at a steep rate but after that flow the stage is increased steady and a maximum of 697 ft stage was observed for the flow of 18000 cusec at Downstream as shown in **Figure 5.10**

5.6 Unsteady flow with Maximum flow conditon and dam

HEC-RAS model was run for the high flow condition and water surface profile was estimated at each cross section and it was found that in the month of July the maximum water surface elevation was calculated. During the moonsoon season a flow of about

18000 cusec was calculated in the month of July and for the month of May and August the water surface profile deplete again as shown in **Figure 5.10**. The max water depth observed is 15 ft against a flow of 18000 cusec in case of dam installed as shown in **Figure 5.11**. Water surface elevation observed in July is 697 for the flow of 18000 cusec at the U/S of the river Ravi due to dam as shown in **Figure 5.12**

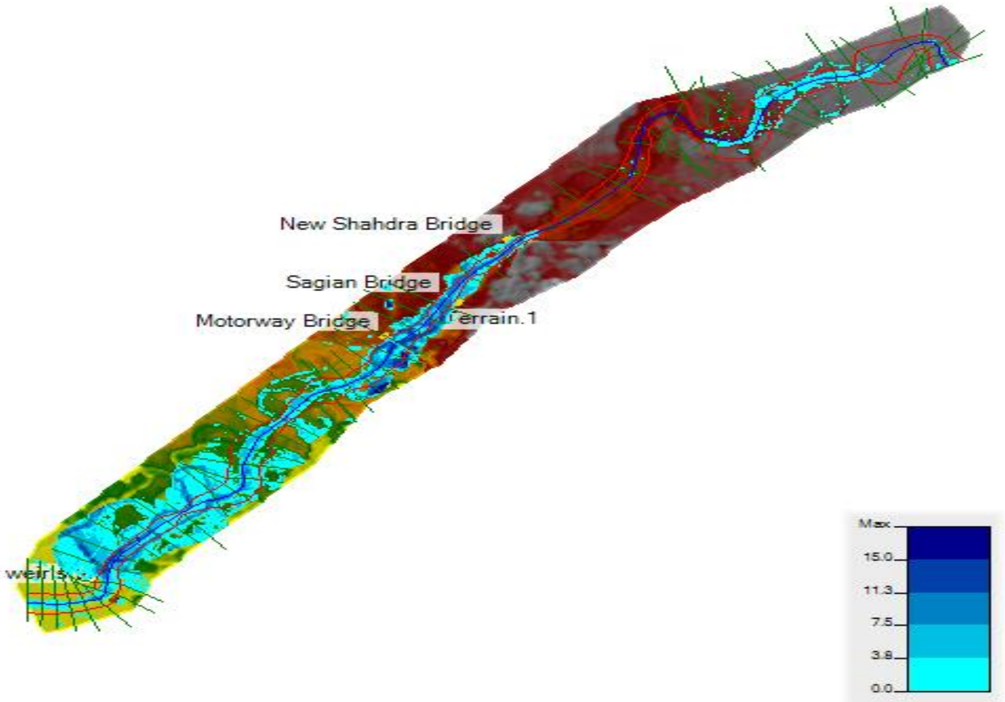

Figure 5.11: Water Surface Profile for the River Ravi after installation of DAM

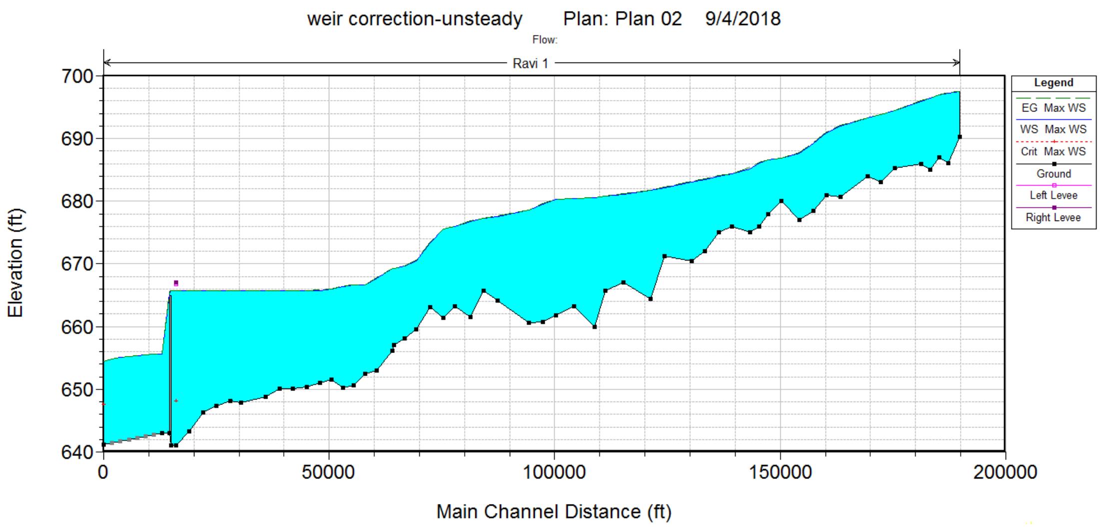

Figure 5.12: Maximum water surface profile with dam installed

The rating curve for the River Ravi was calculated in all section and curve for the dam installed is shown in **Figure 5.13**. Figure shows that at the beginning for a flow of less than 180 cusec, the stage in river rises steep until a Water surface of 656.62ft and after that, a constant trend between water surface and discharge was observed for a flow of 10000 cusec. The stage observed is only 667 ft. and after that, the water surface remains almost constant even for a flow of 10000 cusec as shown in **Figure 5.13**.

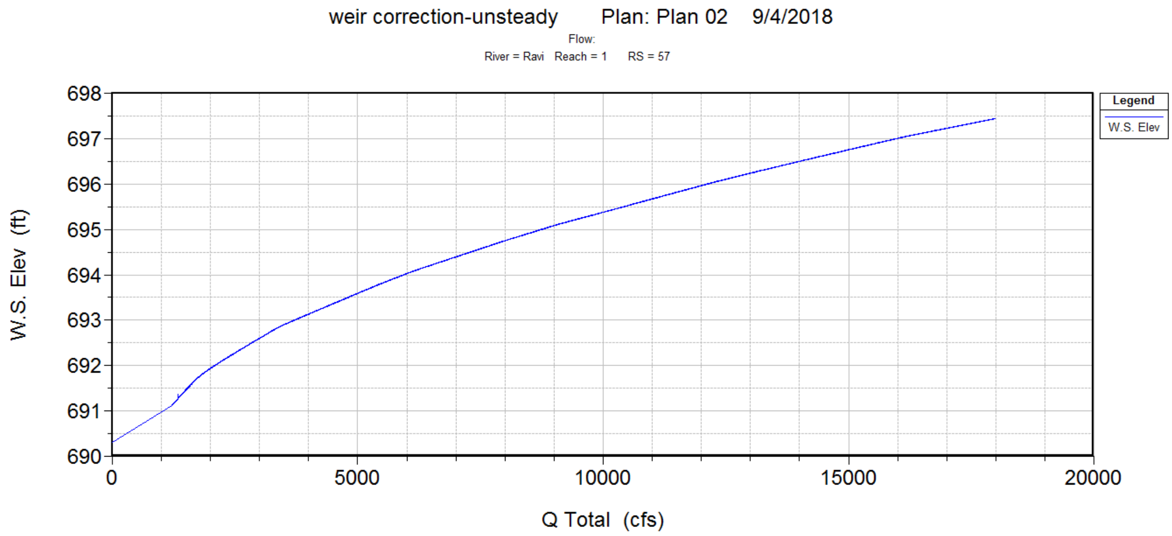

Figure 5.13: Rating Curve for D/S after installation of dam in river Ravi

5.7 Visual MODFLOW

Visual MODFLOW was run for the data of 2003-2014 for pumping wells discharge and recharge from river Ravi and rainfall for different scenarios and then calibrated using 13 observation wells in the vicinity of district Lahore. The Water Level contour for the year 2014 is shown in **Figure 5.14**. The maximum water level observed was 210 m in the vicinity of BRBD canal and along the river Ravi the water level observed varied between 177 m to 210 m. The flow data and pumping data was assumed constant for the whole year that is the model was based on no pumping change scenario.

`

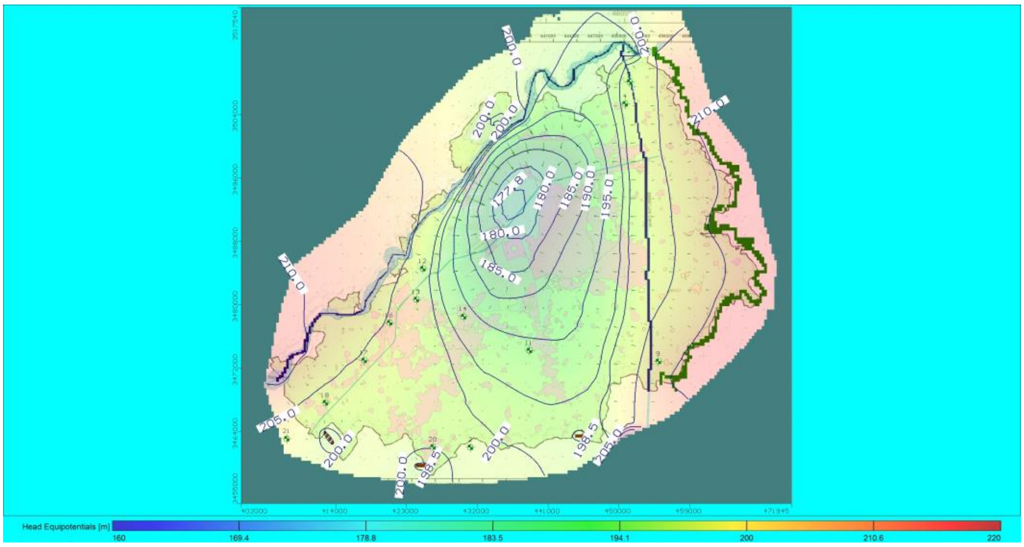

Figure 5.14: Groundwater contours for the year 2014

The groundwater model developed for the River Ravi was callibrated on the 2003-2014 observation wells data and the correlation coefficient for the 12 Year period was 0.94 with the standard error of 0.523 m for the groundwater model. The callibration was based on R^2 & standard error and 95% confidence interval based values was observed for the 12 Year period as shown in Figure 5.15

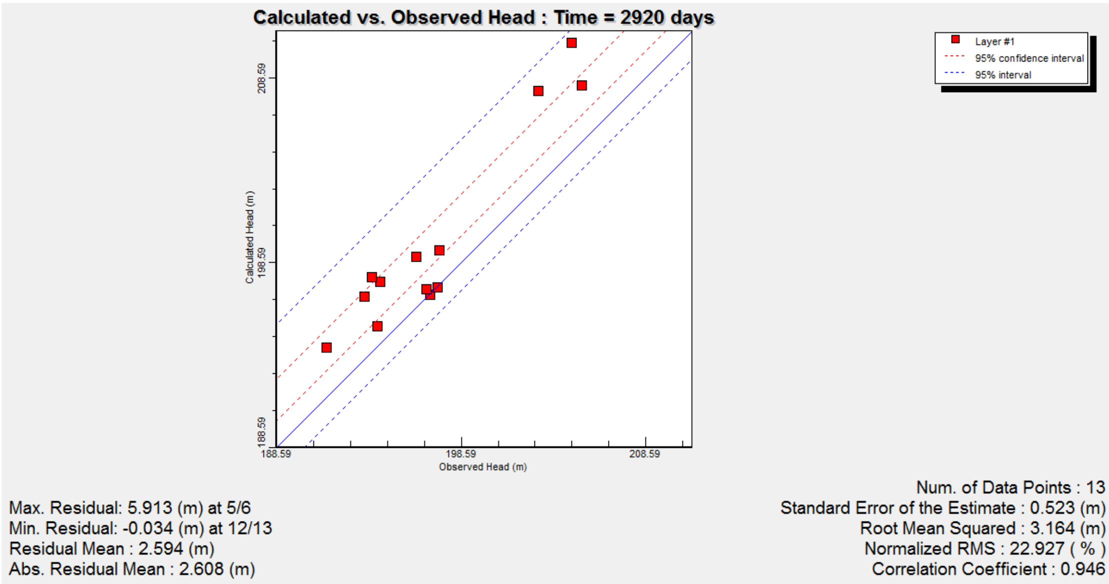

Figure 5.15: Model Calibration for year 2003-2010

The model was run for 12 years data from the year 2003-2014. Then after calibration river stage was changed to check the effect of dam in River Ravi. Since due to dam the river stage rise the effect will be visible. The groundwater model was validated for the year 2010-2014 and a R^2 value of 0.91 and standard error of 0.63 m was found for the year 2014 as shown in **Figure 5.16**.

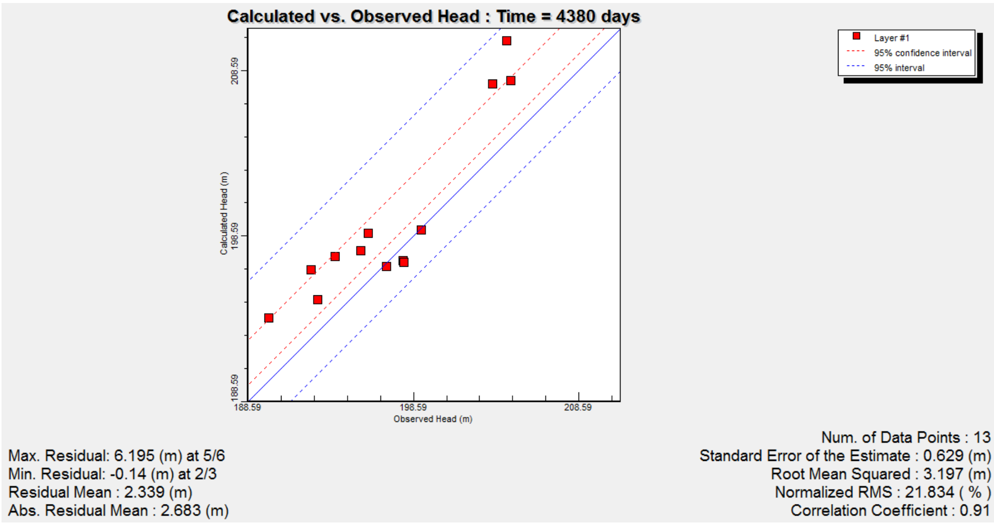

Figure 5.16: Model Validation for year 2014

Groundwater model contours were estimated for the current situation of the year 2017 without changing river stage and assuming the recharge and pumping data constant, as 2014 due to data availability constraint and a minimum water level observed is 172.4m for the year 2017 as shown in **Figure 5.17**.

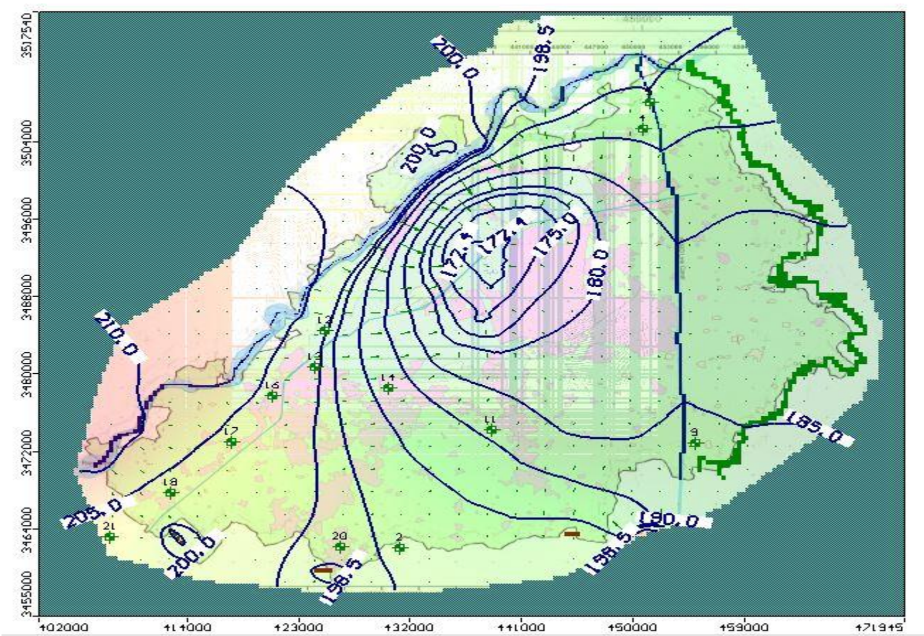

Figure 5.17: Groundwater contour for year 2017 situation

Groundwater Model was extrapolated to the year 2020 for the estimation of Water level. Considering the entire parameters constant and to check what will be future scenario if there is no change in river stage. Tube wells discharge or recharge from the rainfall assuming as constant and it was found that the contour of the 175 m is expanded exponentially and more area is observed where water level was dropped and a minimum of 172 m water level was observed in this scenario as in **Figure 5.18**.

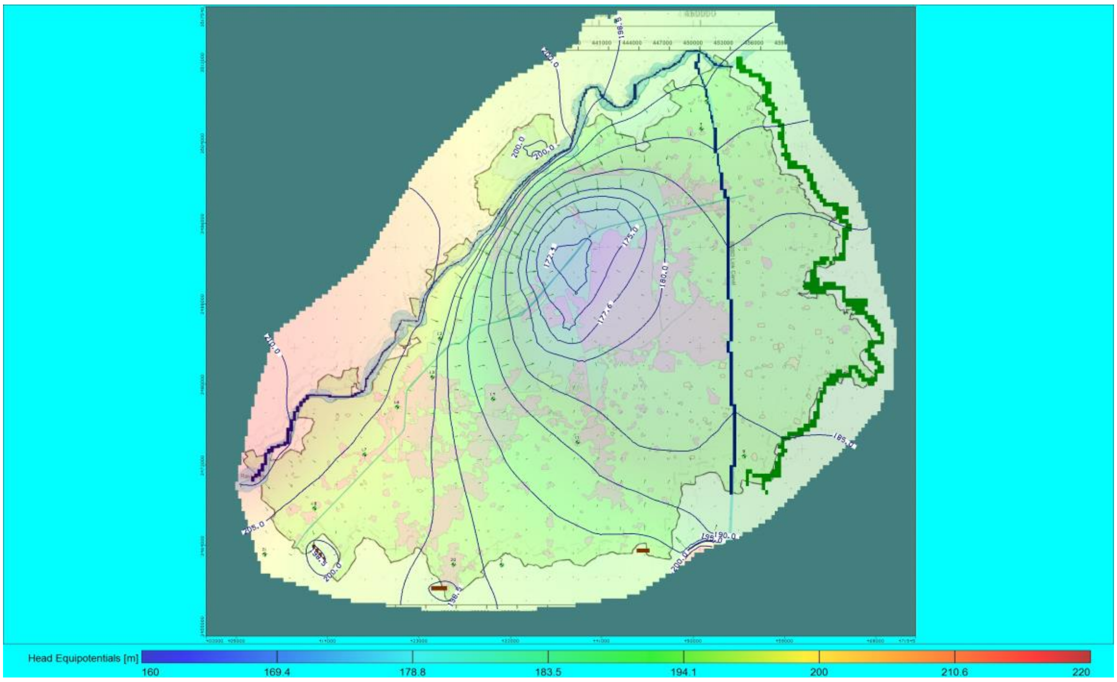

Figure 5.18: Contour 2020 with no changes in River stage

5.8 Groundwater Situation after Rising the River Stage

When groundewater model was run for the change in river stage the contour of 200 m was almost disapear and water level rise for the area. The river stage was increased to 3 m than the previous stage to check the effect better the parameters such as pumping and conductivity parameter was assumed constant and model was run for the steaedy state analysis for the better result.

The ground water level observed after one year of changing river stage and found that the contour of 172 m was disapeared and a minimum water level observed was 175 m near the vicinity of River Ravi as shown in **Figure 5.19**.

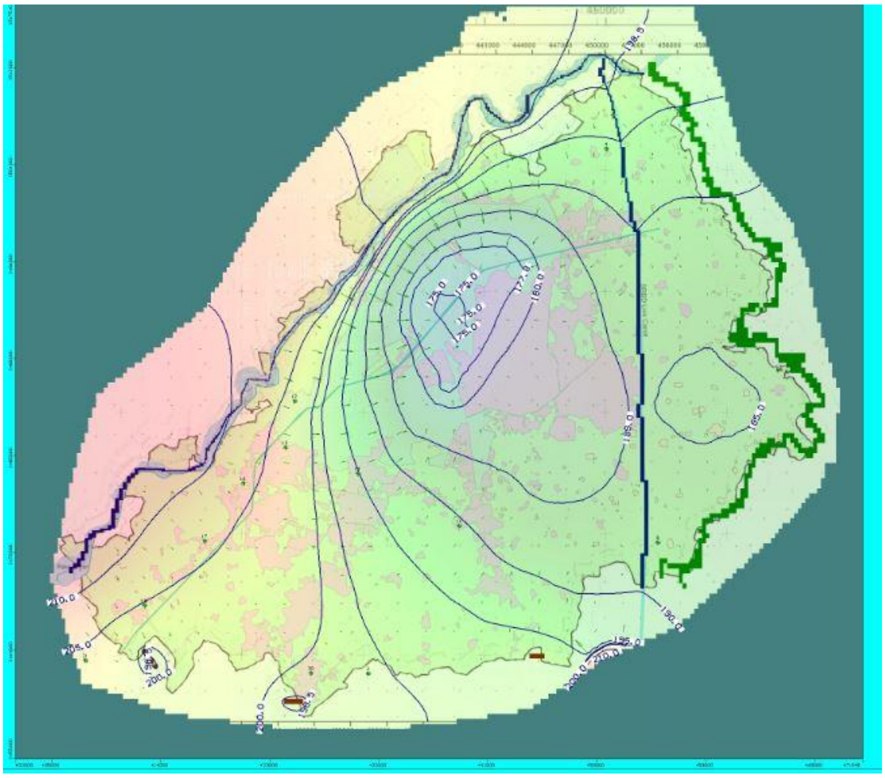

Figure 5.19 : Groundwater contour after 1 year of changing the rive Stage

The model was extrapolated till year 2020 after changing the river stage and the area of the Lahore city which has water level less then 175 m was reduced near river Ravi and a maximum of 185 m contour was observed in the overall Lahore city vicinity as shown in **Figure 5.20**.

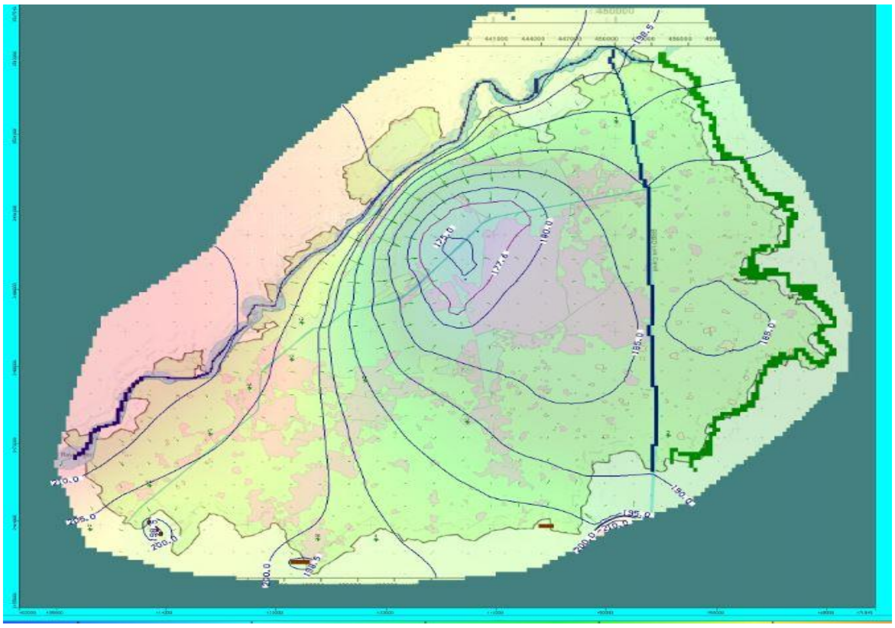

Figure 5.20: Contour after 3 years changing river stage (2020)

The maximum ground water lever observed in the Lahore city was about 80 ft in the center of Lahore city. Groundwater level was depleting at the rate of of about 1-2 ft per year in the Lahore city. The areas which are close to the River ravi has less groundwater depletion rate compare to the areas that are in the center of the city. Most of the observation wells which are close to River has less groundwater depletion. The water level in different observation wells are shown in Figure 5.21.

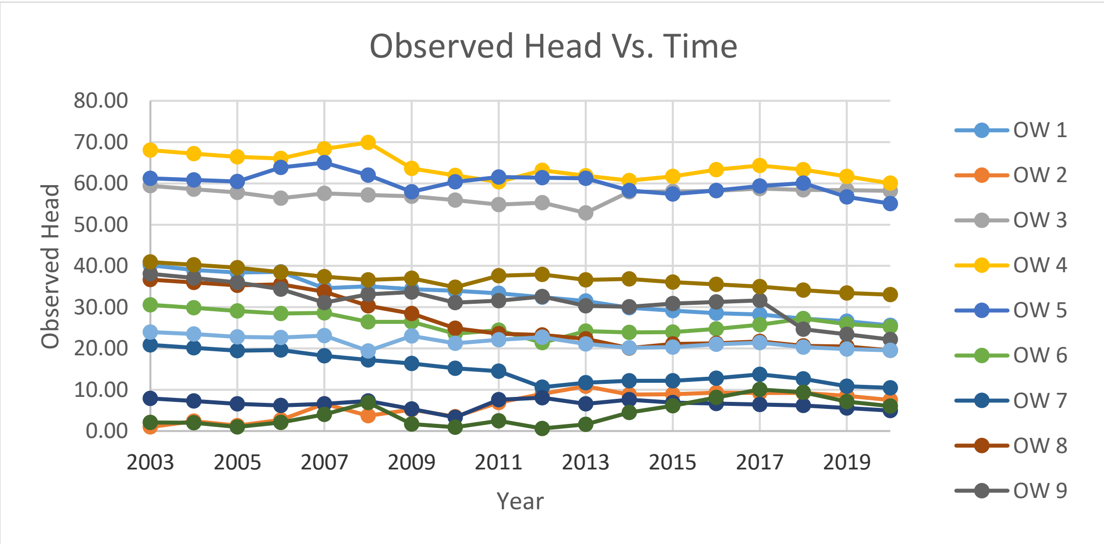

Figure 5.21: Simulated Head Vs. Time in different Location of Lahore city

A dam structure is installed at 3 mile U/S of the Mohlanwall, and 5 mile downstream of the Motorway bridge and water surface profile was computed in the HEC-RAS model. The proposed dam height was 10 ft and the x-section of River Ravi at the proposed location was about 1200 ft. The river x- section of 12000 ft was used for HEC-RAS modelling including flood banks in the study. The back water effect is shown in below Figure. The max height of 15’ was observed in the channel after installaion of the dam in the River Ravi. The recharge in the river Ravi in normal situation is about 6978783 ft^3. When we construct a structure we can get an exctra recharge of 24666069 ft^3 due to the dam structure as shown in **Figure 5.22**

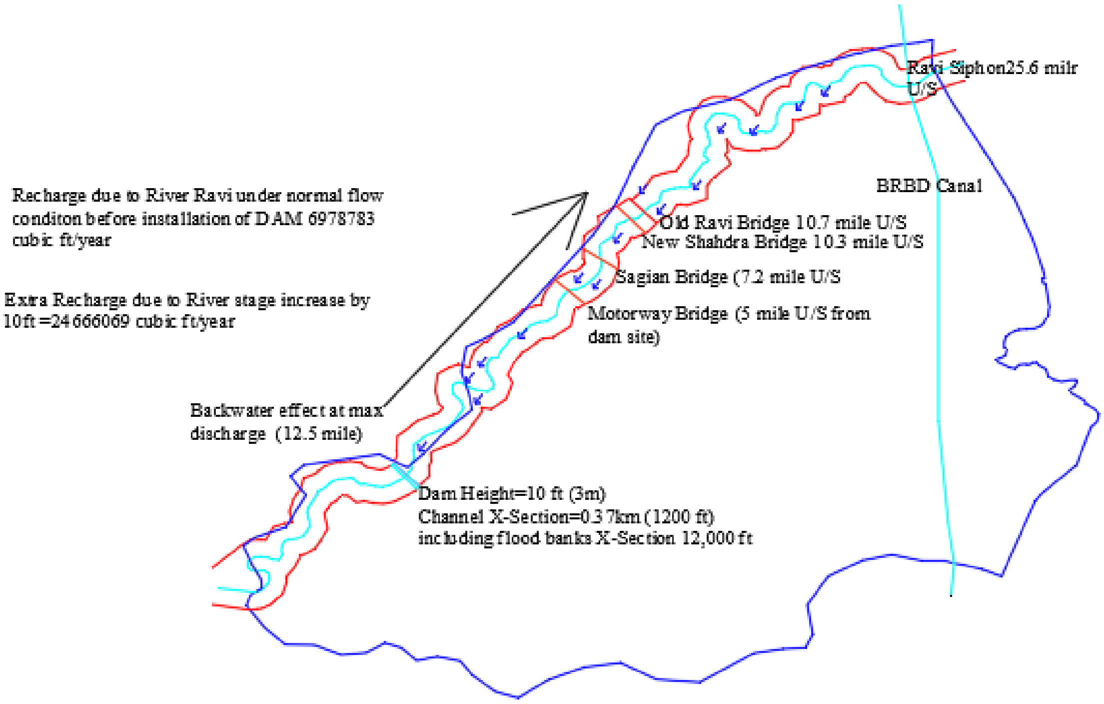

Figure 5.22: Study Area map including proposed dam site

5.9 Groundwater Level Interpolation in ArcMap

Groundwater level of Lahore city was estimated using Visual MODFLOW and then the water level from the ground is computed and groundwater maps of Lahore city was developed in ArcMap for year (2003-2020) before and installation of dam structure.

Thirteen observation well points were used to interpolate the groundwater level on simulated and observed case scenario.

The observed water level maps (2003 &2017) with ther area are shown in **Figure 5.23** and **Figure 5.24**.

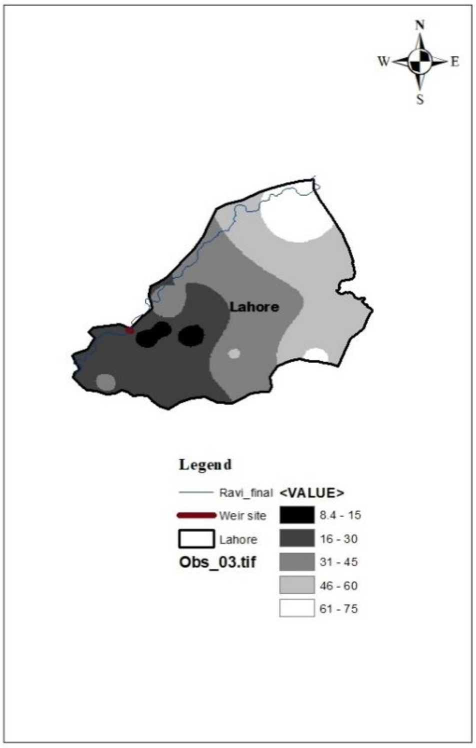

Figure 5.23: Observed GW level (ft.) map of Lahore city for year 2003

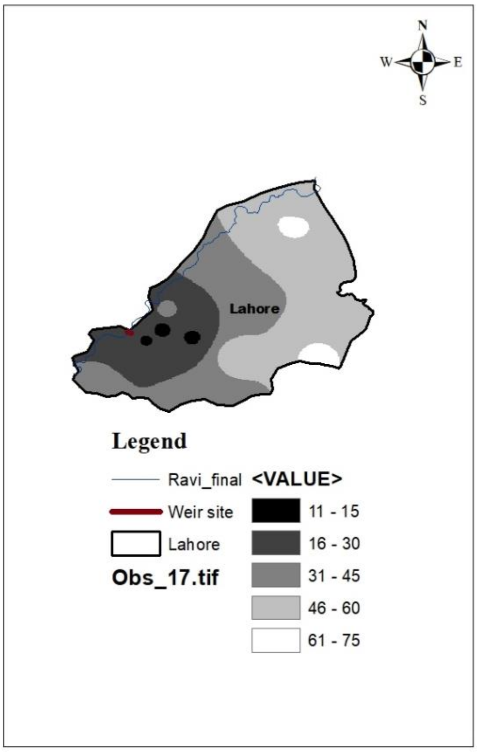

Figure 5.24: Observed GW level (ft.) map of Lahore city for year 2017

Variation of observed ground water level of Lahore city from 2003 to the current situation is shown in Table 5.4. the observed water level near the proposed Dam site is 1-15 ft during the year 2003 which is increase to 11-20 ft. during the year 2017 with a 4 mile^2 more area than the year 2003.

Table 5.4: Variation of observed water levels before installation of DAM in Lahore city (2003-2017)

Year	WL (ft)	Area ($mile^2$)	Year	WL (ft)	Area ($mile^2$)
2003	1-15	19	2017	1-15	14
2003	16-30	202	2017	16-30	148
2003	31-45	224	2017	31-45	219
2003	46-60	172	2017	46-60	250
2003	61-75	44	2017	61-75	30

Simulated groundwater maps are developed for the Lahore city as shown in **Figure 5.25** and **Figure 5.26**

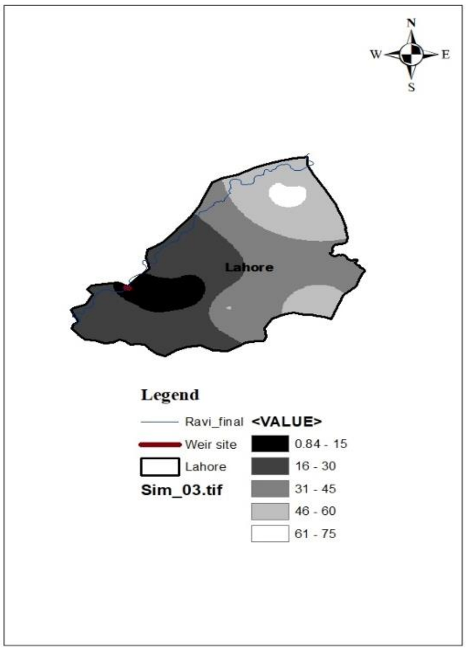

Figure 5.25: Simulated GW level (ft.) map of Lahore city for year 2003

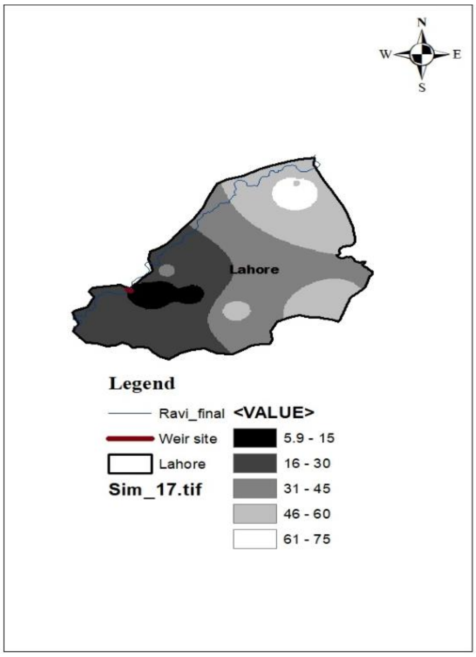

Figure 5.26: Simulated GW level (ft.) map of Lahore city for year 2017

Variation of simulated ground water level of Lahore city by using Visual MODFLWO is shown in **Table 5.5**. where the water level near the proposed dam site increase from 2-11 ft to 5-16 ft with an increase in area variation for year 2003-2017

`

Table 5.5: Variation of simulated water levels before installation of DAM in Lahore city (2003-2017)

Year	WL (ft)	Area (mile^2)	Year	WL (ft)	Area (Km^2)
2003	1-15	35	2017	1-15	16
2003	16-30	176	2017	16-30	145
2003	31-45	211	2017	31-45	264
2003	46-60	193	2017	46-60	214
2003	61-75	55	2017	61-75	24

Visual MODFLOW is run for three year 2018-2020 to check the effect of the DAM structure on groundwater levels. Then groundwater maps are developed in ArcMap showing water levels and their areas of influence by each year.

Groundwater level maps for the Lahore city is developed in ArcMap after raising the water level (DAM structure) and effect of water level fluctuation is checked in Visual MODFLOW which then mapped in ArcMap as shown in **Figure 5.27**, **Figure 5.28** and **Figure 5.29** for year 2018-2020 respectively. Groundwater interpolation maps are shown in Annexure E.

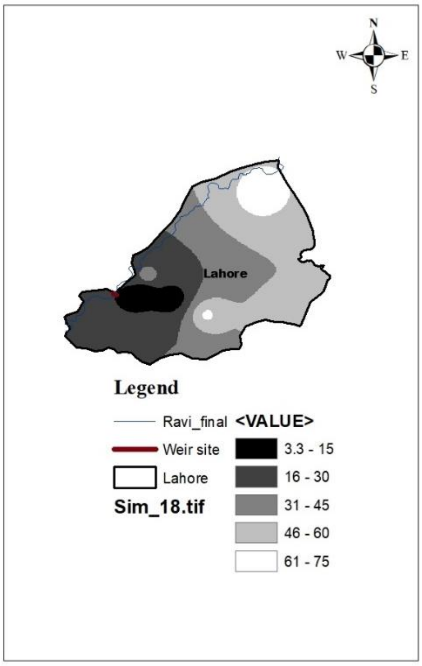

Figure 5.27: Simulated GW level (ft.) map of Lahore city after installation of DAM in year 2018

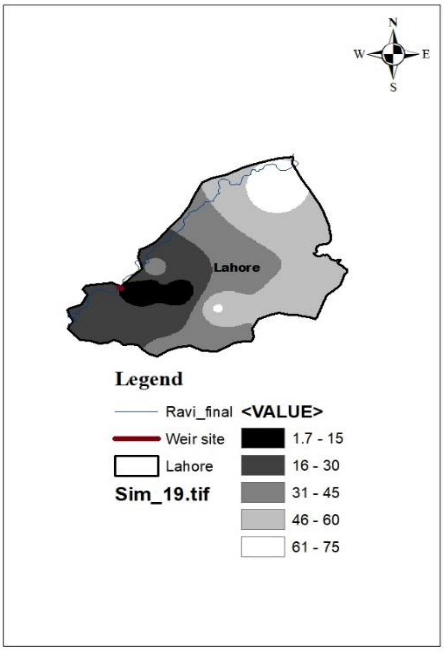

Figure 5.28: Simulated GW level (ft.) map of Lahore city after installation of DAM in year 2019

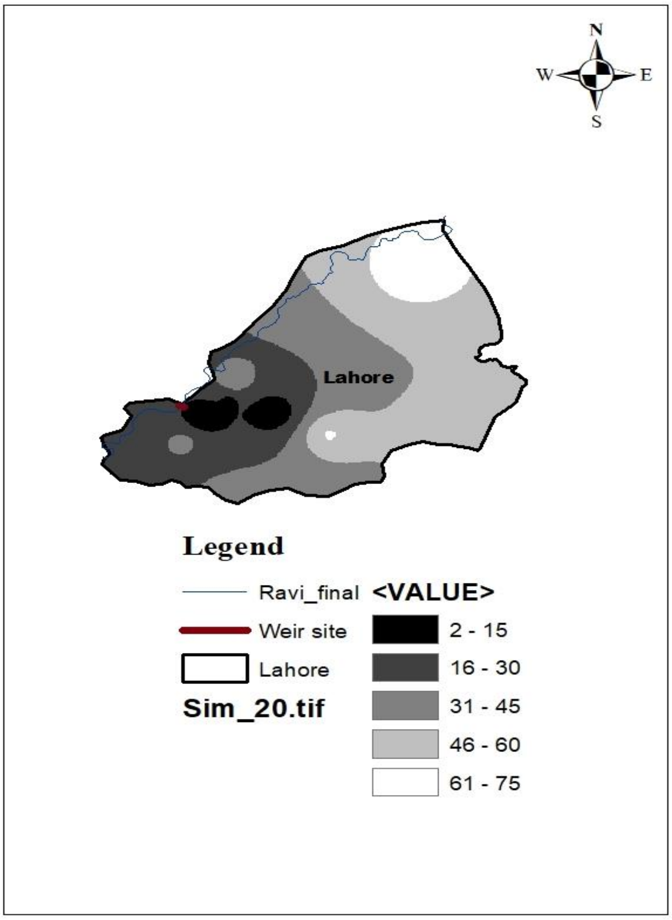

Figure 5.29: Simulated GW level (ft.) map of Lahore city after installation of DAM in year 2020

Groundwater maps were developed for year 2003-2017 for observed and simulated scenario the remaining maps are shown in Annexure D.

After raising the river stage by construction of dam the water level is estimated and water level is reduced for 5-16 ft to 2-12 ft during year 2017-2020 (3 years after construction of dam) the area reduction was calculated as shown in **Table 5.6** and **Table 5.7**

Table 5.6: Variation of simulated water levels after installation of dam in Lahore city (2017-2018)

Year	WL (ft)	Area ($mile^2$)	Year	WL (ft)	Area ($mile^2$)
2017	1-15	16	2018	1-15	14
2017	16-30	145	2018	16-30	105
2017	31-45	264	2018	31-45	195
2017	46-60	214	2018	46-60	310
2017	61-75	24	2018	61-75	26

Table 5.7: Variation of simulated water levels after installation of dam in Lahore city (2019-2020)

Year	WL (ft)	Area ($mile^2$)	Year	WL (ft)	Area ($mile^2$)
2019	1-15	12	2020	1-15	9
2019	16-30	103	2020	16-30	97
2019	31-45	198	2020	31-45	204
2019	46-60	312	2020	46-60	318
2019	61-75	25	2020	61-75	22

`

The difference in water level throughout the Lahore city was estimated using ArcMap and showing in **Figure 5.30**, **Figure 5.31** and **Figure 5.32** for 2018, 2019 and 2020 respectively

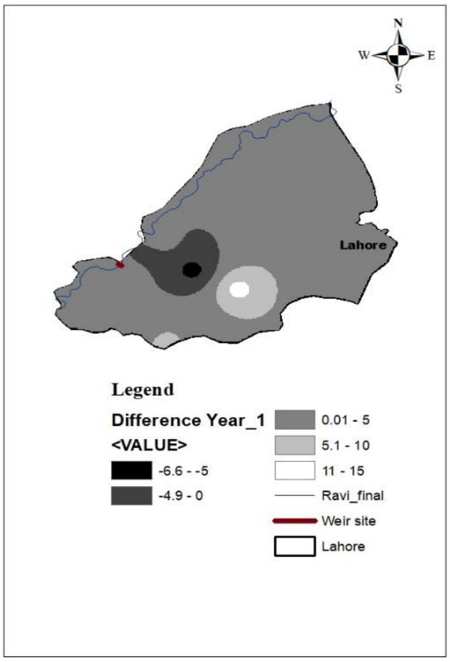

Figure 5.29: water level difference map of Lahore for year 2018

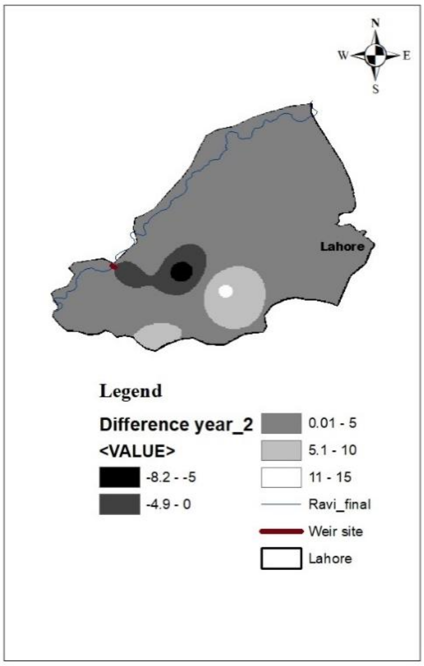

Figure 5.30: water level difference map of Lahore for year 2019

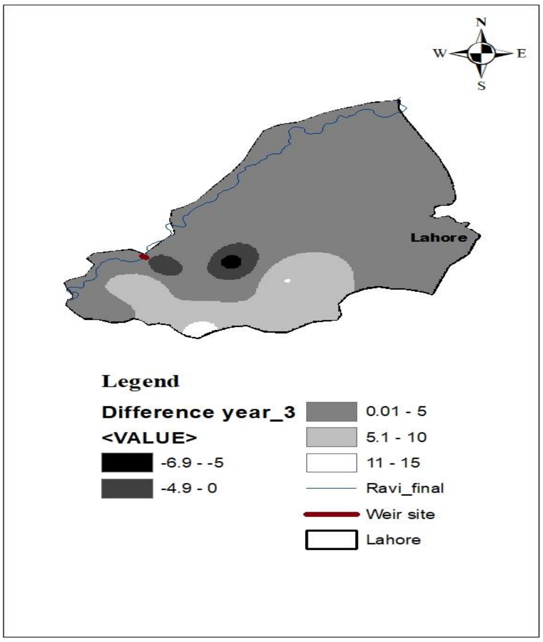

Figure 5.30: water level difference map of Lahore for year 2020

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- Under normal condition recharge capacity of river Ravi was calculated as 6978783 ft^3/year.
- After installation of dam, the extra recharge capacity 24666069 ft^3/year of River Ravi was estimated.
- The water depth in river Ravi under normal condition varies between 2-10 ft depending on the available flow and location of river Ravi from proposed dam site.
- When a dam structure was installed in the River Ravi the head of the river Ravi increase and a backwater effect of about 12.5-mile U/S was simulated.
- The maximum water depth of 15 ft was simulated using HEC-RAS in river Ravi after construction of dam..

6.2 Recommendations

- To maintain aquifer level of Lahore city other recharge options like rainwater harvesting, recharging wells and recharging ponds along with river Ravi should also be consider.
- Regular monitoring of groundwater levels and more piezometric wells should be installed in Lahore city.
- A policy for the private wells should be developed and enforced to control the installation of private tube wells in the city boundary.

`

- There should be data sharing facility for Govt. & Private institutes that do research for the betterment of city. The data should be combined in one department to reduce the time waste and people can learn better this way.
- As river Ravi's water is polluted so a full analysis of water quality is required for the future study and then a law should be enforced on industries surrounding the River boundary that recycled water dumped in the River to reduce quality issues.

REFERENCES

Ahmed, I., and Umar. R., 2009. Groundwater modelling of Yamuna- Krishni interstream, a part of central Ganga Plain Uttar Pardesh. J. Earth Sys. Sci. 118(5), 507-523.

Ahmeed, B., Muhammad, S. K., Mohsin, J. B., and Zakir, H. D., 2010. Hydrological modelling and Flood Hazard Mapping of NULLAH LAI, Proc. Pakistan Acad. Sci. 47(4), 215-226.

Alemu,Y., Kristine, W., and B. Okke., 2017. Spatial and temporal variability of groundwater recharge in Geba basin, North Ethopia. J. African earth sci, 134, 198-212

Ali, S., Saeed, S., and M., Reza., 2012. Probabilistic flood inundation mapping of ungauged rivers: Linking techniques and frequency analysis. Hydrology J, 459, 68-86

Ambe, E. C., Hans, J.V., and Wendland, F.,2017. Modelling groundwater recharge through rainfall in the far north region of Cameron. J. Groundwater and Sust. Developmet, 5, 118-130

Bakshi, G., and Trivedi, S., 2011. The Indus Equation Strategic Foresight Group C-306, Montana, Lokhandwala Complex Andheri West, Mumbai 400 053, India.

Bashir, A., Kaleem, M.S., Butt, M.J., and Zakir D.H., 2010. Hydrological Modelling and Flood Hazard Mapping of Nullah Lai, Pakistan Acad. Sci. 47(4), 215-226.

Baky, A.A., Zaman, A.M., and Khan, A. U., 2012. Managing flood flows for crop production risk management with Hydraulics and GIS Modelling: Case study of Agriculture Areas of Shariatpur. Procedia APCBEE, 1, 318-324

Basharat, M., Rizvi, S.A., 2011. Groundwater extraction and wastewater disposal regulation – Is Lahore aquifer at stake with as usual approach. Pakistan Engineering Congress, World Water Day, 135-152 pp.

Fethi, L.,Ammar, L., Mourad, B., Jamila, T., and Christine , L., 2012. Implementation of a 3-D groundwater flow model in a semi-arid region using MODFLOW and GIS tools: The Ze´ramdine Be´ni Hassen Miocene aquifer system, east-central Tunisia. J. Comp and GeoSci, 48, 187-198

Fouepe, A. T., Gurunandha, V. V. S. R., Ndam, J. N., Sigha, L. N., and Ekodeck, G. E., 2009. Groundwater flow modelling in the upper Anga'a river watershed, Yaounde, Cameroon, AF. J. Environ. Sci. and Tech. 3(10), 341-352.

Francisco, C., Oscar, C.O., Amanda, G.M., Ayuso, J.L., and Dey, L., 2015. Free surface profiles in river flows: Can standard energy-based gradually-varied flow computations be pursued. Hydrology J., 529, 1644-1656

Haghizadeh, A., Lee, T. S., Majid, M., and Hadi, M., 2012. Incorporation of GIS Based Program into Hydraulic Model for Water Level Modelling on River Basin. J. water Res. Prot. 2012(4), 25-31.

Hong, w., Jien, E.G., Meng, J.Z., Xing, H.L., Shao, L.Z., and Li, Z.J., 2015. Effects of Rainfall intensity on groundwater recharge based on simulated rainfall experiments and a groundwater flow model, Catena. 127,80-91

Hussein, I. A., Jummin, L., and Zhang, Y., 2013. Numerical Simulation of groundwater of large-scale irrigation in North China: Case Study of Baoyang Irrigation Area, Shannxi, China. Int. J. Water Res. and Environ. Eng. 5(9) 533-545

Khalid M., Asim, D.R., Salman, T., Shamsa, K., Roshan, A., Anees, H. A. and Tayyab, T., 2013.Groundwater levels susceptibility to degradation in Lahore metropolitan. Sci. Int., 25(1): 123-126

Maheshwara, R., Khosa, R., A.K. Gosin, S. Lahari, S.K. Sinha, B.R. Chahar, and C.T. Dhanya, 2016. Regional scale groundwater modelling study for Ganga River basin. Hydrology J., 541, 727-741

Masood, M., and Kuniyoshi, T. 2012. Assessment of Flood Hazard, Vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model. Natural Hazards. 61, 757-770.

Mirlas, V., Valery, A., Vitaly, K., and Elmira, K., 2015. Assessing Artificial Groundwater Recharge on Irrigated Land using the MODFLOW Model (A Case Study from Karatal Agricultural Area, Kazakhstan). Earth Sci. Res. 4(2), 16-34.

`

Mirudhula, K., 2014. Impact of Lined/ Unllined canal on Groundwater Recharge in the lower Bhavani Basin. Int. J. Inno. and App. Stud. 9(4), 1818-1821.

Mohanty, S., Madan, K.J., Ashwani, K., D.K. Panda., 2013. Comparative evaluation of numerical model and artificial neural network for simulating groundwater flow in Kathajodi–Surua Inter-basin of Odisha, India. Hydrology J., 495, 38-51

Muherjee, D., 2016. A Review of Artificial Groundwater Recharge in India. Int. J. Civ. Eng. 3(1), 60-65.

NESPAK, Binnie & Partners., 1986, Technical Proposal for Groundwater Resources Evaluation and study of Aquifer under Lahore.

NESPAK, Binnie & Partners., 1988, Technical Proposal for Groundwater Resources Evaluation and study of Aquifer under Lahore, Volume III, Chapter 4.

NESPAK, Binnie & Partners., 1991, Groundwater Resources Evaluation and study of Aquifer under Lahore, Supporting Volume I, Groundwater Model.

Pradeep, G. N. K., and Anil, P. K., 2014, Development of Groundwater Flow Model using Visual MODFLOW. Int. J. Adv. Res. 2(6), 649-656.

Punys, P., I., Adamonyte., A. Kvarciejus., E.Martiniatis., G. Vyciene., and E. Kasiulis., 2015. Riverine hydrokinetic resource assessment. A case study of a lowland river in Lithuania. Renewable and Sust. Energy reviws,50, 643-652

Senthilkumar, M., and Elango, L., 2011. Modelling the impact of a subsurface barrier on groundwater flow in the lower Palar River basin, southern India. Hydrogeology J. 19: 917-928

Sidique, A.H.M., Faisal, H., Hyongki, L., and Shum, C. K., 2011. Inter-comparison study of water level estimated derived from hydrodynamic- hydrologic model and satellite altimetry for a complex deltaic environment. J. Remote Sensing and Environ, 115, 1522-1531

Vijai, S., and Rohit, G., 2011. Development of conceptual groundwater flow model for Pali Area, India. AF. J. Environ. Sci. and Tech. 5(12), 1085-1092.

Vladimir M., Antonenko, V., Kulagin, V., and Kuldeeva, E., 2015. Assessing Artificial Groundwater Recharge on Irrigated Land Using the MODFLOW Model. J. Earth Science Research, 4, 16-34.

WAPDA, 1980. Hydrogeological Data of Bari Doab, Volume-1. Basic Data Release No.1 by Directorate General of Hydrogeology, WAPDA, Lahore

Water and Sanitation Agency (WASA), 2013. WASA Handbook, Lahore, Pakistan.155 pp. wheat, mustard weeds grown in field irrigated with industrial effluents. Bulletin of Environmental

Weicai, W., Yang, G., Pablo, I. A., Yanbin, L., Yang, X., Guoqing, Z., Shengai, L., and Lu, A., 2015. Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas. GeomorphologRy.1-14

Wiktoria C., Artur, R. P., Bartlomiej, W., and Hanna, H., 2016. Modelling the flooding capacity of a Polish Carpathian river: A comparison of constrained and free channel conditions. Geomorphology, 272, 32-42

`

ANNEXURES

Annexure A	Observation Wells Data
Annexure B	Data analysis of discharge and rainfall
Annexure C	River x-section from Indian Boarder to Shahdra
Annexure D	River x-section from Shahdra to Head Balloki
Annexure E	Groundwater level interpolation maps

`

Annexure A

Observation Wells Data

Table A.1: Observation Wells Data

Well Name	X [m]	Y [m]	Screen ID	Screen Elev. [m]	Obs. Time [day]	HEAD [m]
11	437976.9	3470582	12	183.7	365	195.938
11	437976.9	3470582	12	183.7	730	195.598
11	437976.9	3470582	12	183.7	1095	195.398
11	437976.9	3470582	12	183.7	1460	195.4468
11	437976.9	3470582	12	183.7	1825	194.252
11	437976.9	3470582	12	183.7	2190	194.38
11	437976.9	3470582	12	183.7	2555	194.1788
11	437976.9	3470582	12	183.7	2920	194.0508
11	437976.9	3470582	12	183.7	3285	193.874
11	437976.9	3470582	12	183.7	3650	193.58
11	437976.9	3470582	12	183.7	4015	193.31
11	437976.9	3470582	12	183.7	4380	192.8
12	424441.9	3480890	13	192.7	365	199.0194
12	424441.9	3480890	13	192.7	730	198.7994
12	424441.9	3480890	13	192.7	1095	198.5794
12	424441.9	3480890	13	192.7	1460	198.3782
12	424441.9	3480890	13	192.7	1825	198.427
12	424441.9	3480890	13	192.7	2190	197.7656
12	424441.9	3480890	13	192.7	2555	197.7656
12	424441.9	3480890	13	192.7	2920	196.903
12	424441.9	3480890	13	192.7	3285	197.156
12	424441.9	3480890	13	192.7	3650	196.2172
12	424441.9	3480890	13	192.7	4015	197.0828
12	424441.9	3480890	13	192.7	4380	196.9792
13	423653.6	3477039	14	185.7	365	195.0574
13	423653.6	3477039	14	185.7	730	194.8374
13	423653.6	3477039	14	185.7	1095	194.6274
13	423653.6	3477039	14	185.7	1460	194.6792
13	423653.6	3477039	14	185.7	1825	194.2464
13	423653.6	3477039	14	185.7	2190	193.9416
13	423653.6	3477039	14	185.7	2555	193.6886
13	423653.6	3477039	14	185.7	2920	193.332
13	423653.6	3477039	14	185.7	3285	193.1308
13	423653.6	3477039	14	185.7	3650	192.9266
13	423653.6	3477039	14	185.7	4015	192.2652
13	423653.6	3477039	14	185.7	4380	192.4176
14	429646.1	3474879	15	185.7	365	194.8806
14	429646.1	3474879	15	185.7	730	194.6706

`

Well Name	X [m]	Y [m]	Screen ID	Screen Elev. [m]	Obs. Time [day]	HEAD [m]
14	429646.1	3474879	15	185.7	1095	194.4506
14	429646.1	3474879	15	185.7	1460	194.5268
14	429646.1	3474879	15	185.7	1825	193.9934
14	429646.1	3474879	15	185.7	2190	192.9358
14	429646.1	3474879	15	185.7	2555	192.3688
14	429646.1	3474879	15	185.7	2920	191.302
14	429646.1	3474879	15	185.7	3285	190.8936
14	429646.1	3474879	15	185.7	3650	190.793
14	429646.1	3474879	15	185.7	4015	190.5126
14	429646.1	3474879	15	185.7	4380	189.8268
16	420209.4	3474105	17	186.7	365	196.3092
16	420209.4	3474105	17	186.7	730	195.9992
16	420209.4	3474105	17	186.7	1095	195.6792
16	420209.4	3474105	17	186.7	1460	195.1702
16	420209.4	3474105	17	186.7	1825	194.1796
16	420209.4	3474105	17	186.7	2190	194.7892
16	420209.4	3474105	17	186.7	2555	194.9416
16	420209.4	3474105	17	186.7	2920	194.1796
16	420209.4	3474105	17	186.7	3285	194.332
16	420209.4	3474105	17	186.7	3650	194.6368
16	420209.4	3474105	17	186.7	4015	193.951
16	420209.4	3474105	17	186.7	4380	193.8748
17	416986.5	3469341	18	189.7	365	199.1754
17	416986.5	3469341	18	189.7	730	198.9654
17	416986.5	3469341	18	189.7	1095	198.7554
17	416986.5	3469341	18	189.7	1460	198.4262
17	416986.5	3469341	18	189.7	1825	198.11
17	416986.5	3469341	18	189.7	2190	197.8654
17	416986.5	3469341	18	189.7	2555	197.9934
17	416986.5	3469341	18	189.7	2920	197.332
17	416986.5	3469341	18	189.7	3285	198.1702
17	416986.5	3469341	18	189.7	3650	198.2708
17	416986.5	3469341	18	189.7	4015	197.8654
17	416986.5	3469341	18	189.7	4380	197.9416
18	412052.6	3464017	19	188.7	365	198.1236
18	412052.6	3464017	19	188.7	730	197.9136
18	412052.6	3464017	19	188.7	1095	197.7036
18	412052.6	3464017	19	188.7	1460	197.6
18	412052.6	3464017	19	188.7	1825	197.7036
18	412052.6	3464017	19	188.7	2190	197.9322

`

Well Name	X [m]	Y [m]	Screen ID	Screen Elev. [m]	Obs. Time [day]	HEAD [m]
18	412052.6	3464017	19	188.7	2555	197.3226
18	412052.6	3464017	19	188.7	2920	196.713
18	412052.6	3464017	19	188.7	3285	198.0084
18	412052.6	3464017	19	188.7	3650	198.1608
18	412052.6	3464017	19	188.7	4015	197.7036
18	412052.6	3464017	19	188.7	4380	198.0084
2	430497.1	3458403	3	183.7	365	197.0724
2	430497.1	3458403	3	183.7	730	197.1029
2	430497.1	3458403	3	183.7	1095	197.4768
2	430497.1	3458403	3	183.7	1460	198.3424
2	430497.1	3458403	3	183.7	1825	198.9276
2	430497.1	3458403	3	183.7	2190	199.7902
2	430497.1	3458403	3	183.7	2555	198.2144
2	430497.1	3458403	3	183.7	2920	197.428
2	430497.1	3458403	3	183.7	3285	198.446
2	430497.1	3458403	3	183.7	3650	197.8852
2	430497.1	3458403	3	183.7	4015	198.19
2	430497.1	3458403	3	183.7	4380	199.08
20	425765	3458435	21	184.7	365	197.011
20	425765	3458435	21	184.7	730	196.861
20	425765	3458435	21	184.7	1095	196.651
20	425765	3458435	21	184.7	1460	196.5992
20	425765	3458435	21	184.7	1825	196.7516
20	425765	3458435	21	184.7	2190	195.618
20	425765	3458435	21	184.7	2555	196.7272
20	425765	3458435	21	184.7	2920	196.1664
20	425765	3458435	21	184.7	3285	196.4468
20	425765	3458435	21	184.7	3650	196.6236
20	425765	3458435	21	184.7	4015	196.1176
20	425765	3458435	21	184.7	4380	195.8372
21	407149.1	3459470	22	186.7	365	193.6028
21	407149.1	3459470	22	186.7	730	193.4328
21	407149.1	3459470	22	186.7	1095	193.1128
21	407149.1	3459470	22	186.7	1460	193.5212
21	407149.1	3459470	22	186.7	1825	194.6978
21	407149.1	3459470	22	186.7	2190	193.826
21	407149.1	3459470	22	186.7	2555	194.2832
21	407149.1	3459470	22	186.7	2920	193.7468
21	407149.1	3459470	22	186.7	3285	194.7892
21	407149.1	3459470	22	186.7	3650	195.4506

`

Well Name	X [m]	Y [m]	Screen ID	Screen Elev. [m]	Obs. Time [day]	HEAD [m]
21	407149.1	3459470	22	186.7	4015	196.0084
21	407149.1	3459470	22	186.7	4380	195.4232
4	450147	3501695	5	195.7	365	203.812
4	450147	3501695	5	195.7	730	203.572
4	450147	3501695	5	195.7	1095	203.332
4	450147	3501695	5	195.7	1460	202.9022
4	450147	3501695	5	195.7	1825	203.2558
4	450147	3501695	5	195.7	2190	203.1308
4	450147	3501695	5	195.7	2555	203.0272
4	450147	3501695	5	195.7	2920	202.75
4	450147	3501695	5	195.7	3285	202.4176
4	450147	3501695	5	195.7	3650	202.57
4	450147	3501695	5	195.7	4015	201.808
4	450147	3501695	5	195.7	4380	203.3808
5	450710.1	3504464	6	197.7	365	206.4416
5	450710.1	3504464	6	197.7	730	206.1916
5	450710.1	3504464	6	197.7	1095	205.9416
5	450710.1	3504464	6	197.7	1460	205.8166
5	450710.1	3504464	6	197.7	1825	206.5268
5	450710.1	3504464	6	197.7	2190	207.0084
5	450710.1	3504464	6	197.7	2555	205.1034
5	450710.1	3504464	6	197.7	2920	204.57
5	450710.1	3504464	6	197.7	3285	204.1128
5	450710.1	3504464	6	197.7	3650	204.951
5	450710.1	3504464	6	197.7	4015	204.55
5	450710.1	3504464	6	197.7	4380	204.2
9	454404.4	3469200	10	189.7	365	205.3588
9	454404.4	3469200	10	189.7	730	205.2488
9	454404.4	3469200	10	189.7	1095	205.1288
9	454404.4	3469200	10	189.7	1460	206.1712
9	454404.4	3469200	10	189.7	1825	206.5248
9	454404.4	3469200	10	189.7	2190	205.6134
9	454404.4	3469200	10	189.7	2555	204.3668
9	454404.4	3469200	10	189.7	2920	205.1044
9	454404.4	3469200	10	189.7	3285	205.461
9	454404.4	3469200	10	189.7	3650	205.4092
9	454404.4	3469200	10	189.7	4015	205.3604
9	454404.4	3469200	10	189.7	4380	204.4704

`

Annexure B:

Data analysis of discharge and rainfall

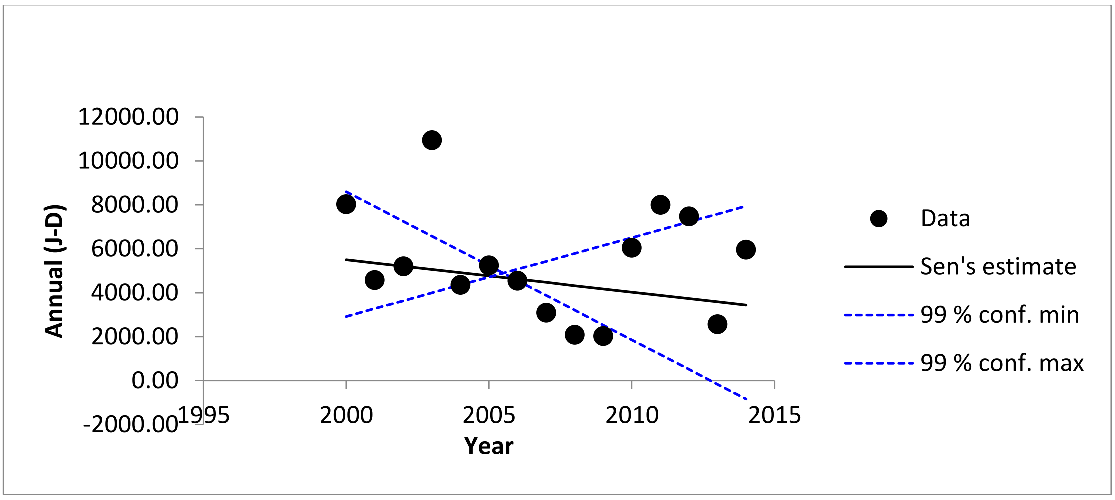

Figure B.1: Annual average daily discharge in cusec trend (2003-2014)

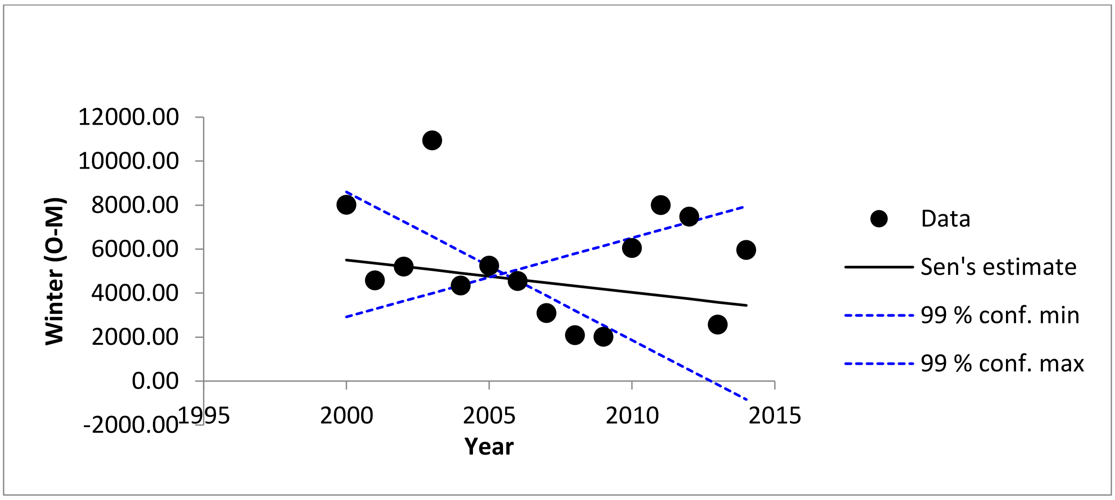

Figure B.2: Winter average daily discharge in cusec trend (2003-2014)

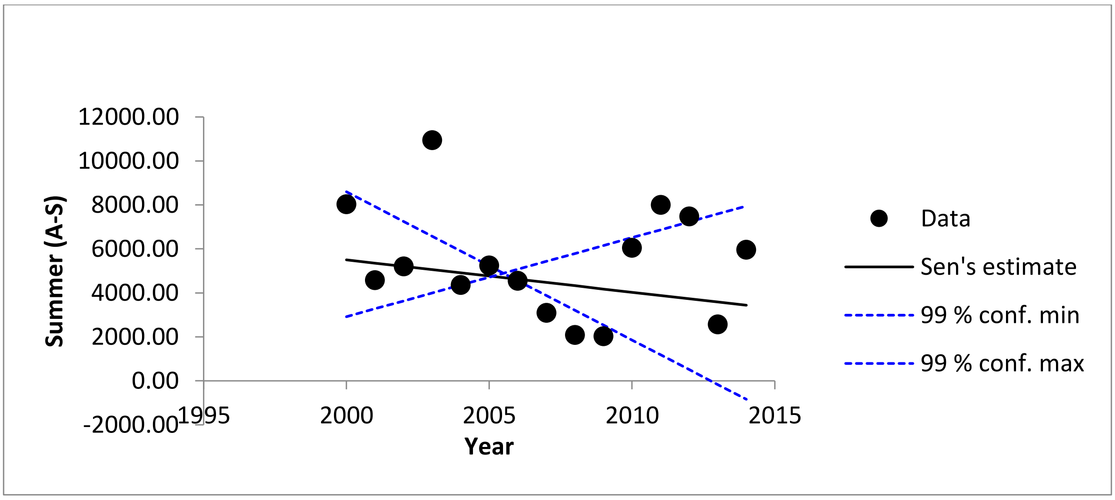

Figure B.3: Summer average daily discharge in cusec trend (2003-2014)

`

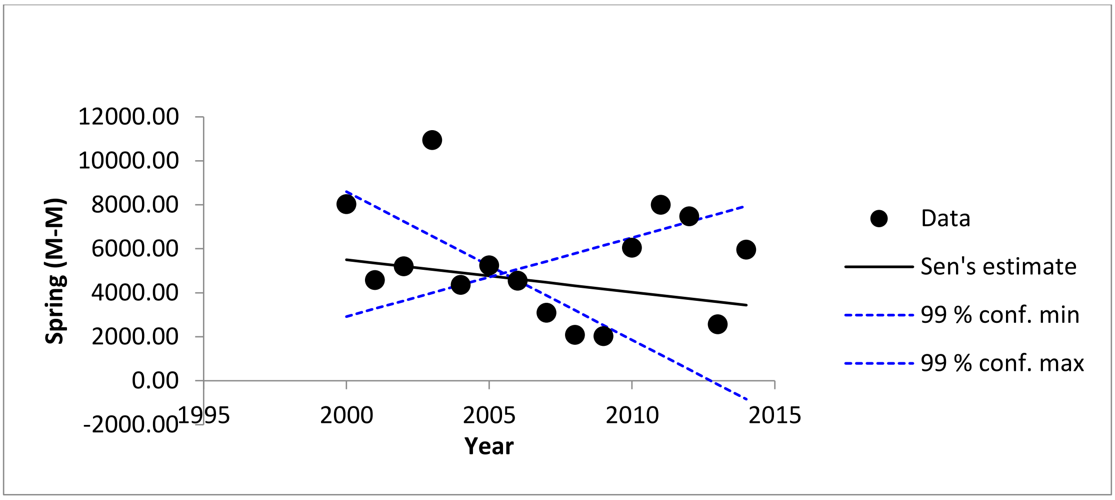

Figure B.4: Spring average daily discharge in cusec trend (2003-2014)

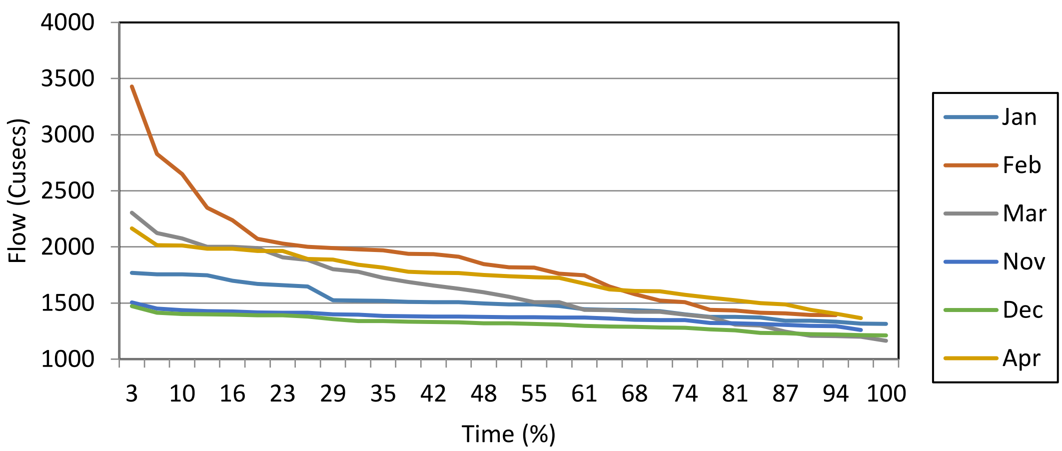

Figure B.5: Flow duration curve November - April (2003-2014)

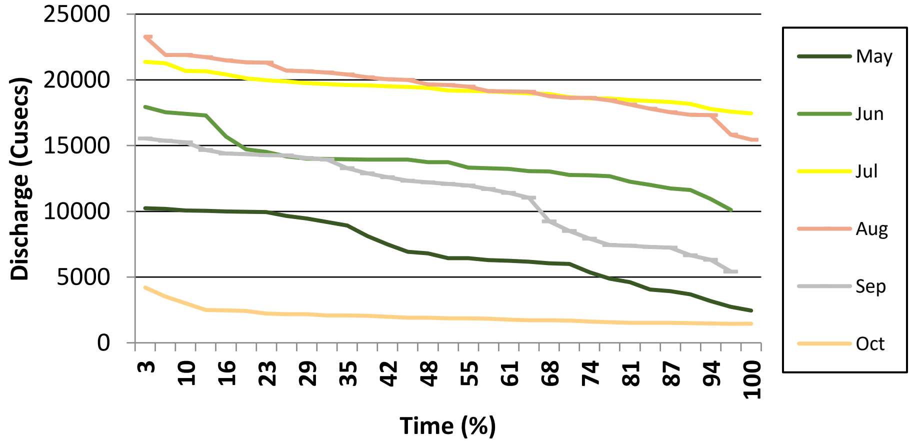

Figure B.6: Flow duration curve May - October (2003-2014)

`

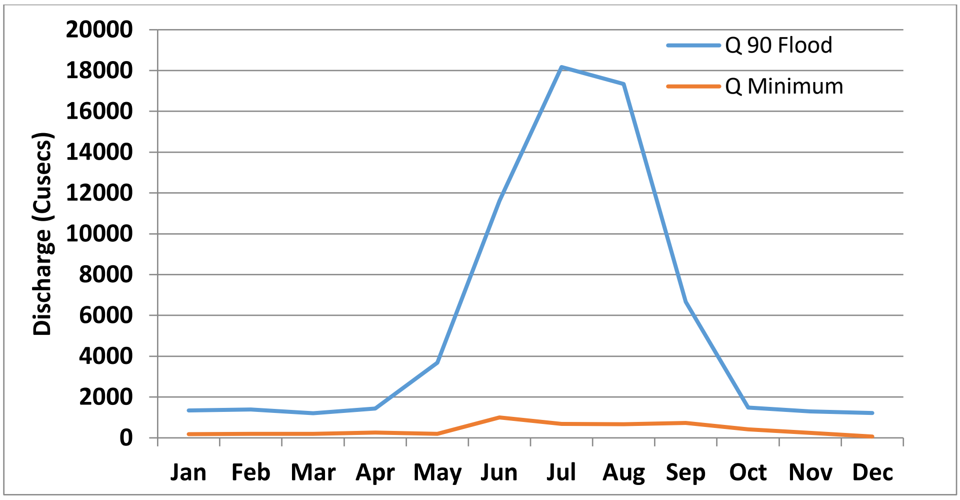

Figure B.7: Minimum and Q90 flood in river Ravi discharge in cusec (2003-2014)

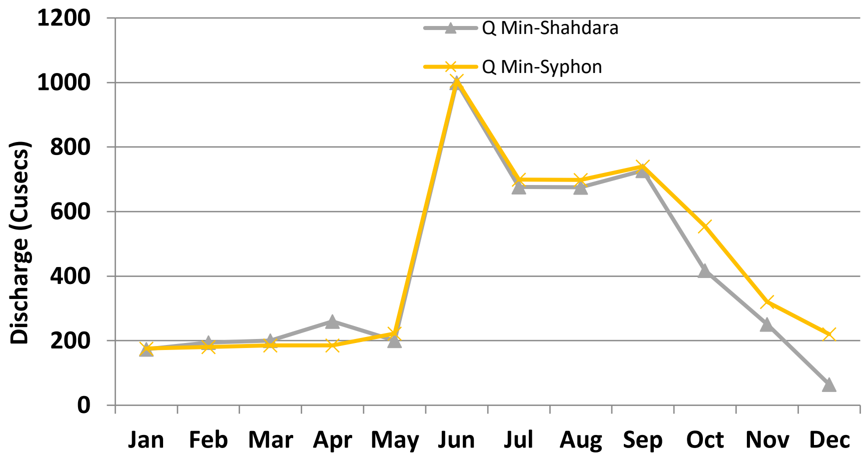

Figure B.8: Minimum flow in river Ravi discharge in cusec (2003-2014)

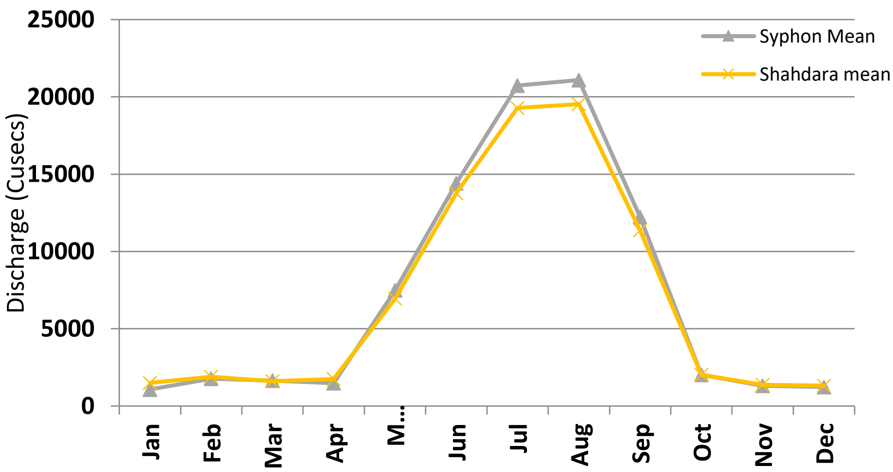

Figure B.8: Mean flow in river Ravi discharge in cusec (2003-2014)

`

Annexure C

River x-section from Indian Boarder to Shahdra

`

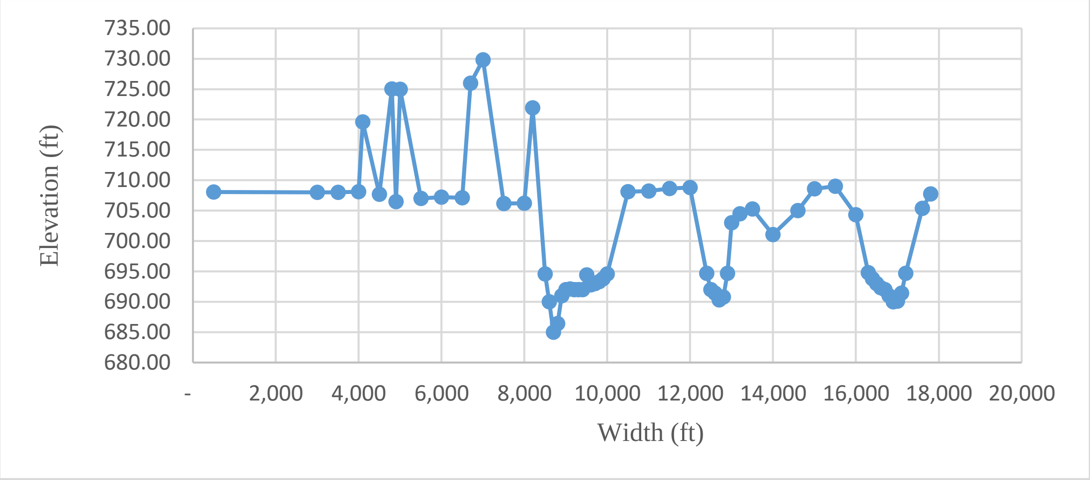

Figure C.1: Ravi Section at RD 81500

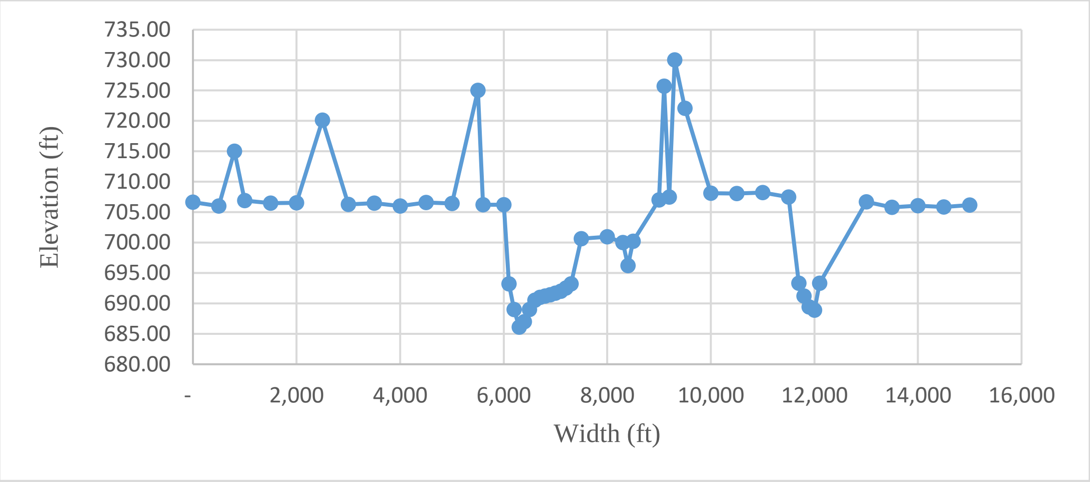

Figure C.2: Ravi Section at RD 79000

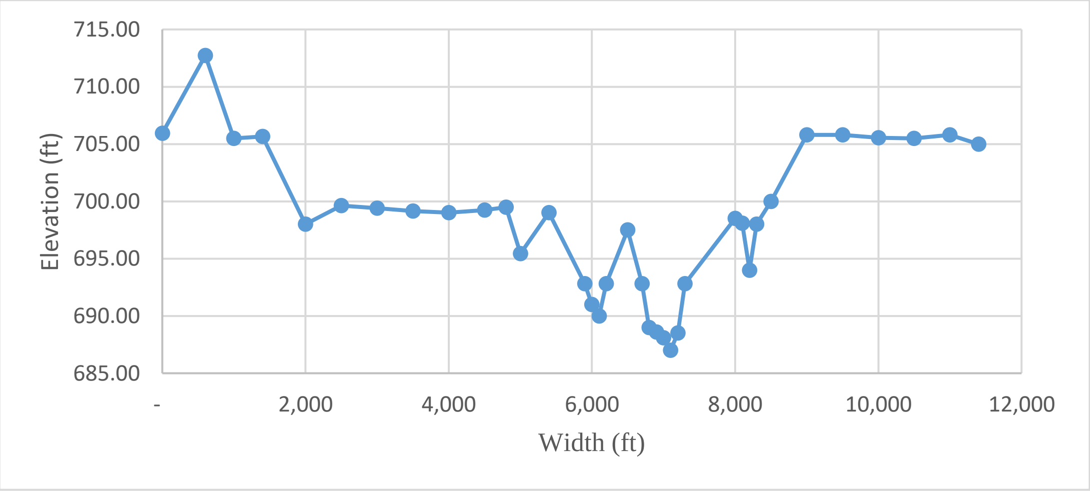

Figure C.3: Ravi Section at RD 77000

`

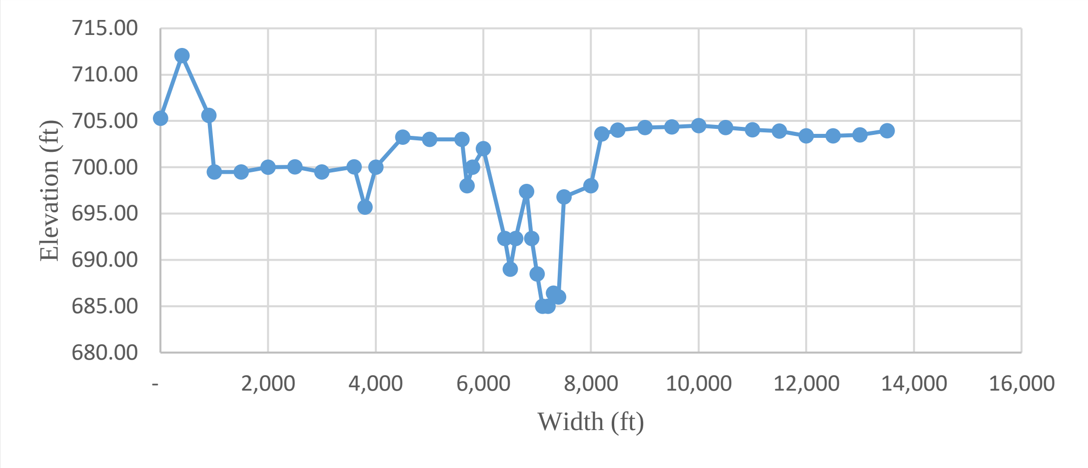

Figure C.4: Ravi Section at RD 75000

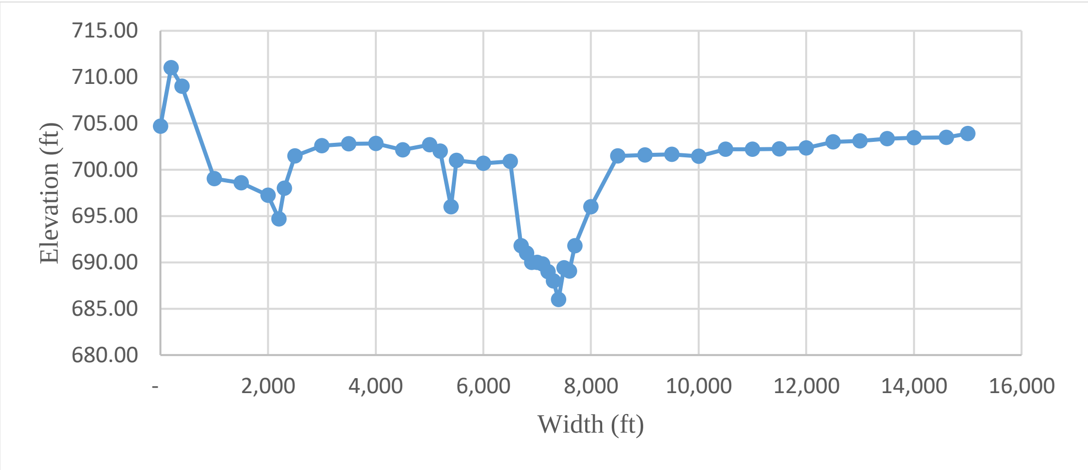

Figure C.5: Ravi Section at RD 73000

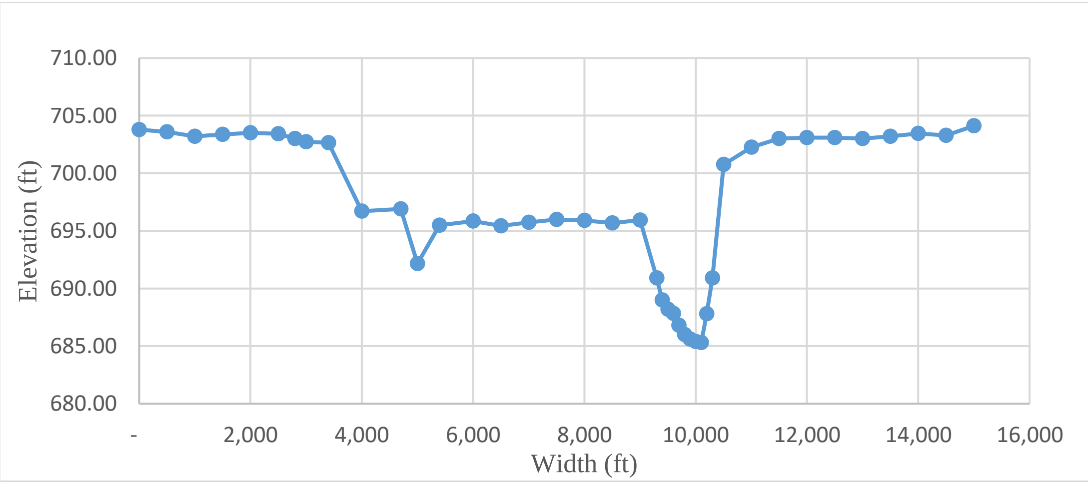

Figure C.6: Ravi Section at RD 67000

`

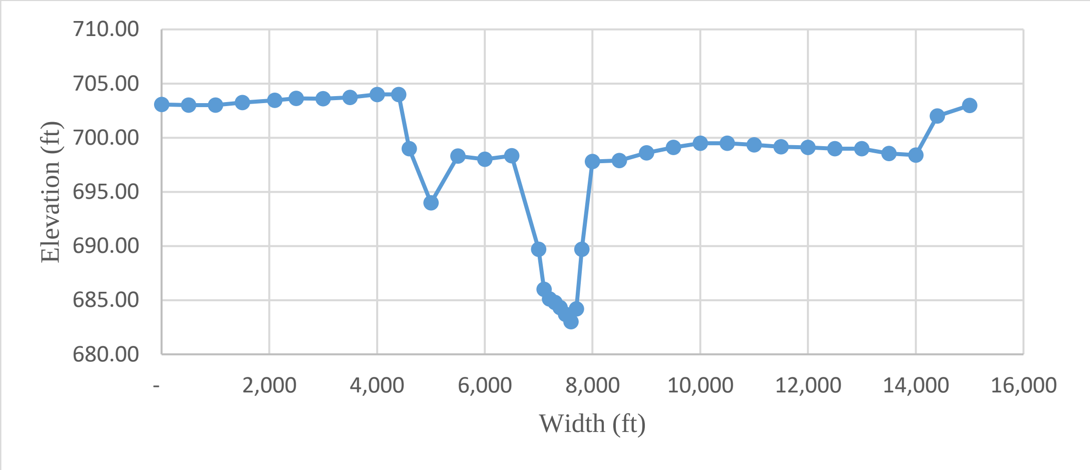

Figure C.7: Ravi Section at RD 64000

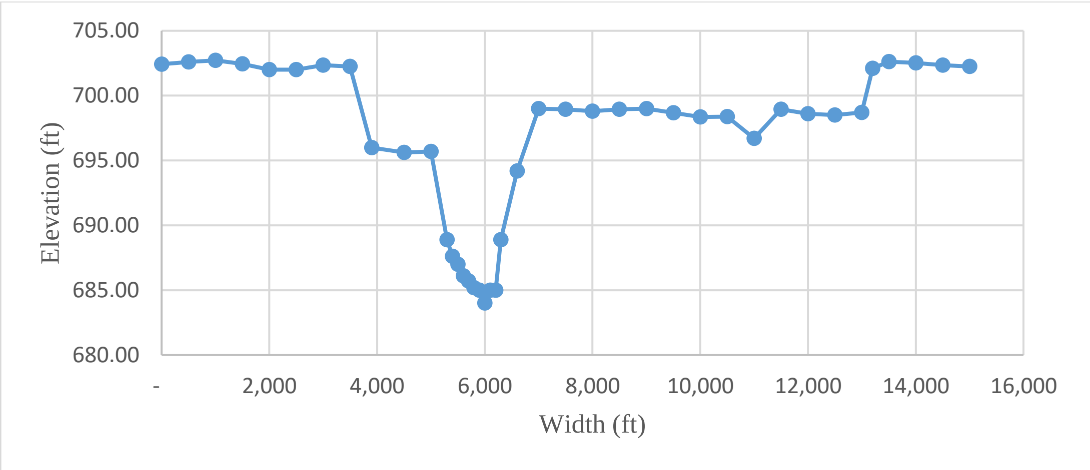

Figure C.8: Ravi Section at RD 61000

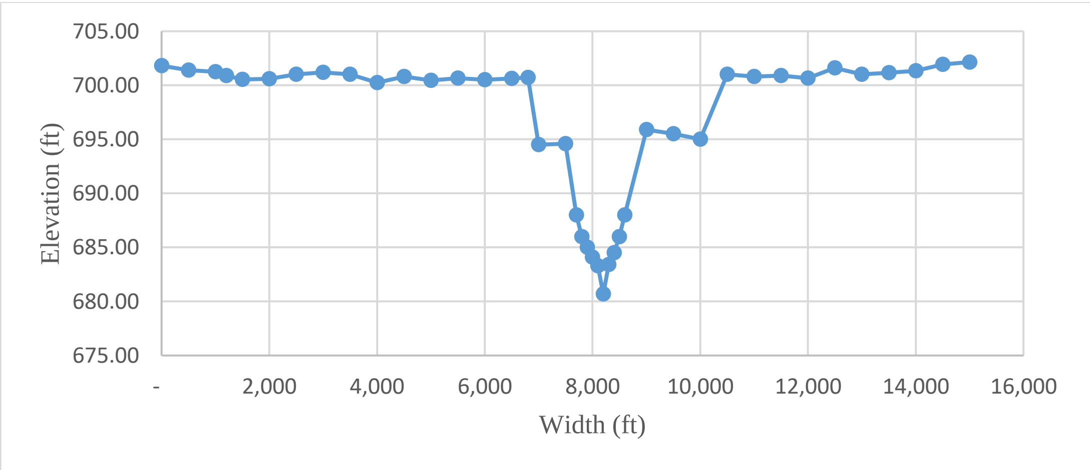

Figure C.9: Ravi Section at RD 55000

`

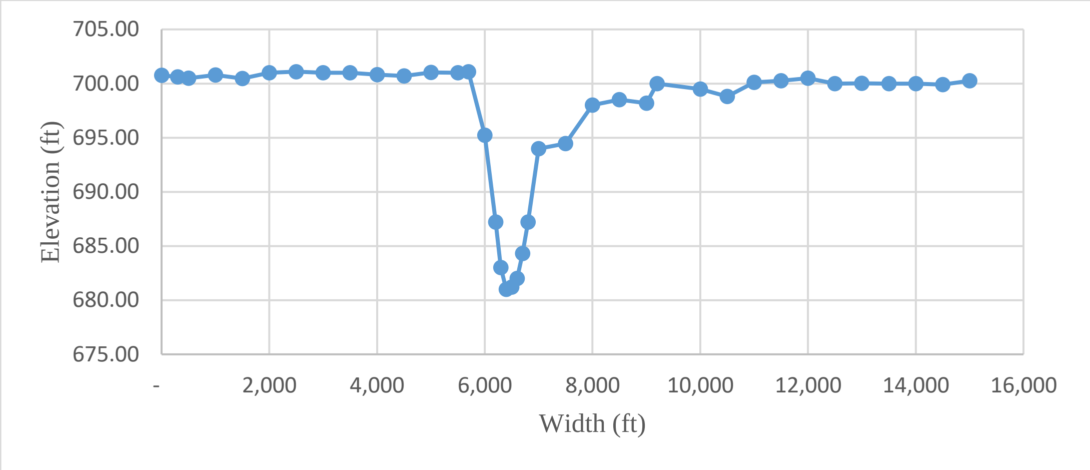

Figure C.10: Ravi Section at RD 52000

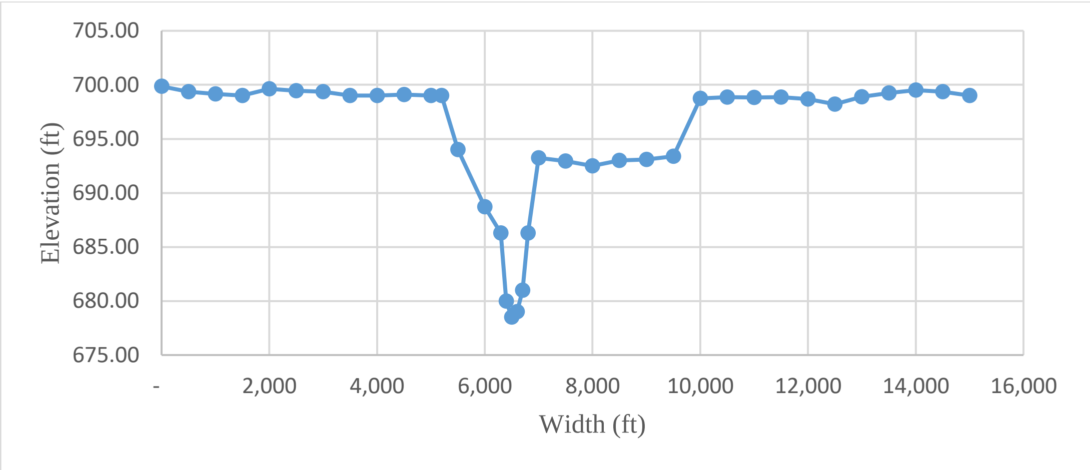

Figure C.11: Ravi section at RD 49000

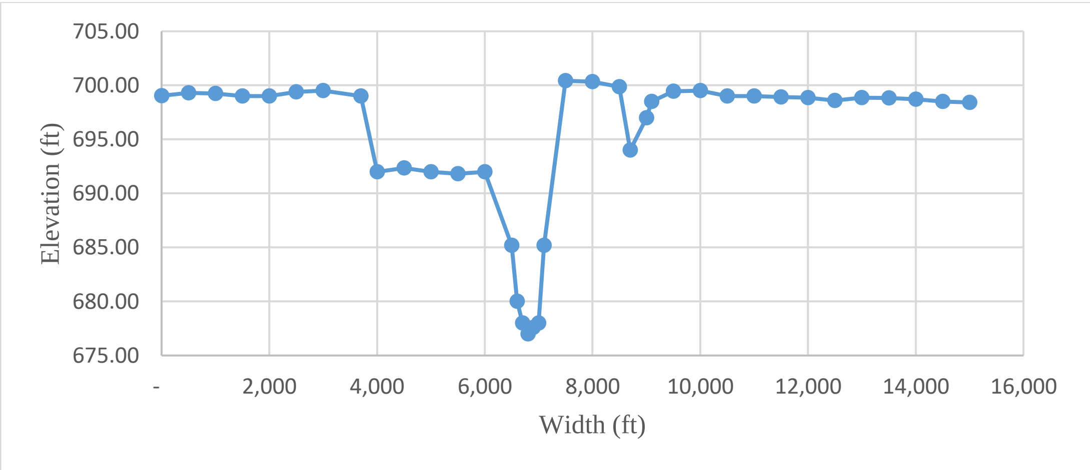

Figure C.12: Ravi Section at RD 46000

`

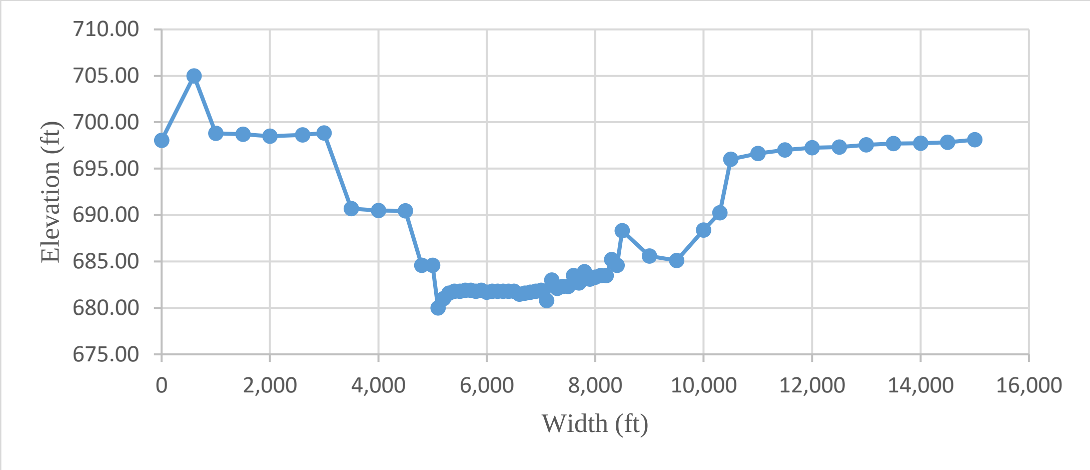

Figure C.13: Ravi Section at RD 42000

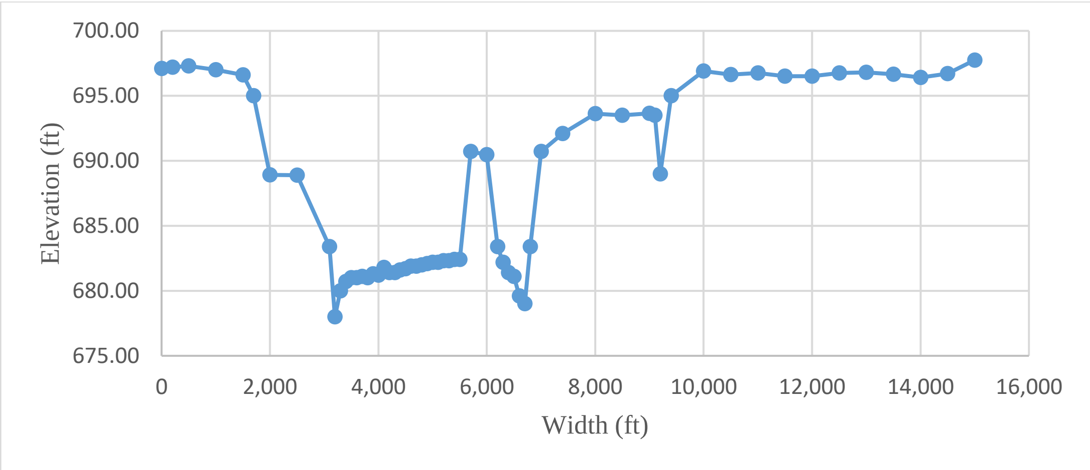

Figure C.14: Ravi Section at RD 39000

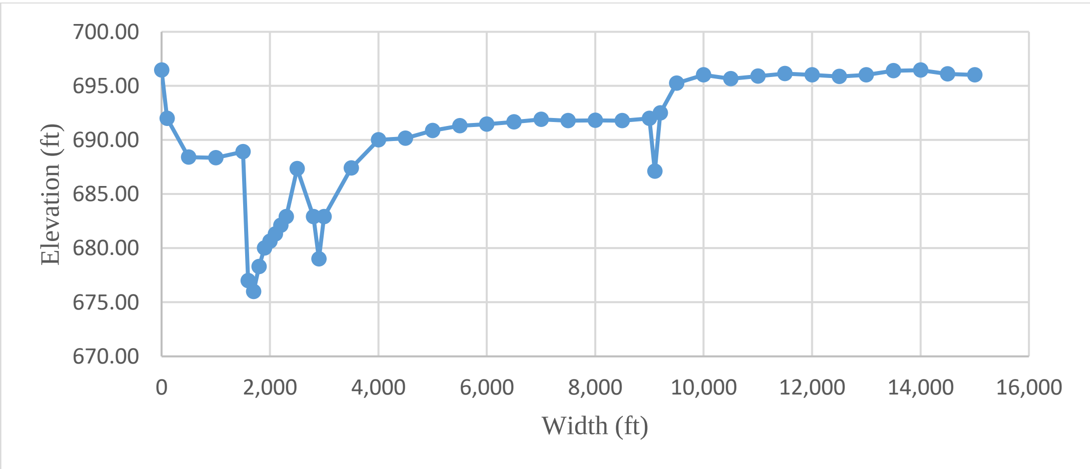

Figure C.15: Ravi Section at RD 37000

`

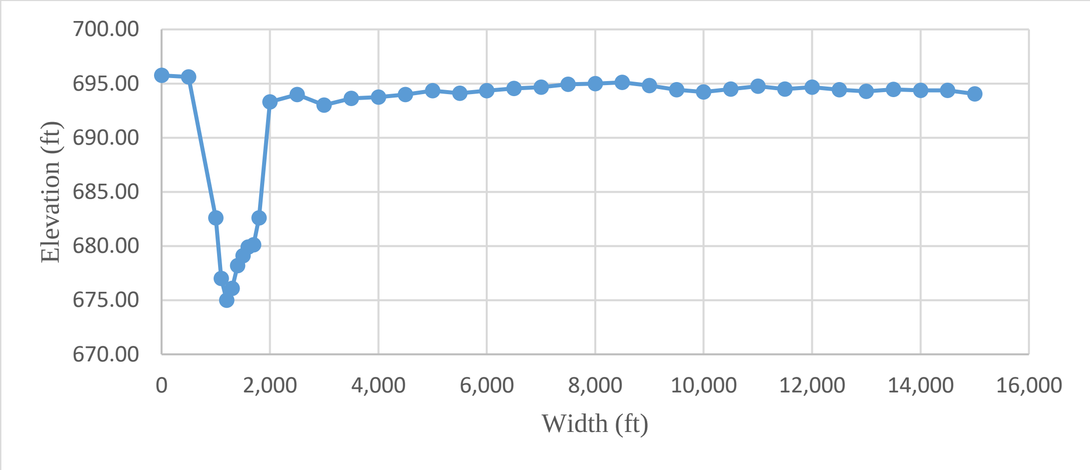

Figure C.16: Ravi Section at RD 35000

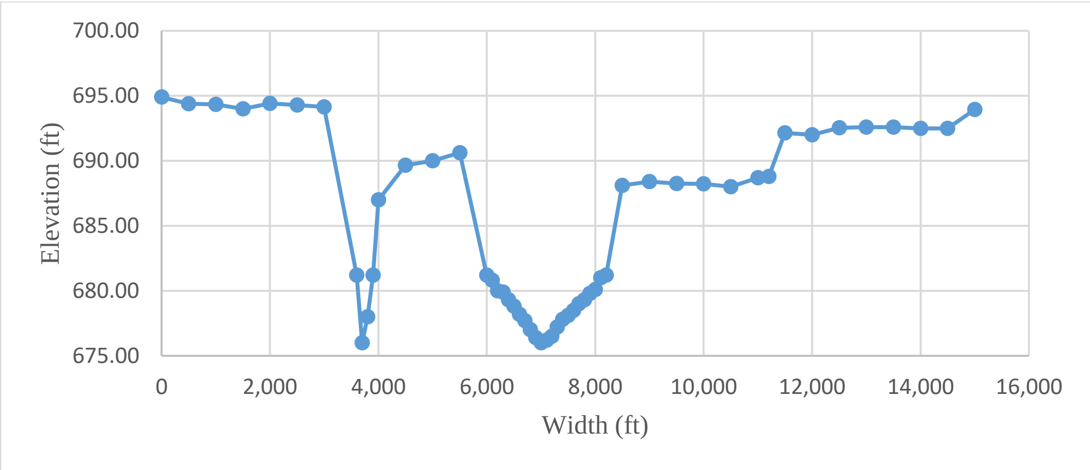

Figure C.17: Ravi Section at RD 31000

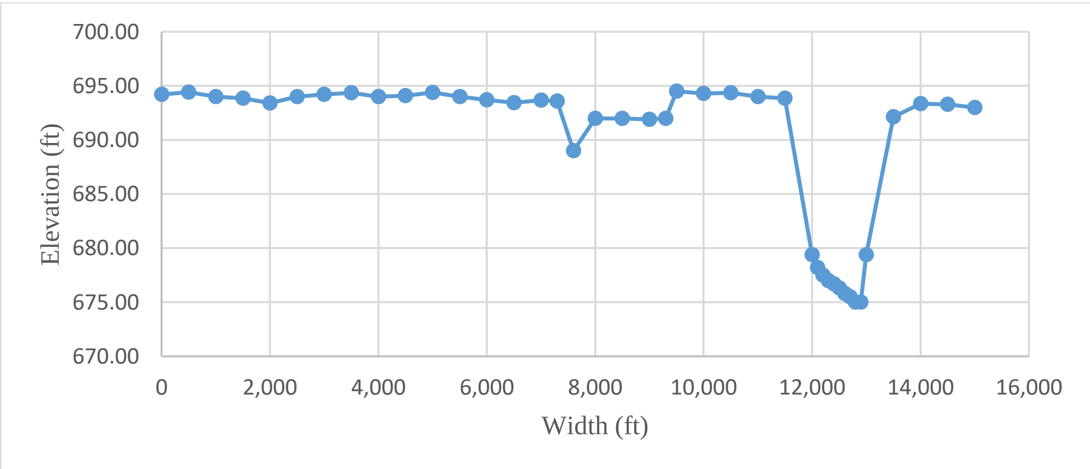

Figure C.18: Ravi Section at RD 28000

`

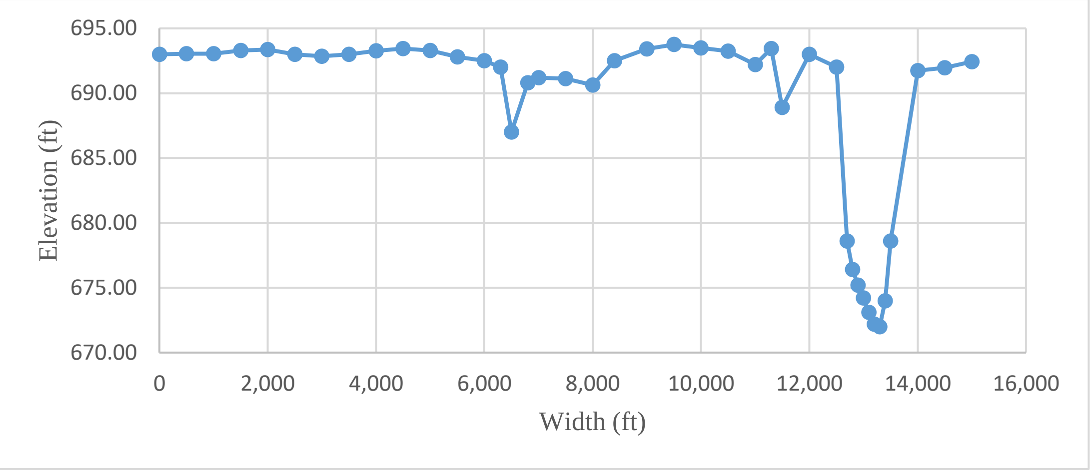

Figure C.19: Ravi Section at RD 25000

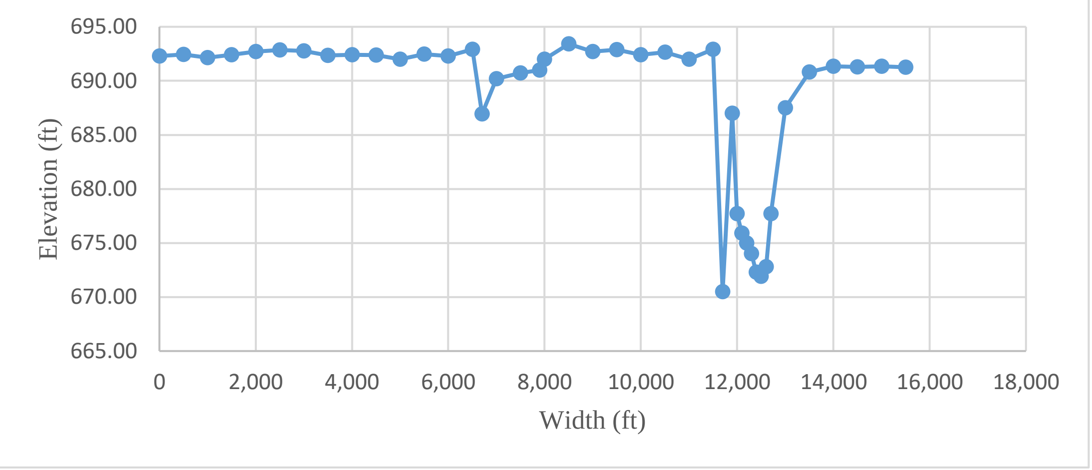

Figure C.20: Ravi Section at RD 22000

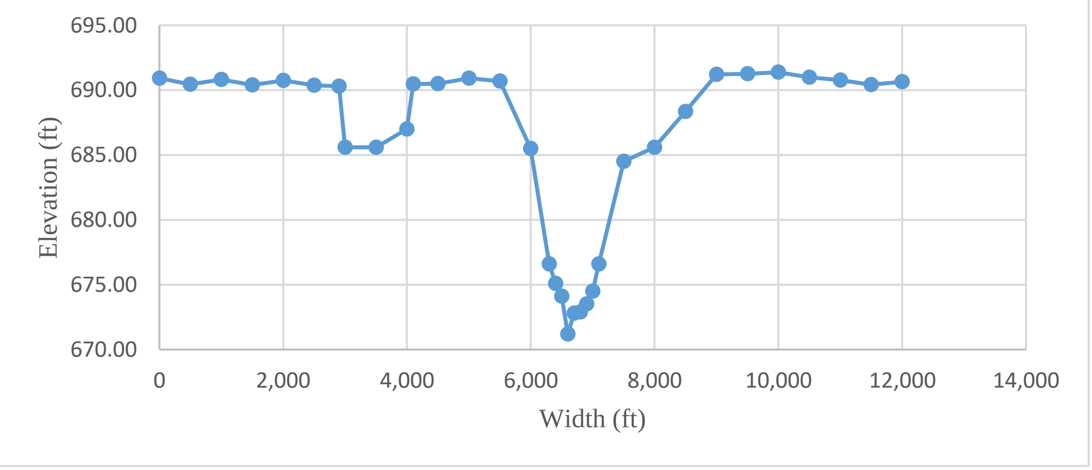

Figure C.21: Ravi Section at RD 16000

`

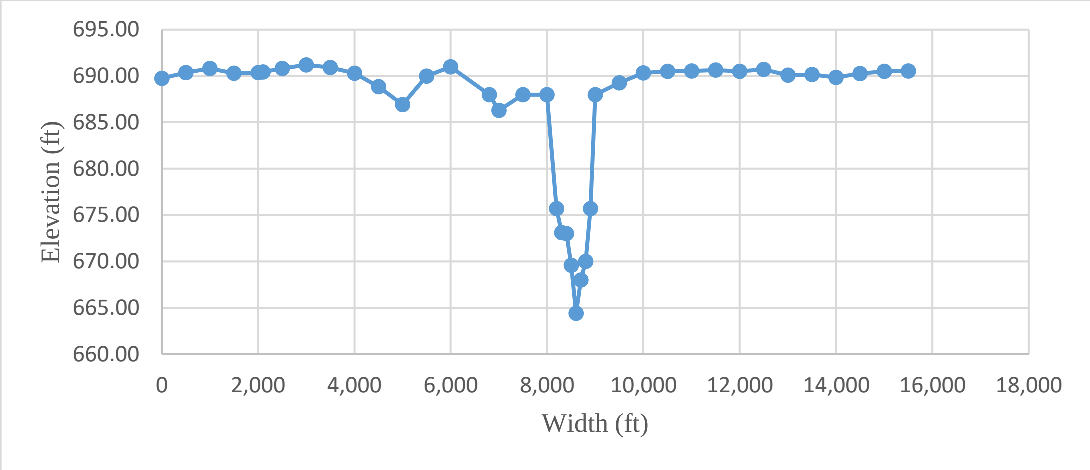

Figure C.22: Ravi Section at RD 13000

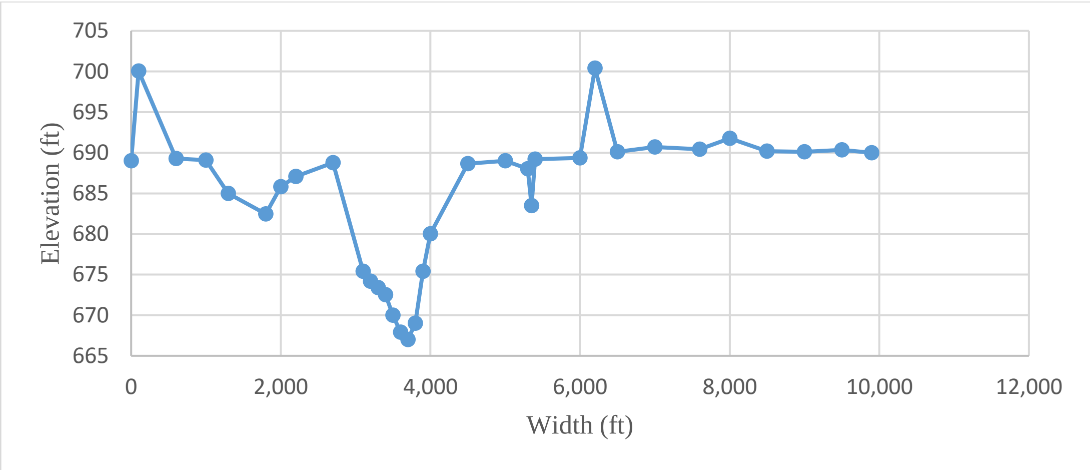

Figure C.23: Ravi Section at RD 7000

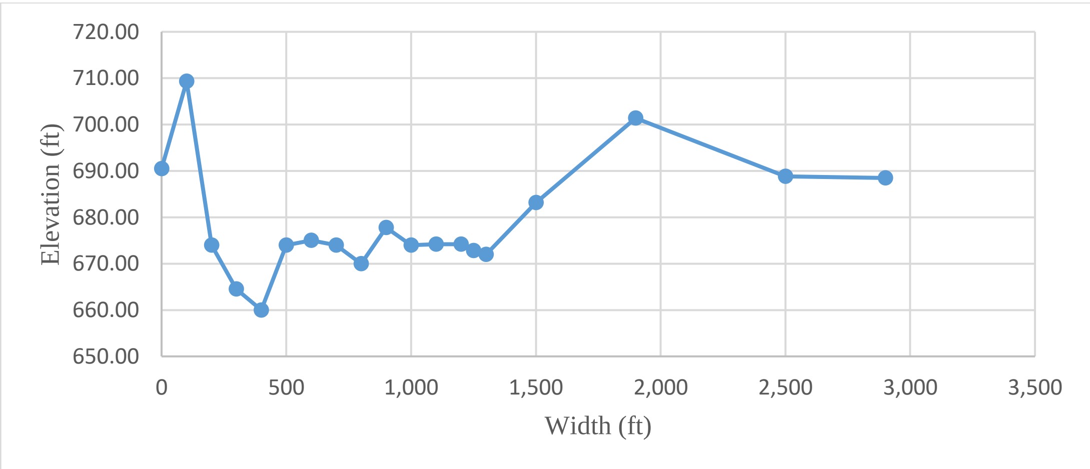

Figure C.24: Ravi Section at RD 500

`

Annexure D

River Section Shahdra to head Balloki

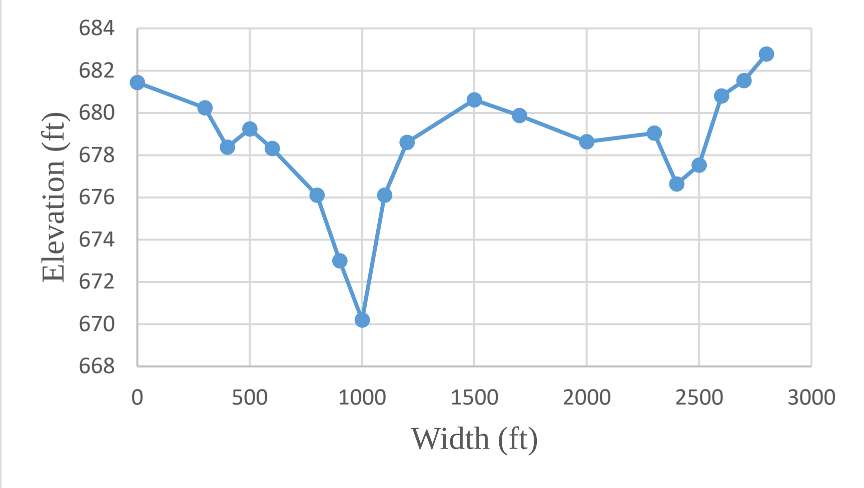

Figure D.1: Ravi Section at RD 4000

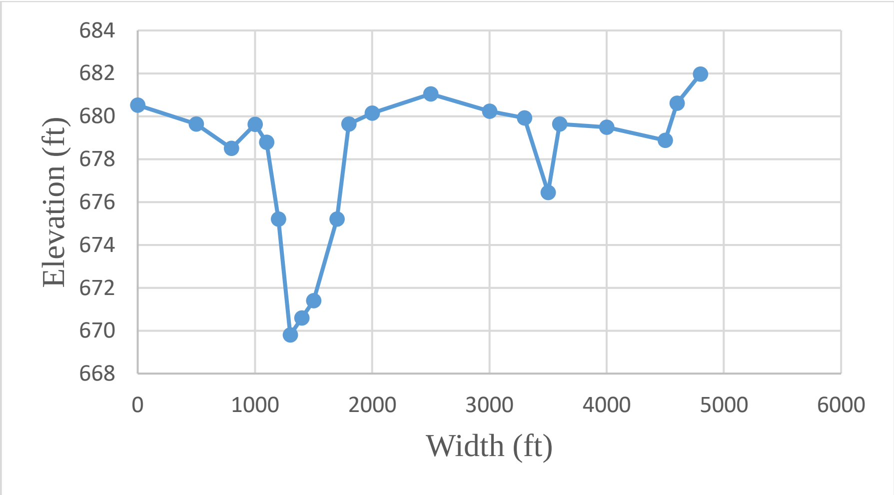

Figure D.2: Ravi Section at RD 8000

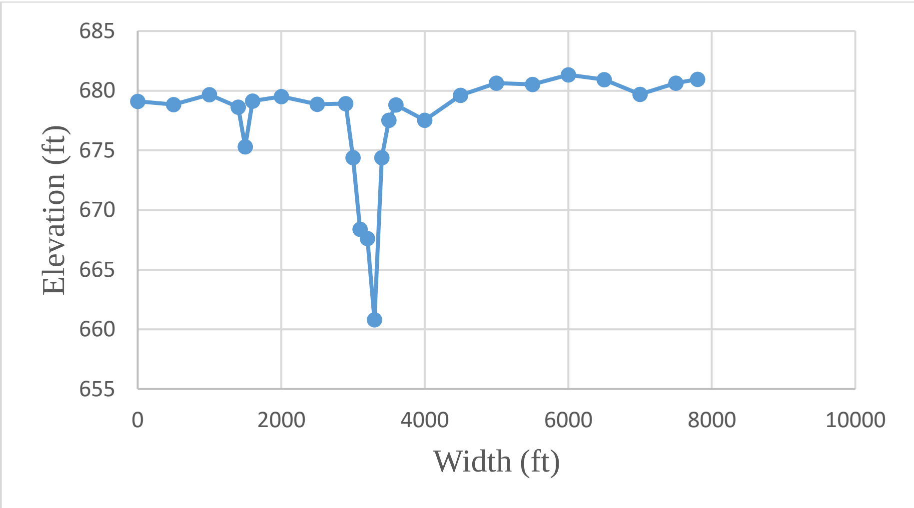

Figure D.3: Ravi Section at RD 11000

`

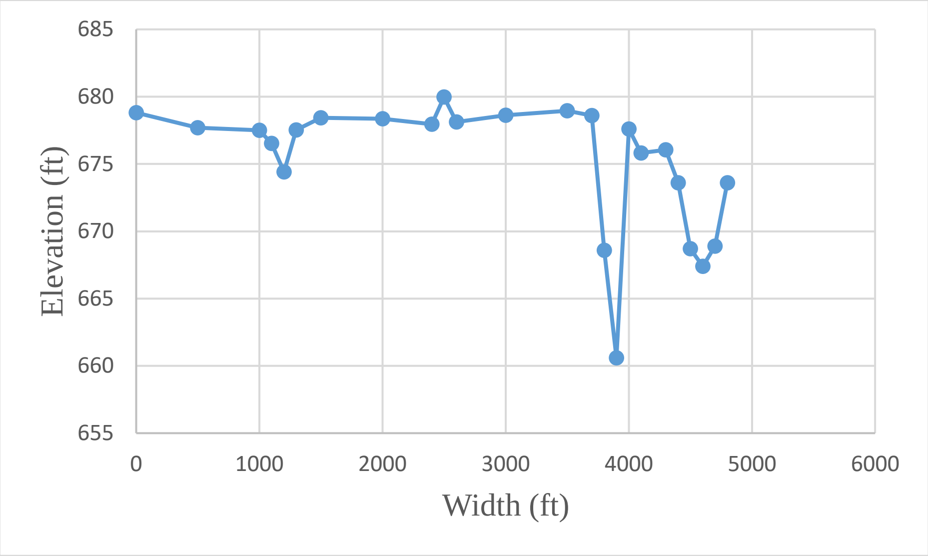

Figure D.4: Ravi Section at RD 14000

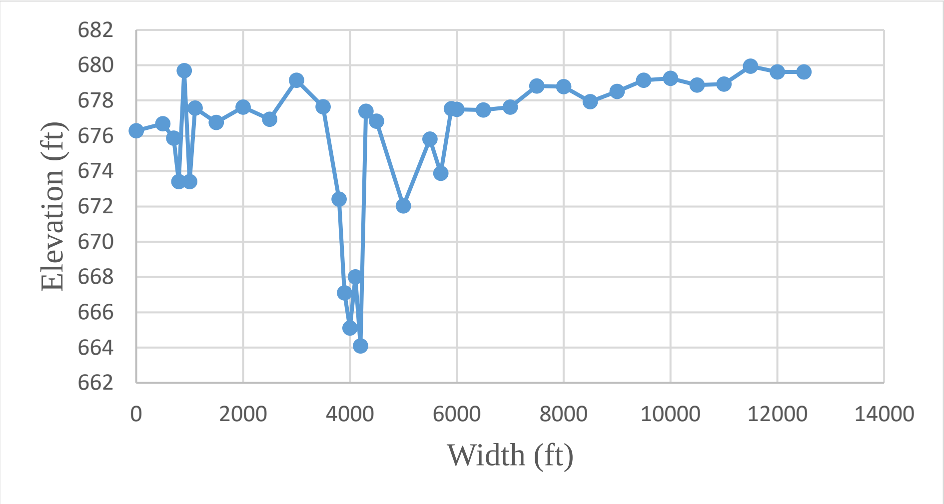

Figure D.5: Ravi Section at RD 21000

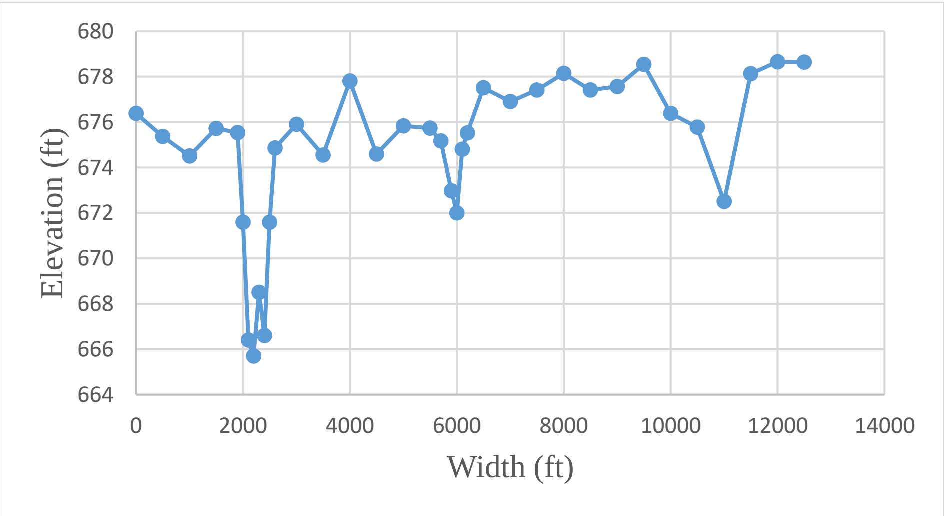

Figure D.6: Ravi Section at RD 24000

`

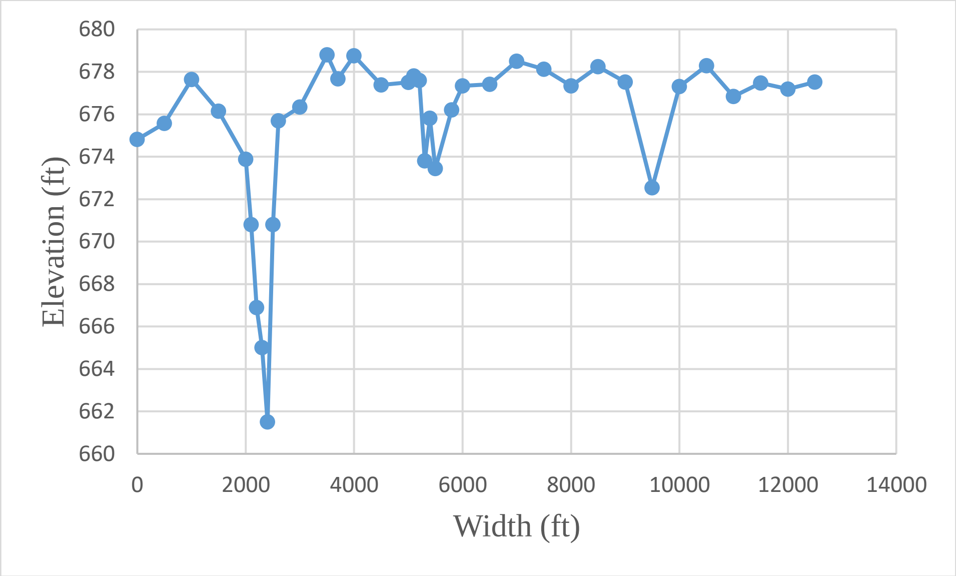

Figure D.7: Ravi Section at RD 27000

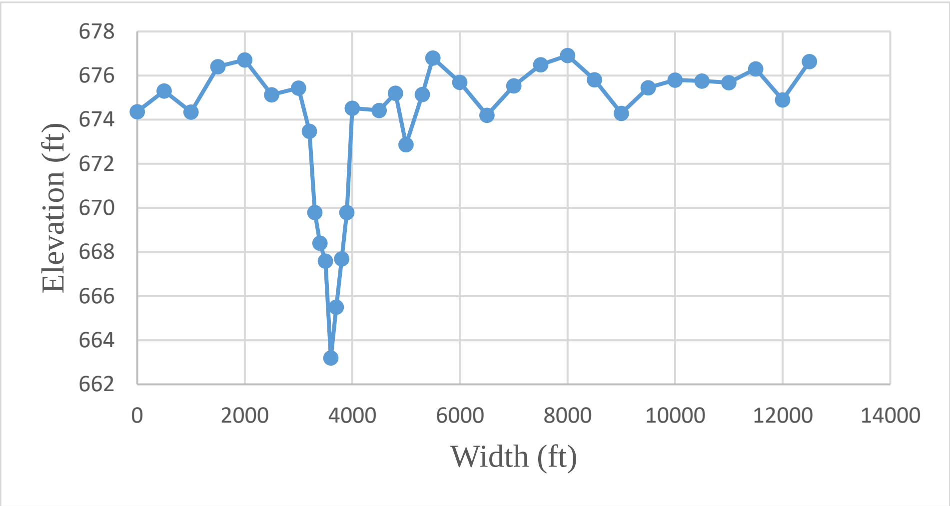

Figure D.8: Ravi Section at RD 30500

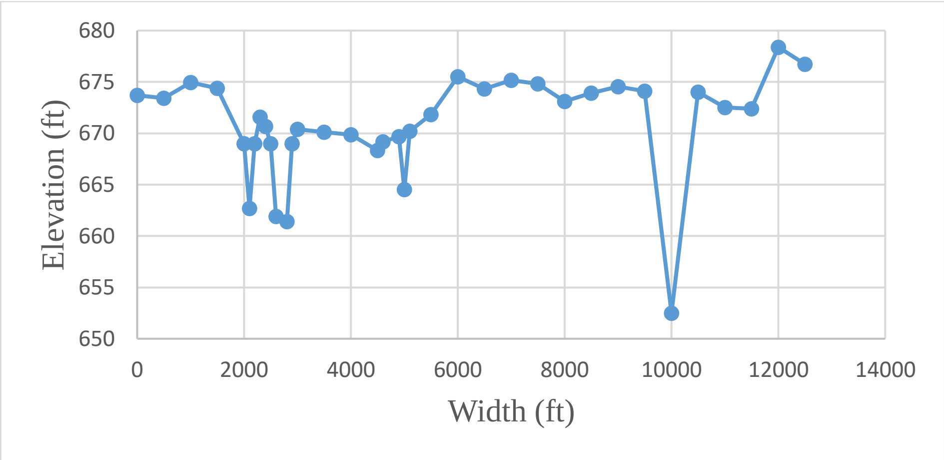

Figure D.9: Ravi Section at RD 33000

`

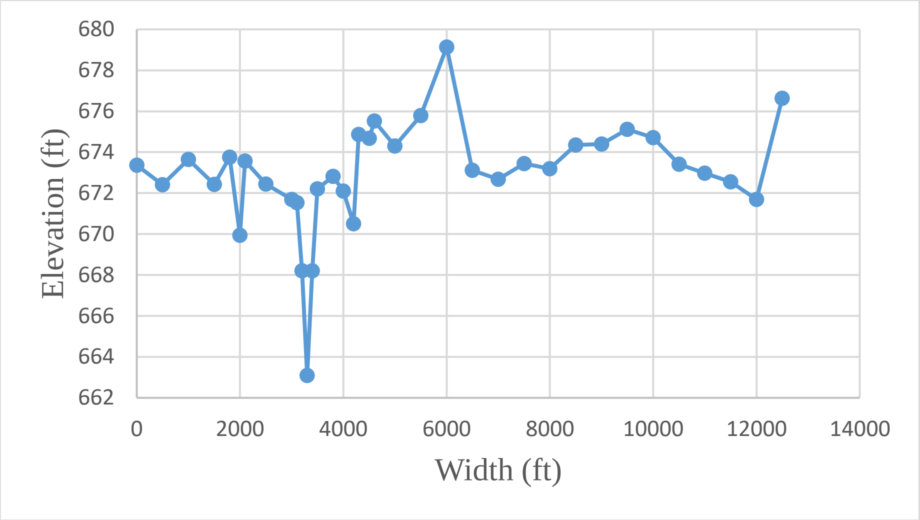

Figure D.10: Ravi Section at RD 36000

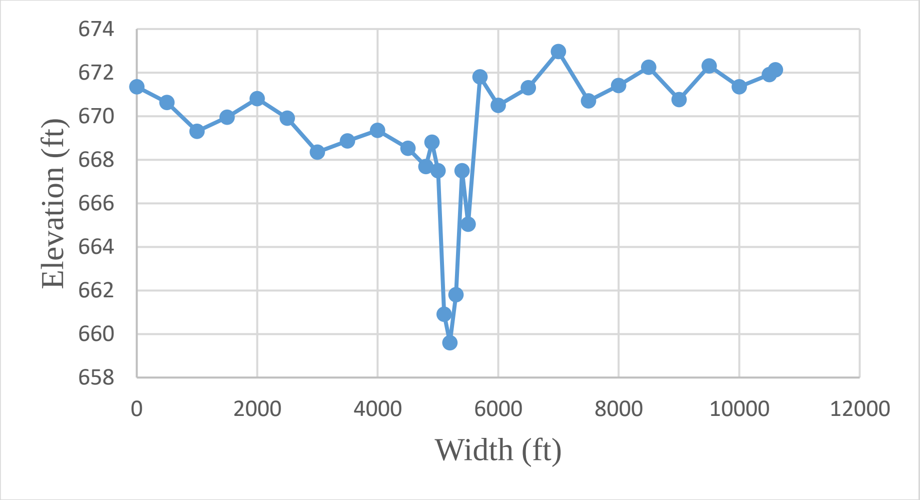

Figure D.11: Ravi Section at RD 39000

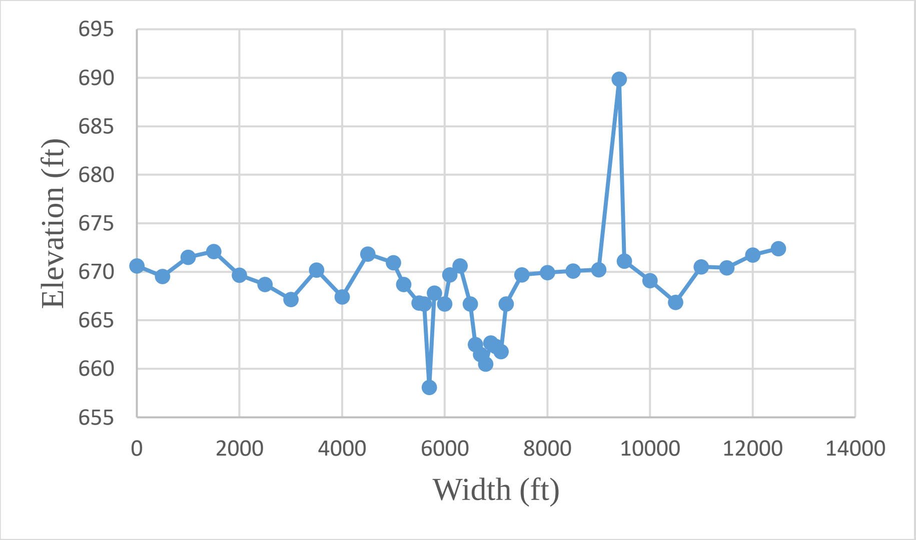

Figure D.12: Ravi Section at RD 41500

`

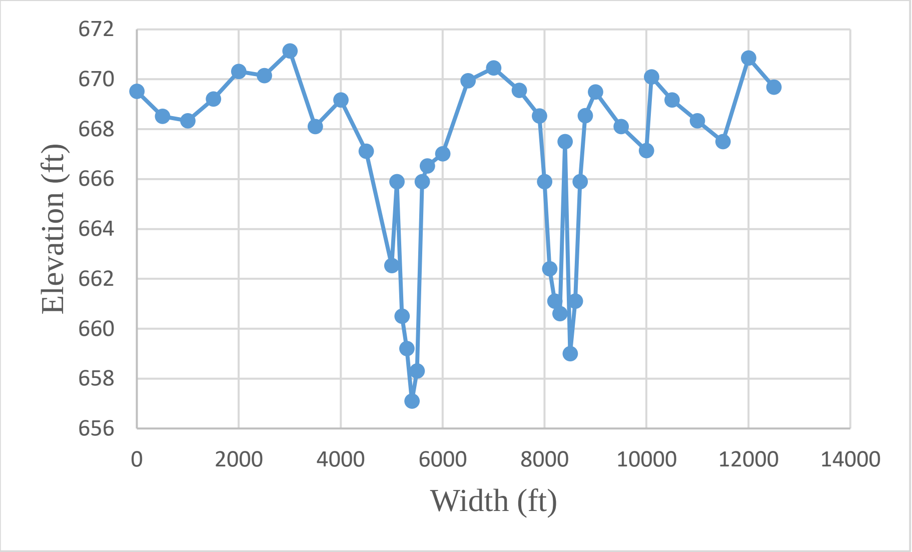

Figure D.13: Ravi Section at RD 44000

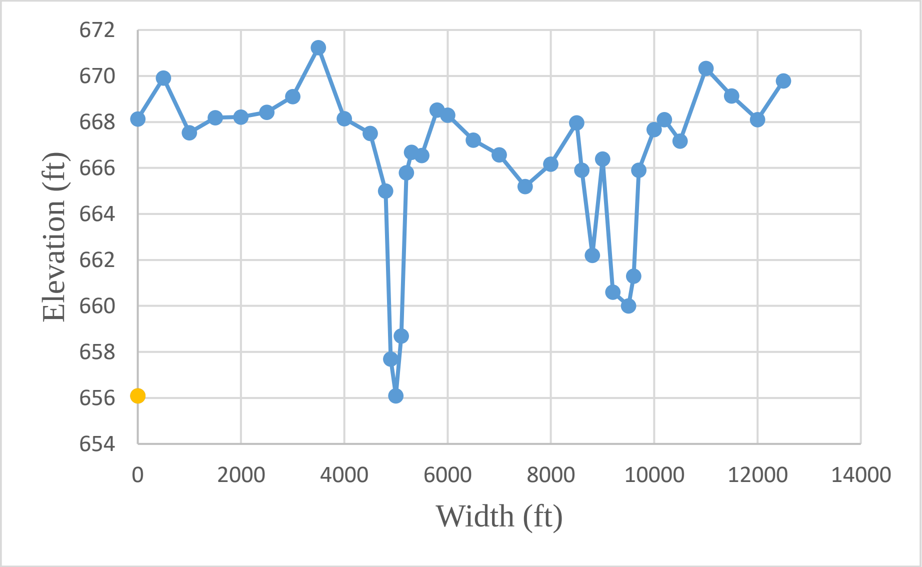

Figure D.14: Ravi Section at RD 47000

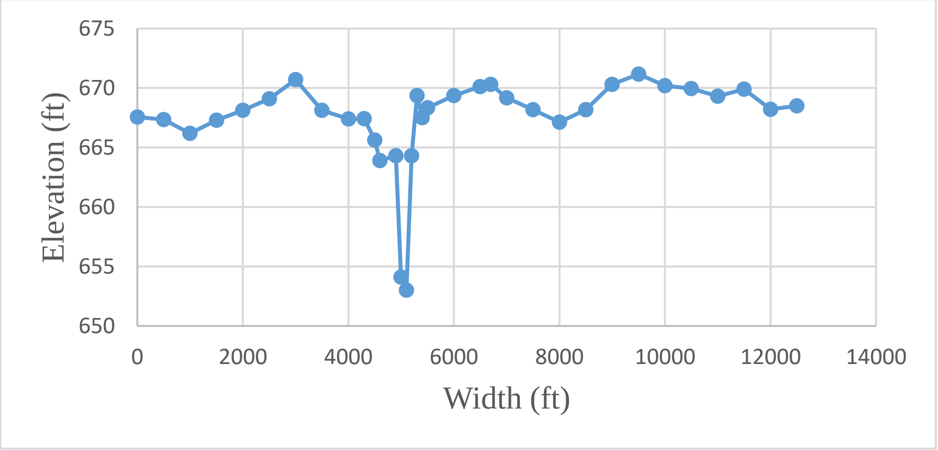

Figure D.15: Ravi Section at RD 50500

`

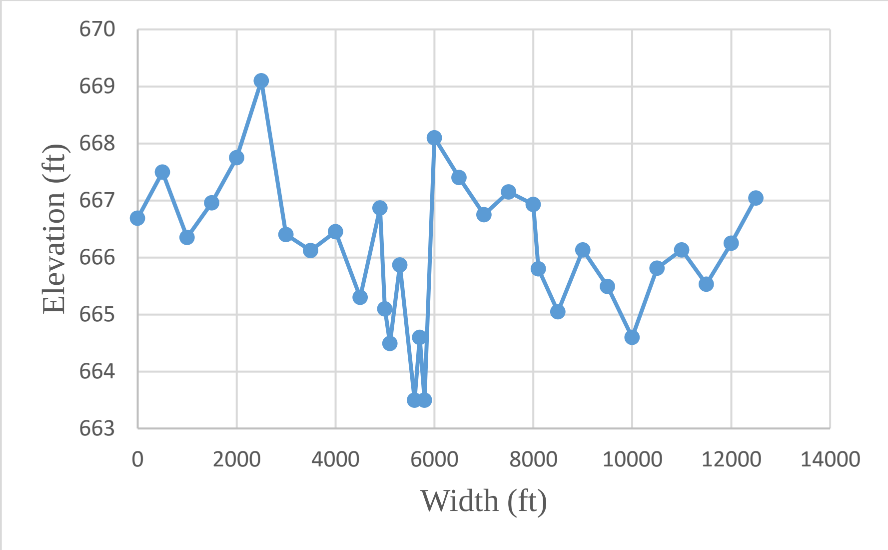

Figure D.16: Ravi Section at RD 53000

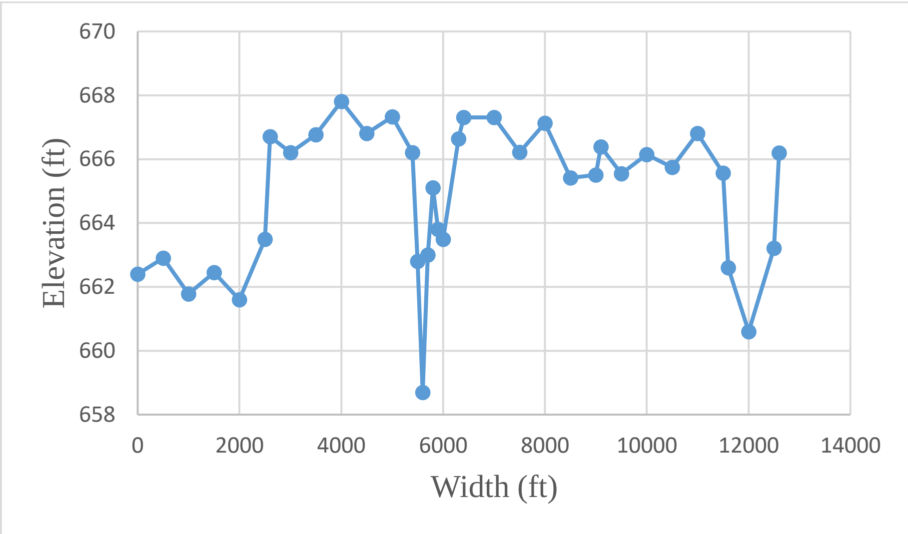

Figure D.17: Ravi Section at RD 55500

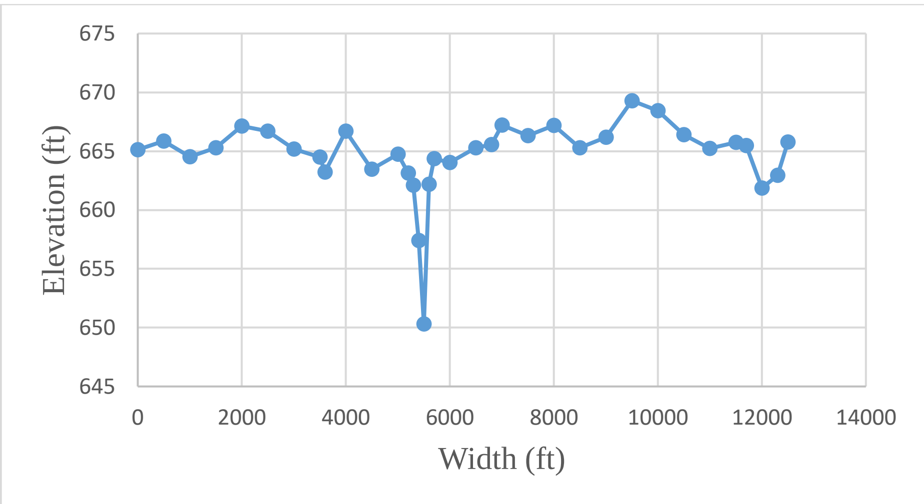

Figure D.18: Ravi Section at RD 58000

`

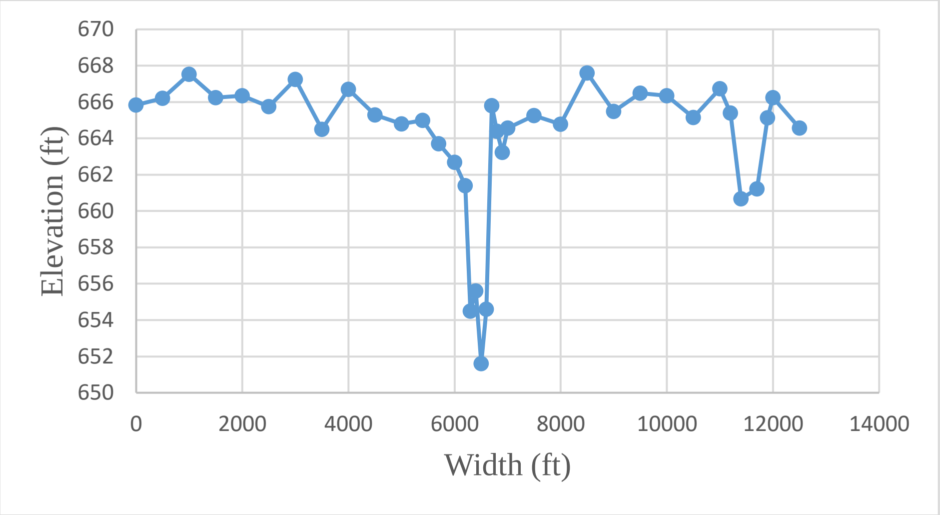

Figure D.19: Ravi Section at RD 60500

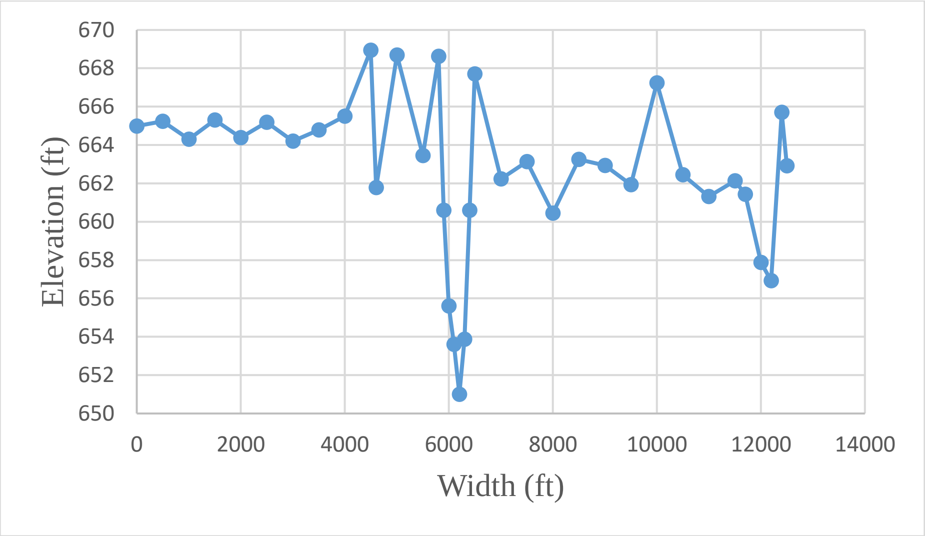

Figure D.20: Ravi Section at RD 63000

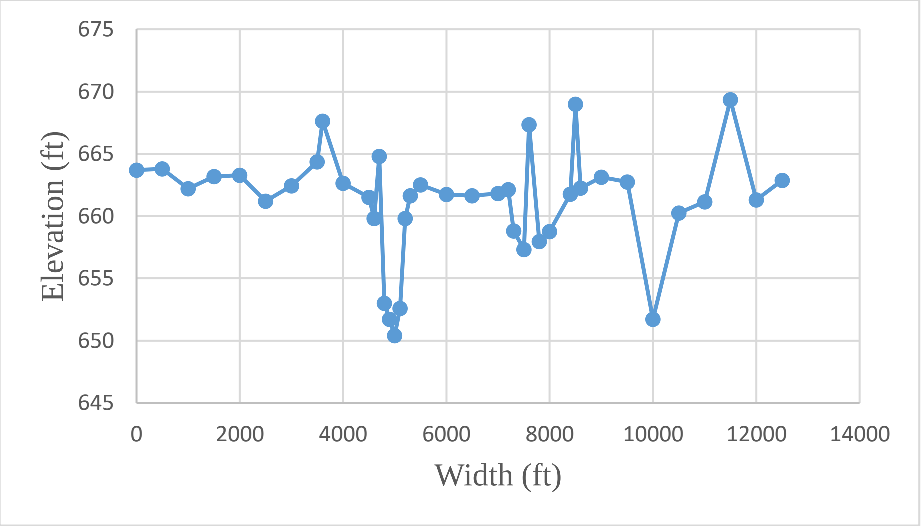

Figure D.21: Ravi Section at RD 66000

`

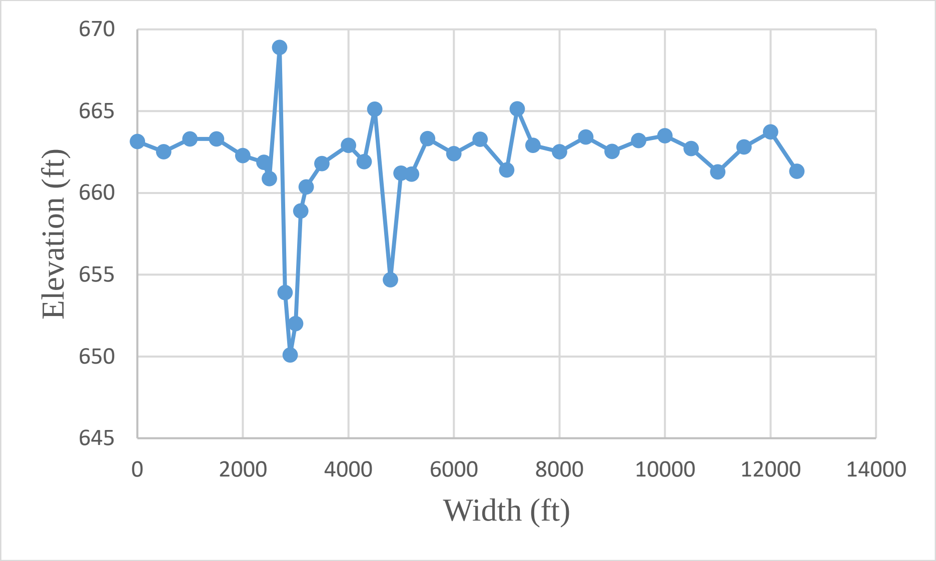

Figure D.22: Ravi Section at RD 69000

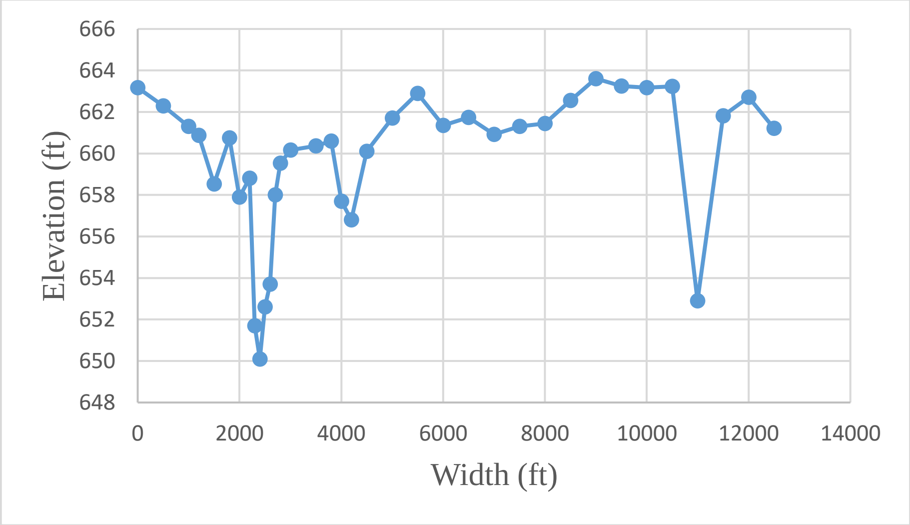

Figure D.23: Ravi Section at RD 72000

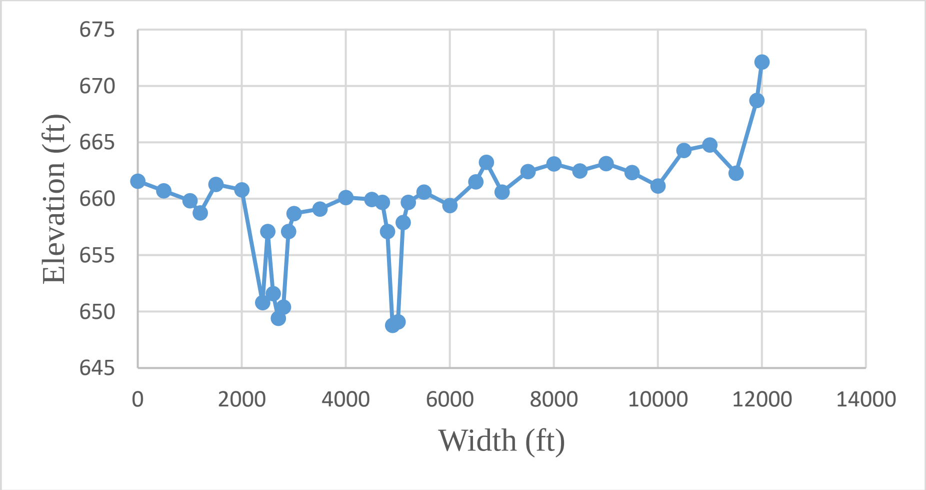

Figure D.24: Ravi Section at RD 75000

`

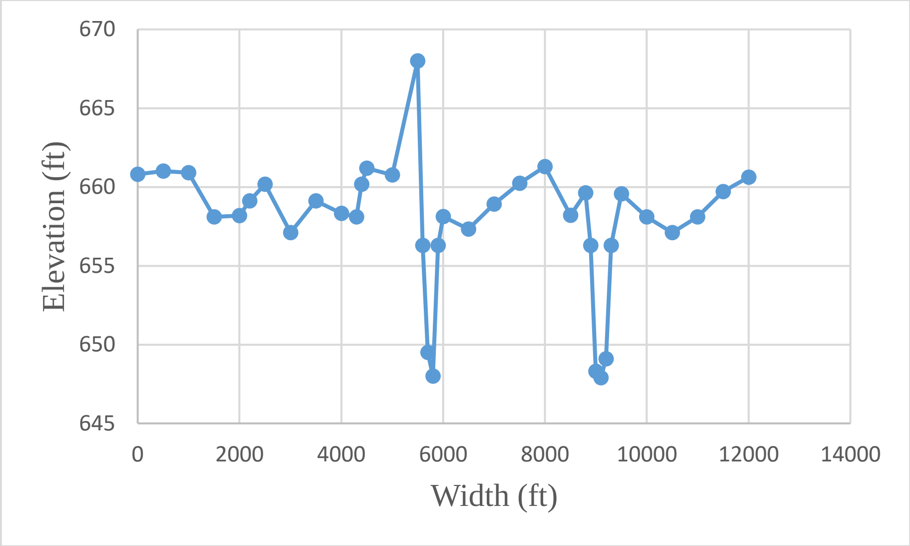

Figure D.25: Ravi Section at RD80500

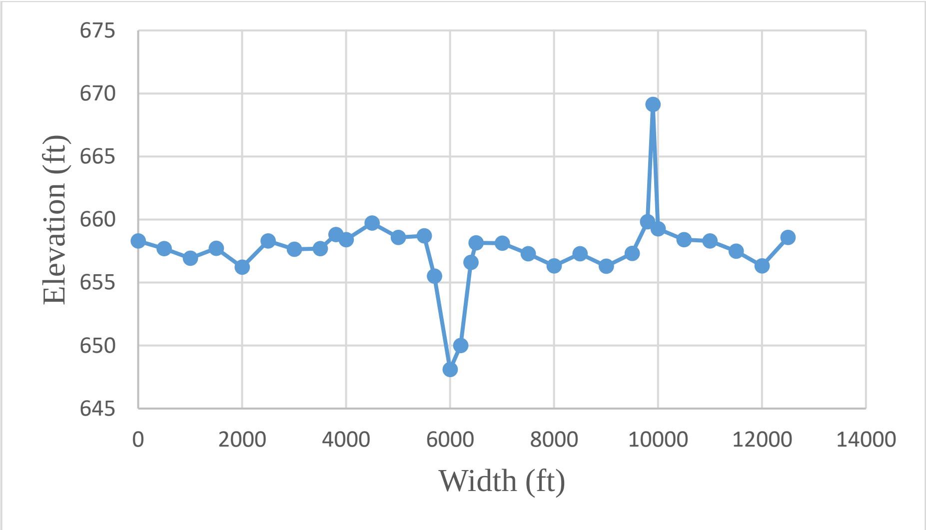

Figure D.26: Ravi Section at RD 83000

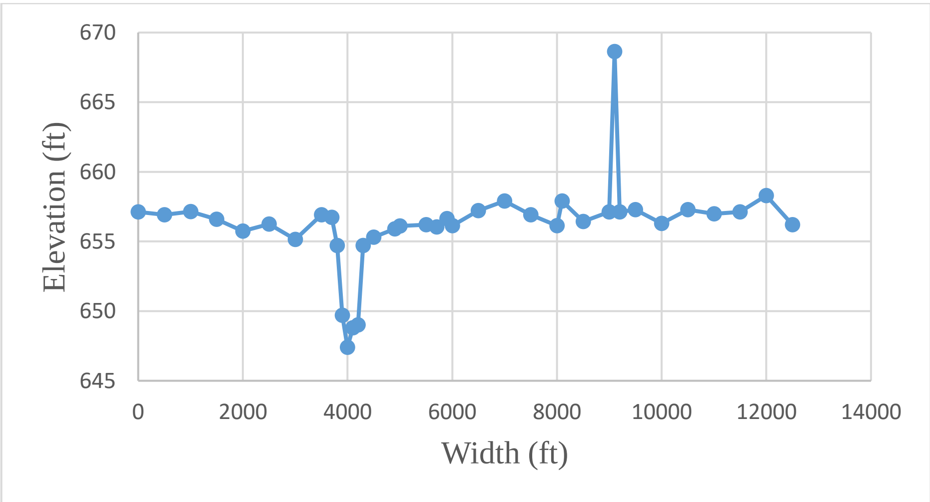

Figure D.27: Ravi Section at RD 86000

`

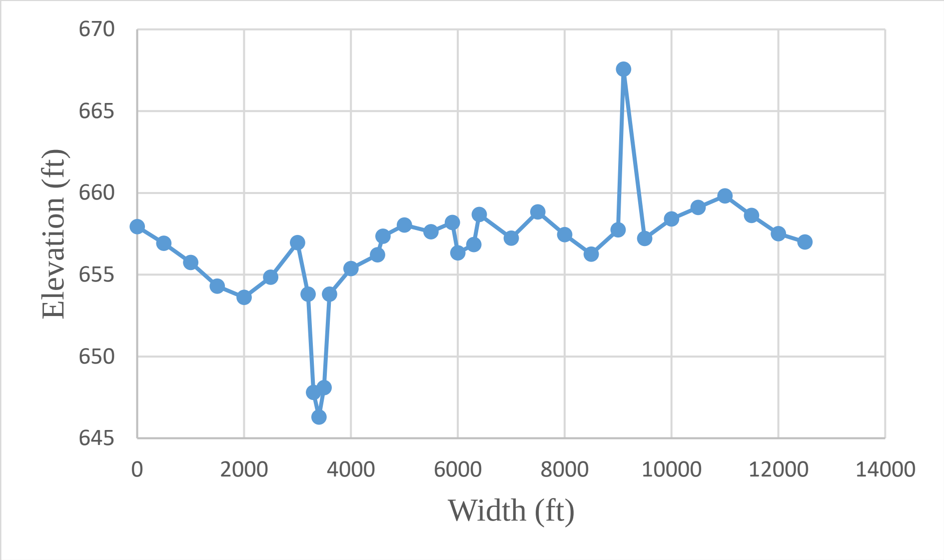

Figure D.28: Ravi Section at RD 89000

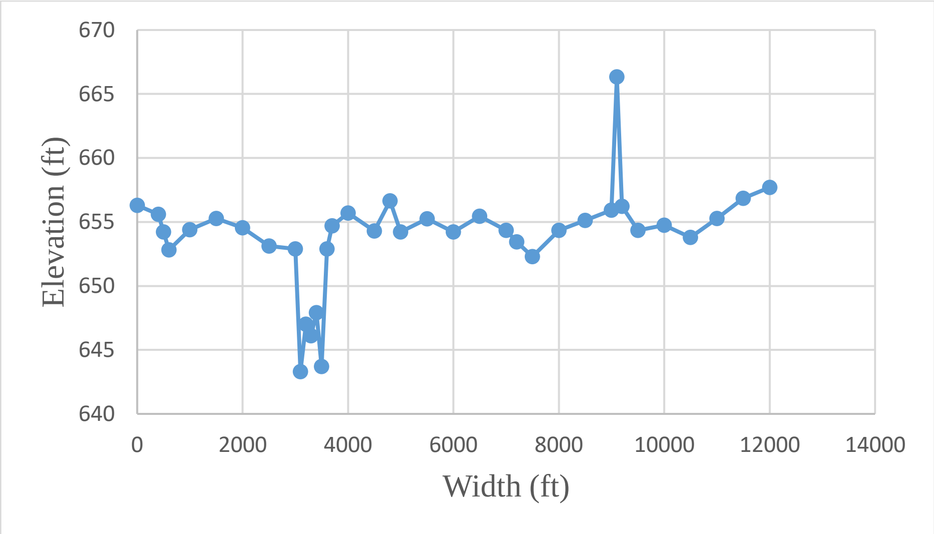

Figure D.29: Ravi Section at RD 92000

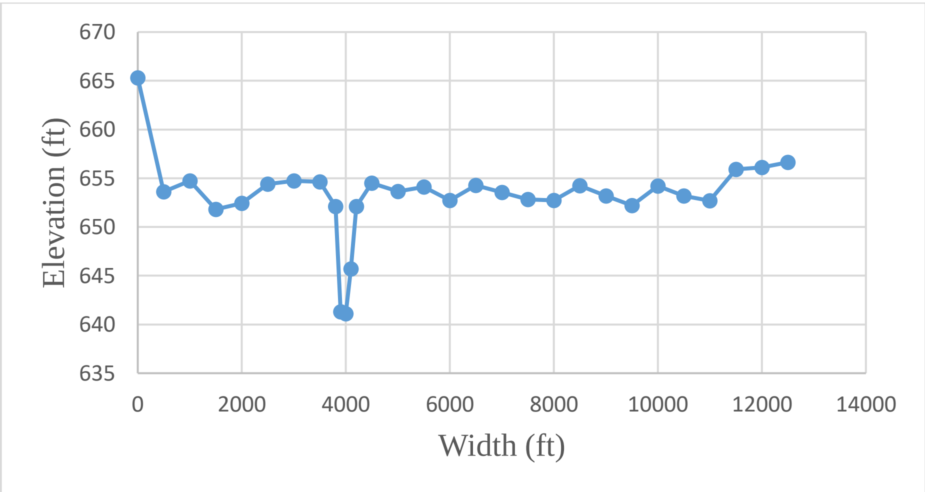

Figure D.30: Ravi Section at RD 95000

`

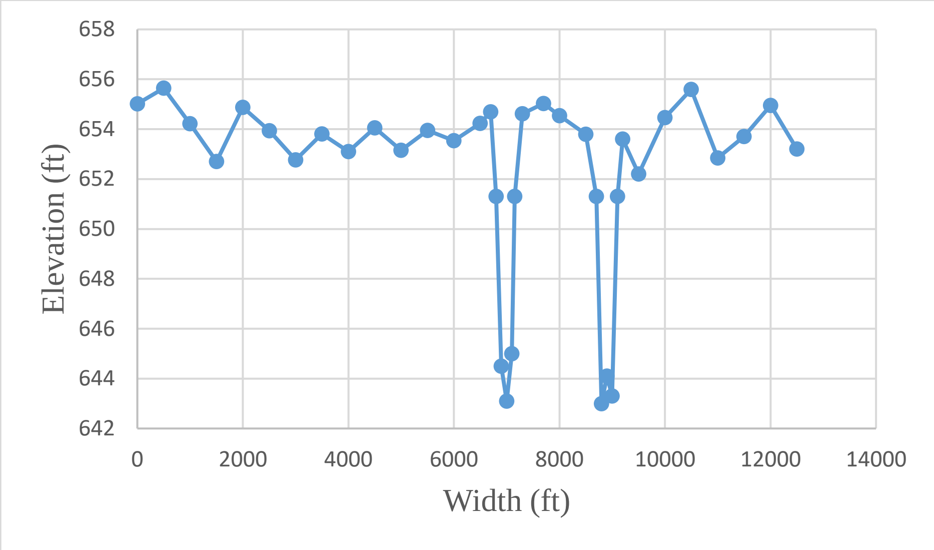

Figure D.31: Ravi Section at RD 98000

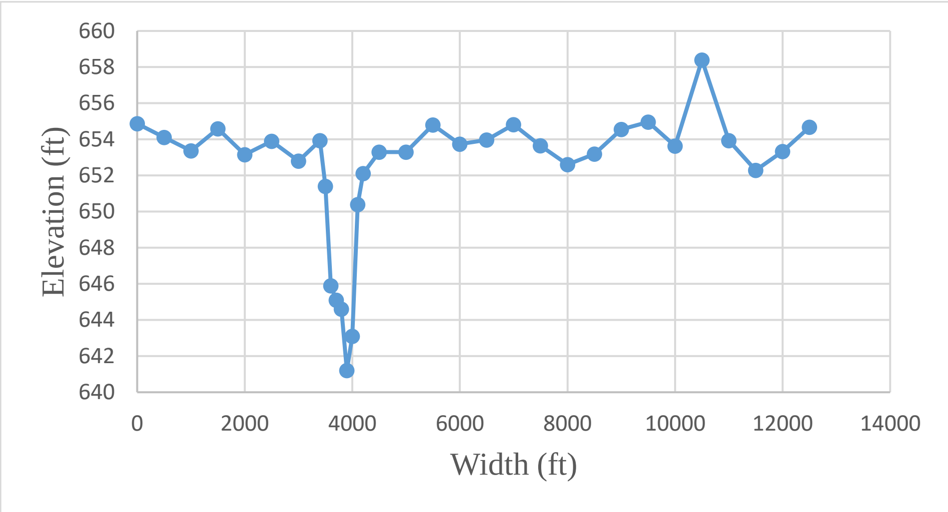

Figure D.32: Ravi Section at RD 111000

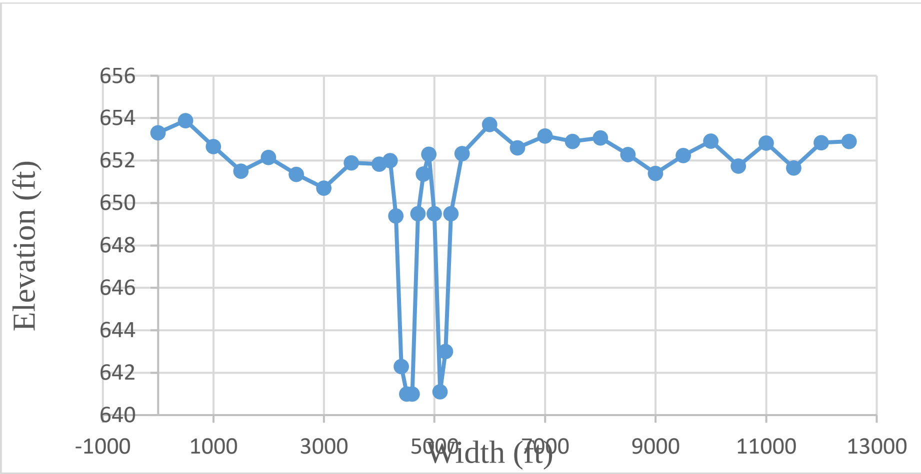

Figure D.33: Ravi Section at RD 114000

`

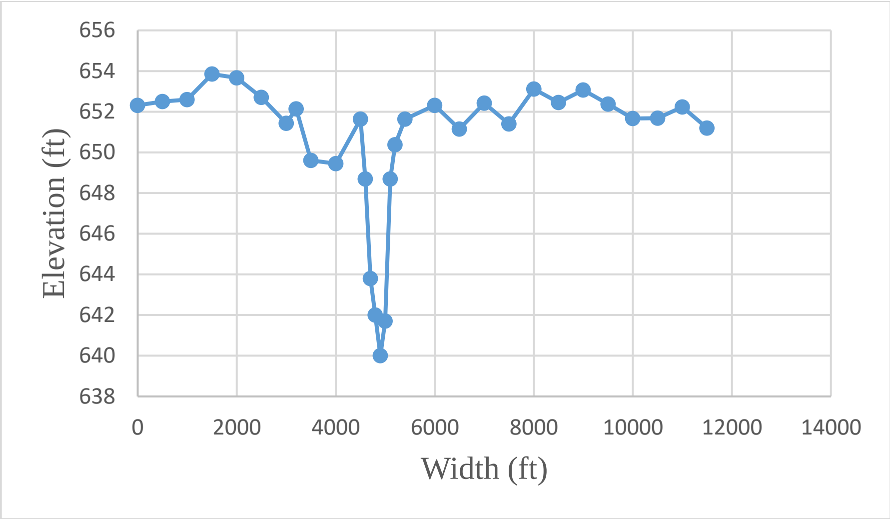

Figure D.34: Ravi Section at RD 117000

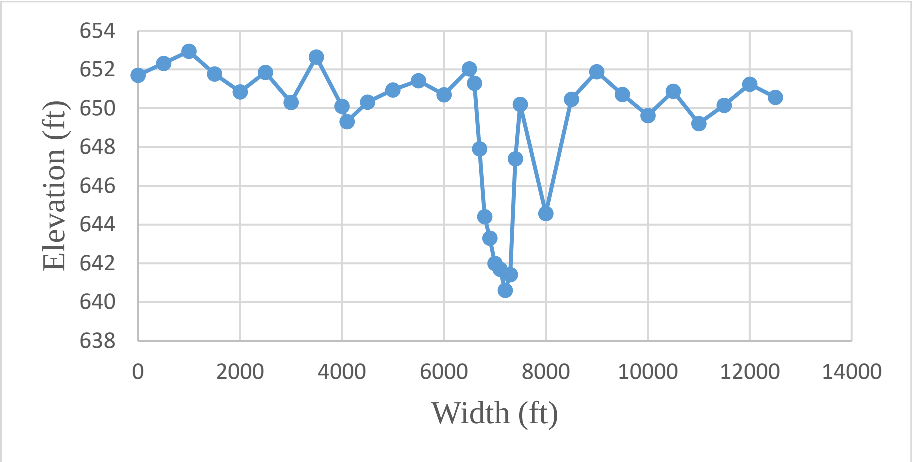

Figure D.35: Ravi Section at RD 123000

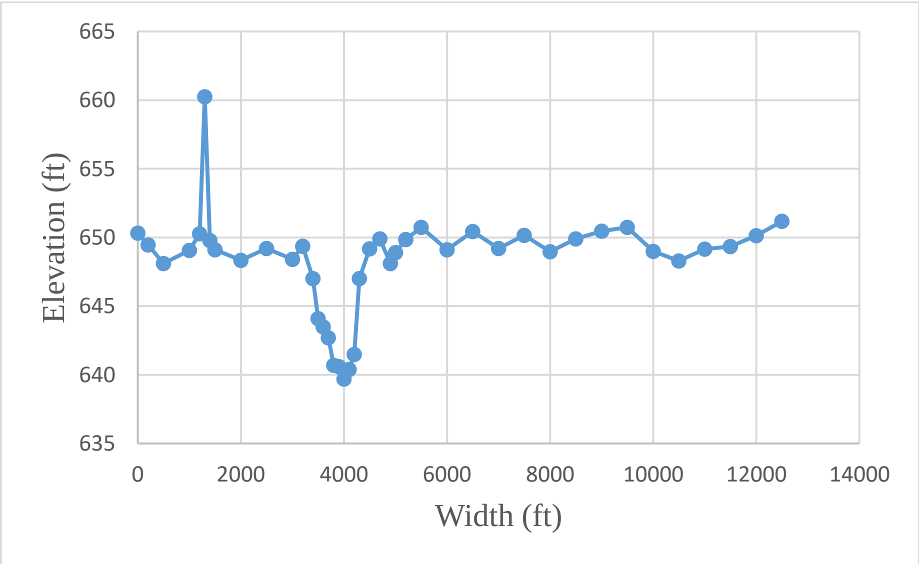

Figure D.36: Ravi Section at Rd 126000

`

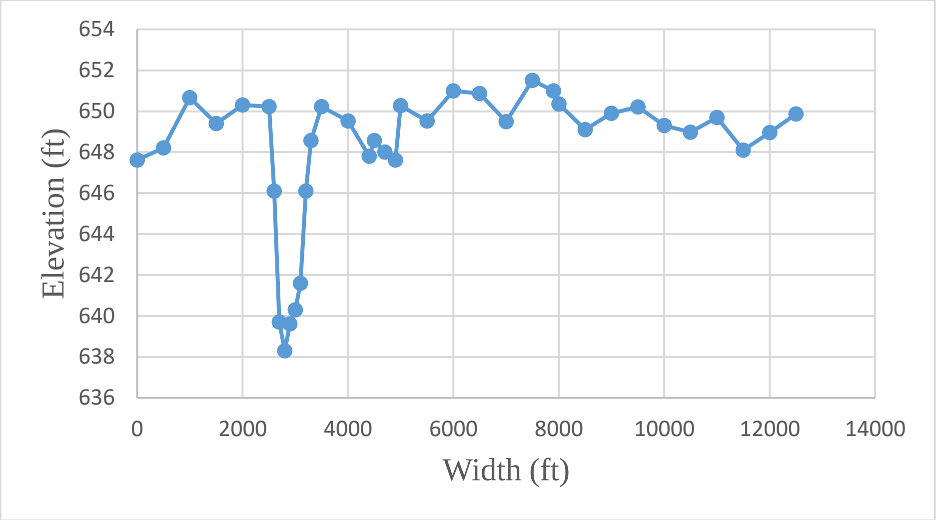

Figure D.37: Ravi Section at RD 129000

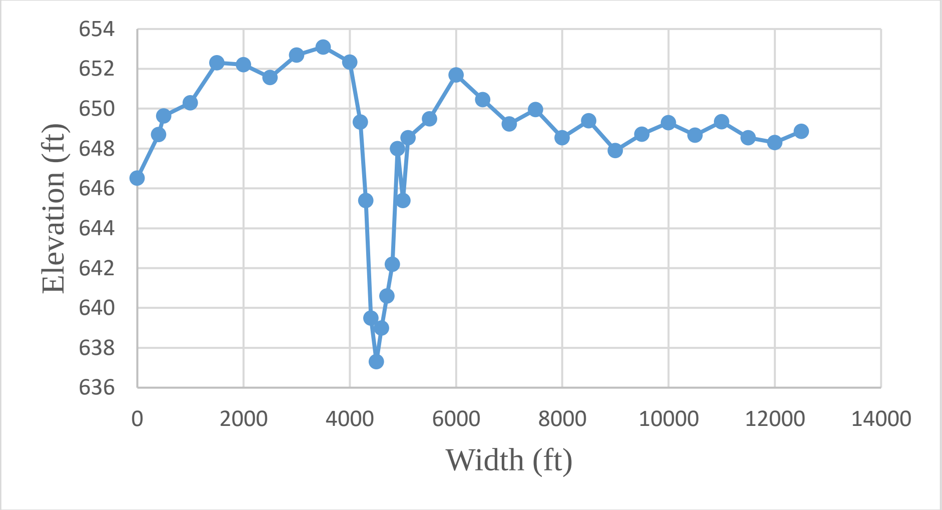

Figure D.38: Ravi Section at Rd 132000

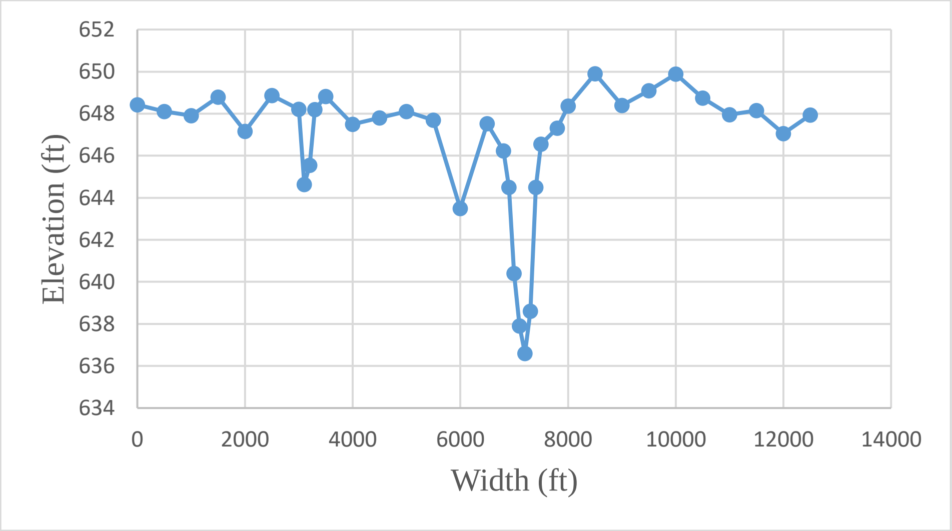

Figure D.39: Ravi Section at RD 135000

`

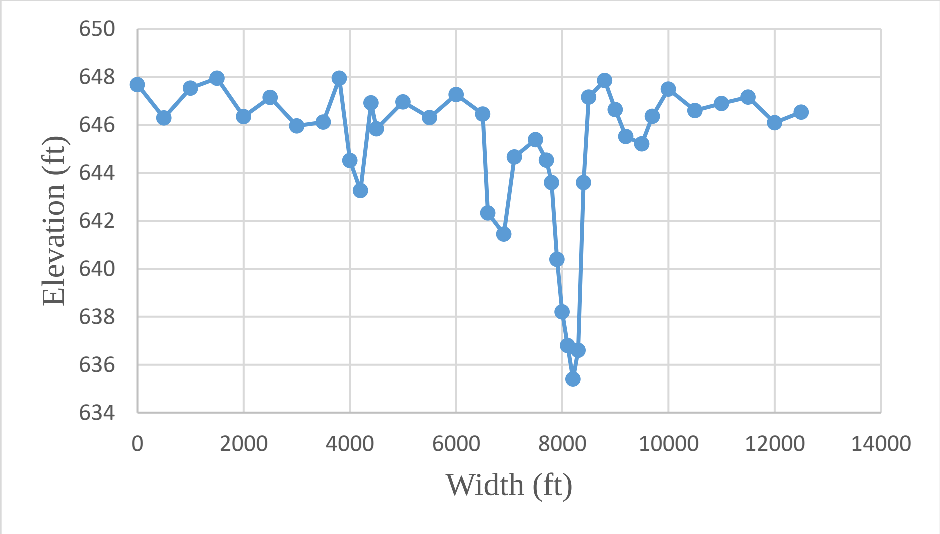

Figure D.40: Ravi Section at RD 138000

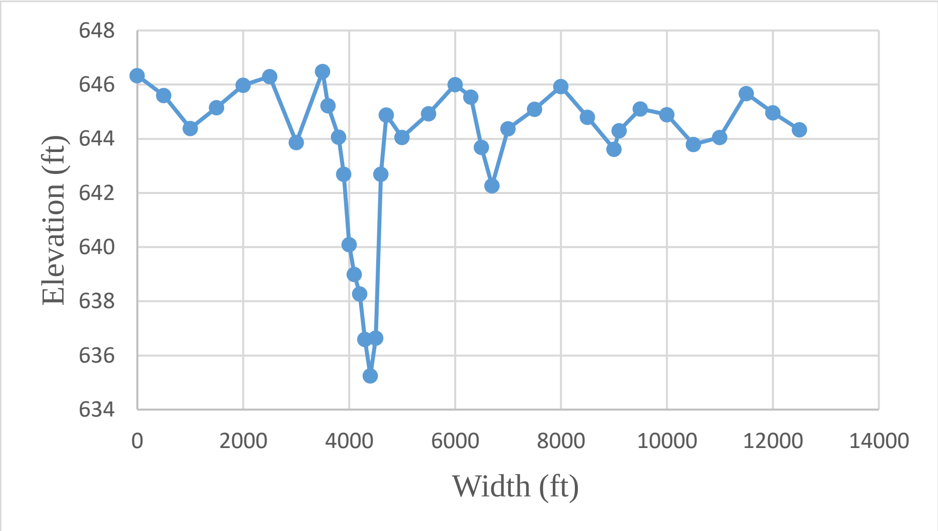

Figure D.41: Ravi Section at RD 141000

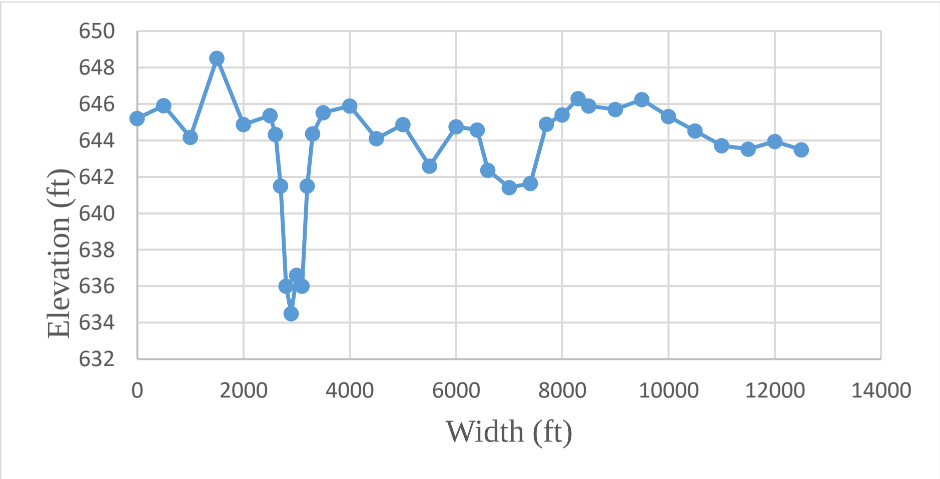

Figure D.42: Ravi Section at RD 144000

`

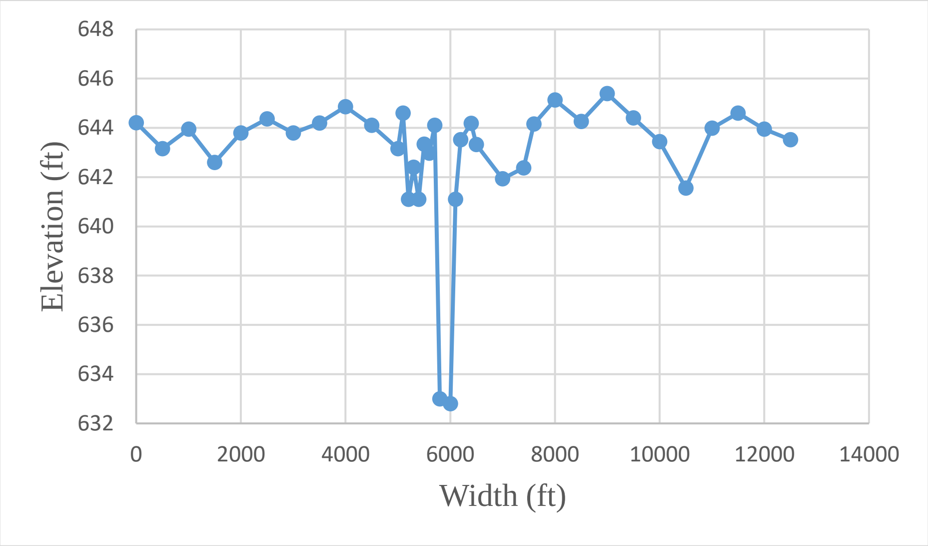

Figure D.43: Ravi Section at RD 147000

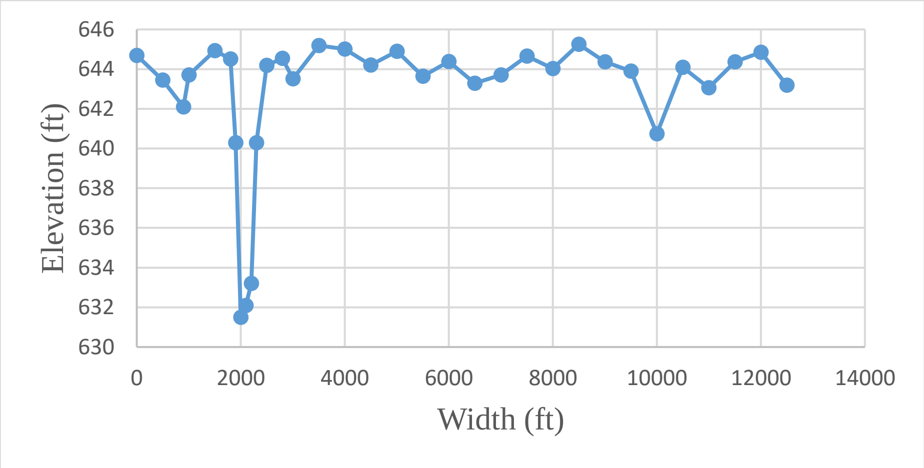

Figure D.44: Ravi Section at RD 154000

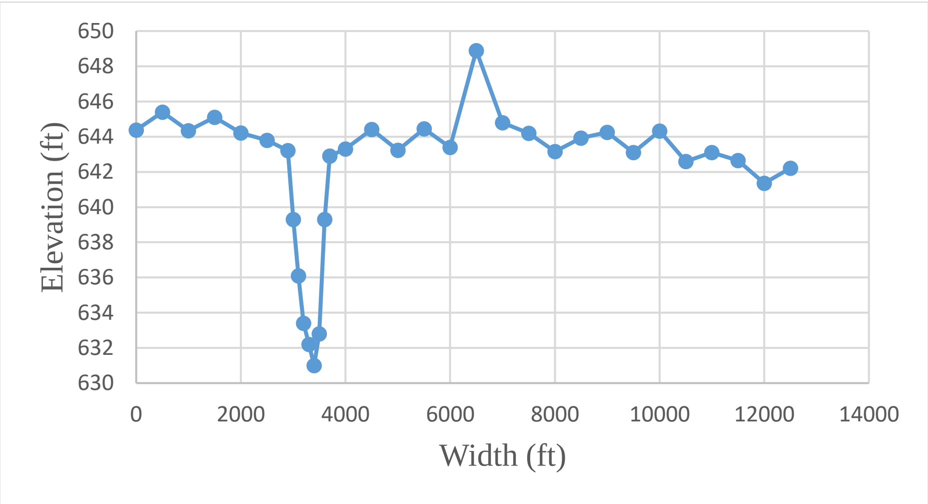

Figure D.45: Ravi Section at RD 156500

`

Annexure E

Observed Groundwater level maps of Lahore city

Simulated Groundwater level maps of Lahore city

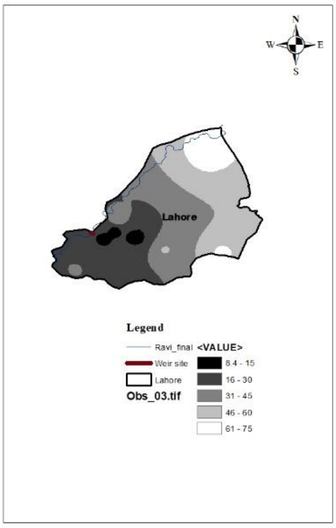

Figure E.1: Observed WL (ft.) map of Lahore city in year 2003

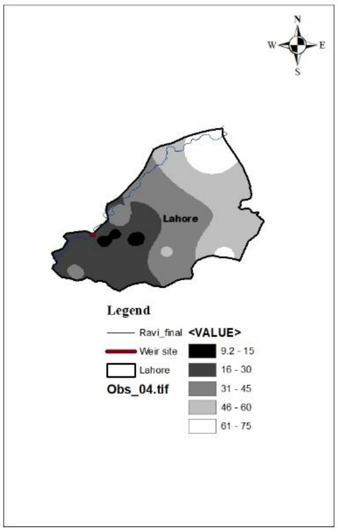

Figure E.2: Observed WL (ft.) map of Lahore city in year 2004

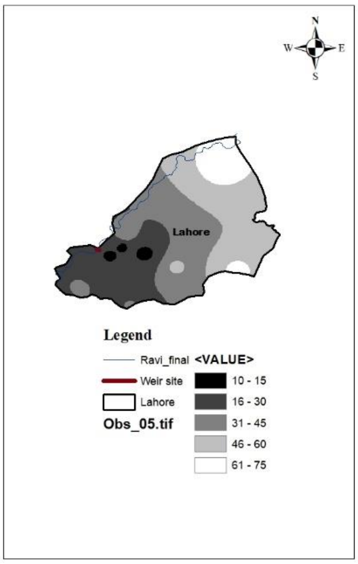

Figure E.3: Observed WL (ft.) map of Lahore city in year 2005

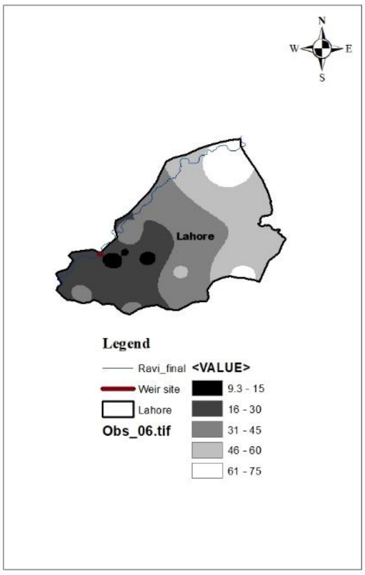

Figure E.4: Observed WL (ft.) map of Lahore city in year 2006

`

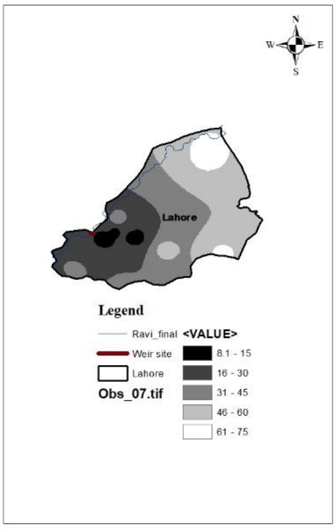

Figure E.5: Observed WL (ft.) map of Lahore city in year 2007

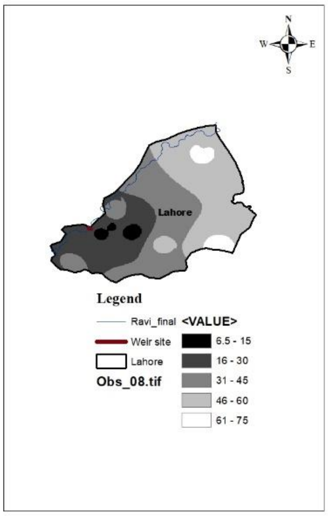

Figure E.6: Observed WL (ft.) map of Lahore city in year 2008

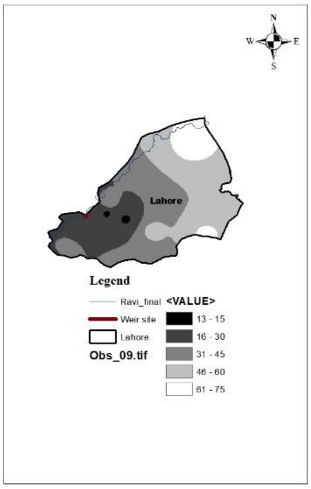

Figure E.7: Observed WL (ft.) map of Lahore city in year 2009

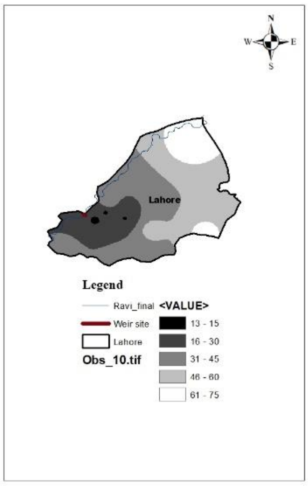

Figure E.8: Observed WL (ft.) map of Lahore city in year 2010

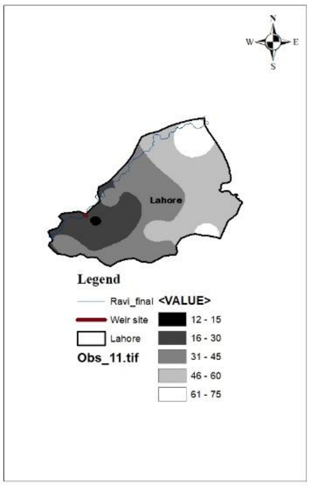

Figure E.9: Observed WL (ft.) map of Lahore city in year 2011

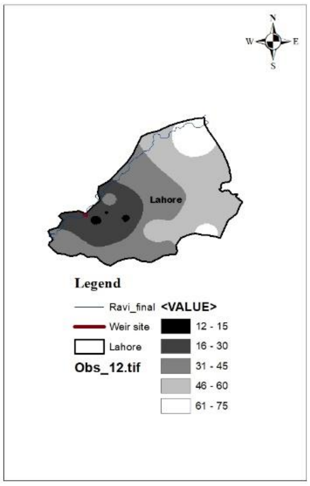

Figure E.10: Observed WL (ft.) map of Lahore city in year 2012

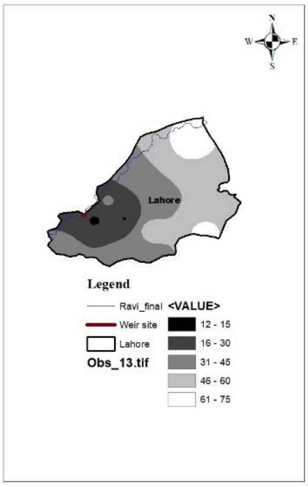

Figure E.11: Observed WL (ft.) map of Lahore city in year 2013

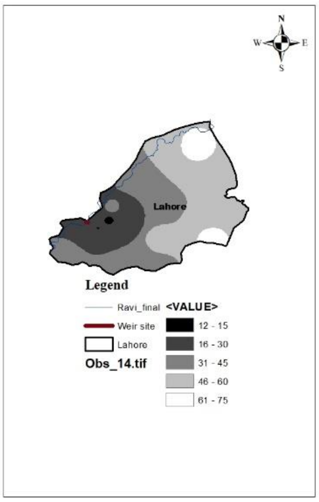

Figure E.12: Observed WL (ft.) map of Lahore city in year 2014

`

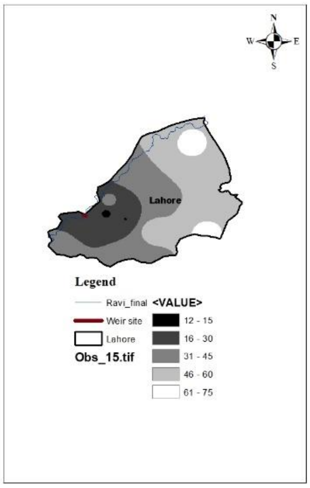

Figure E.13: Observed WL (ft.) map of Lahore city in year 2015

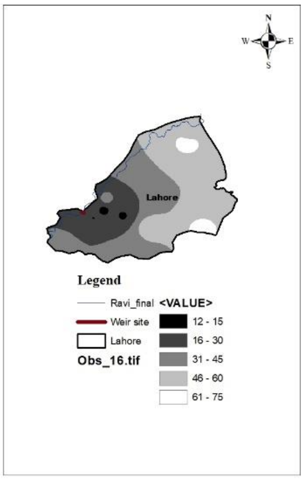

Figure E.14: Observed WL (ft.) map of Lahore city in year 2016

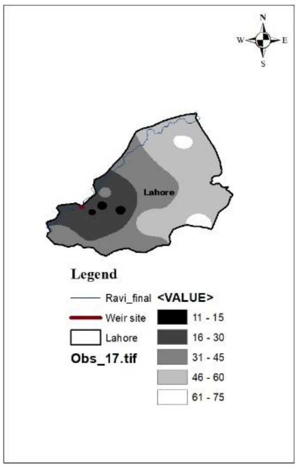

Figure E.15: Observed WL (ft.) map of Lahore city in year 2017

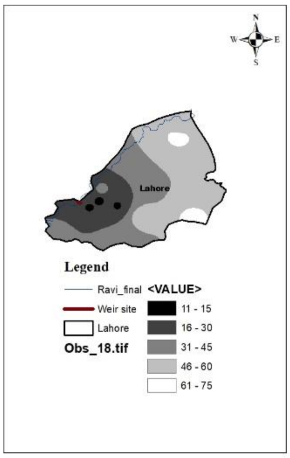

Figure E.16: Observed WL (ft.) map of Lahore city in year 2018

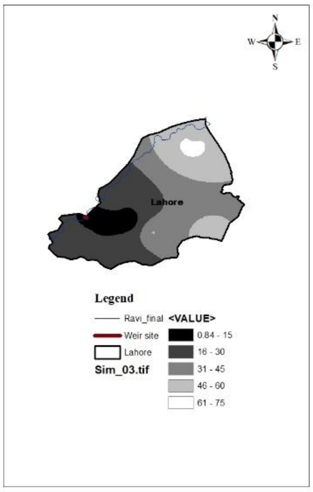

Figure E.17: Simulated WL (ft.) map of Lahore city in year 2003

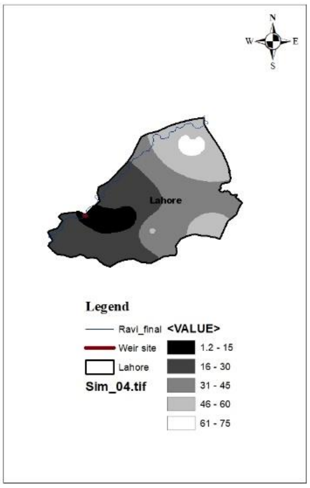

Figure E.18: Simulated WL (ft.) map of Lahore city in year 2004

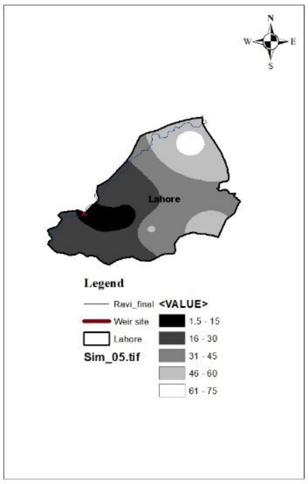

Figure E.19: Simulated WL (ft.) map of Lahore city in year 2005

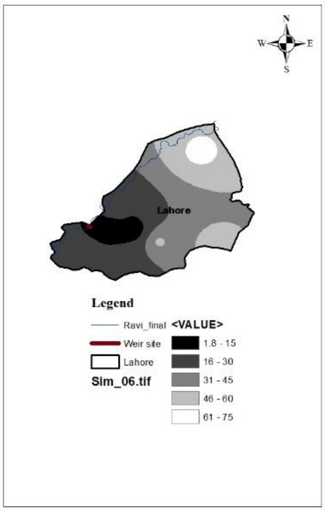

Figure E.20: Simulated WL (ft.) map of Lahore city in year 2006

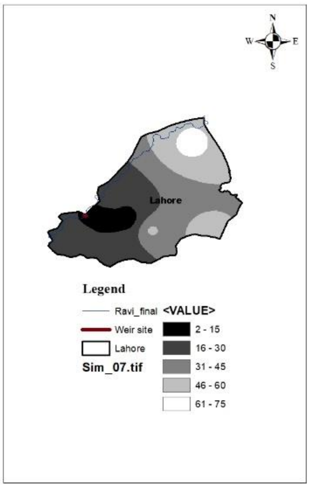

Figure E.21: Simulated WL (ft.) map of Lahore city in year 2007

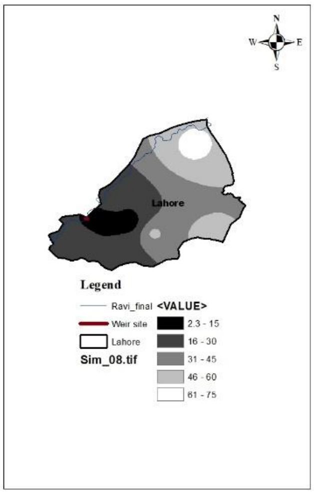

Figure E.22: Simulated WL (ft.) map of Lahore city in year 2008

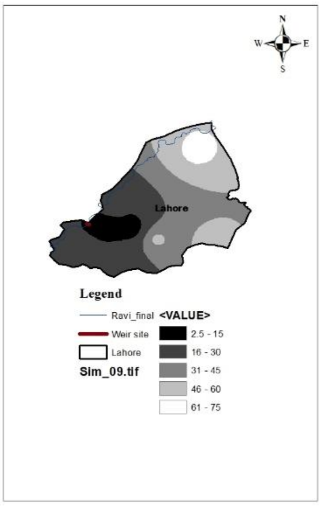

Figure E.23: Simulated WL (ft.) map of Lahore city in year 2009

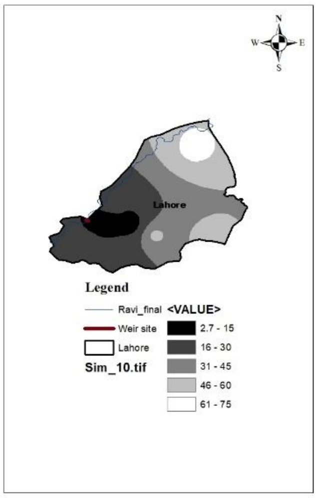

Figure E.24: Simulated WL (ft.) map of Lahore city in year 2010

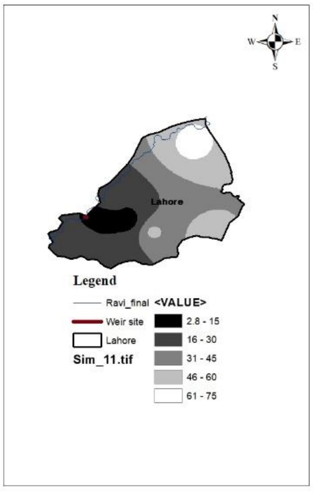

Figure E.25: Simulated WL (ft.) map of Lahore city in year 2011

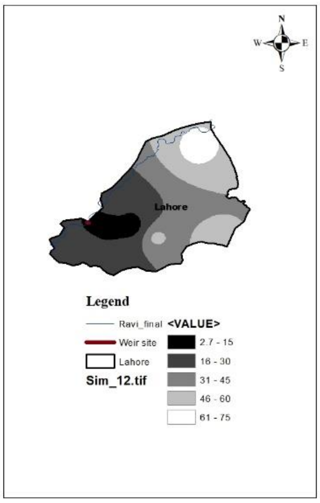

Figure E.26: Simulated WL (ft.) map of Lahore city in year 2012

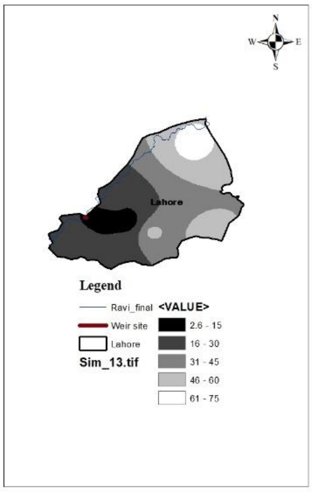

Figure E.27: Simulated WL (ft.) map of Lahore city in year 2013

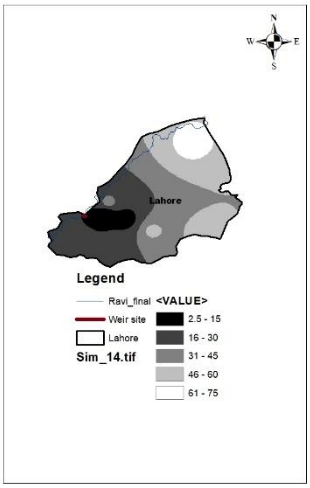

Figure E.28: Simulated WL (ft.) map of Lahore city in year 2014

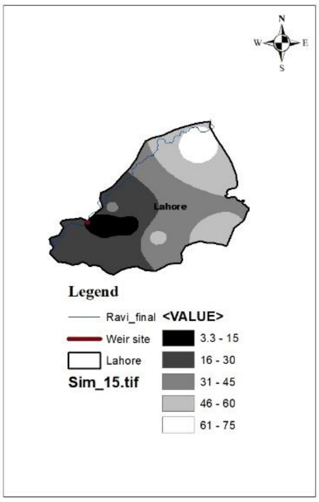

Figure E.29: Simulated WL (ft.) map of Lahore city in year 2015

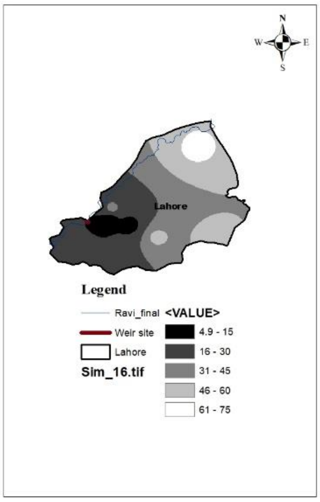

Figure E.30: Simulated WL (ft.) map of Lahore city in year 2016

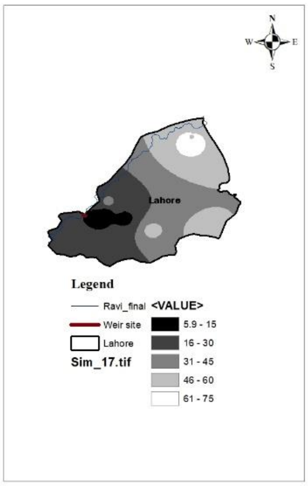

Figure E.31: Simulated WL (ft.) map of Lahore city in year 2017

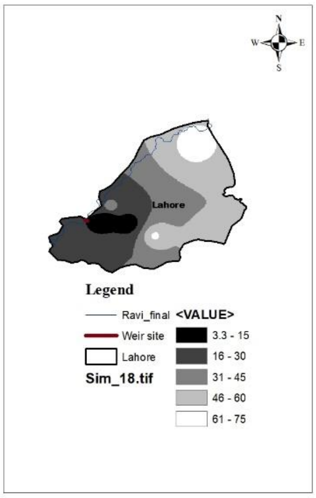

Figure E.32: Simulated WL (ft.) map of Lahore city in year 2018

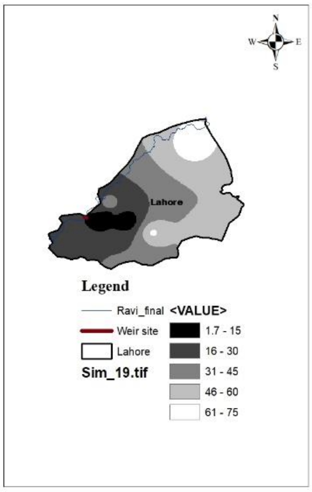

Figure E.33: Simulated WL (ft.) map of Lahore city in year 2019

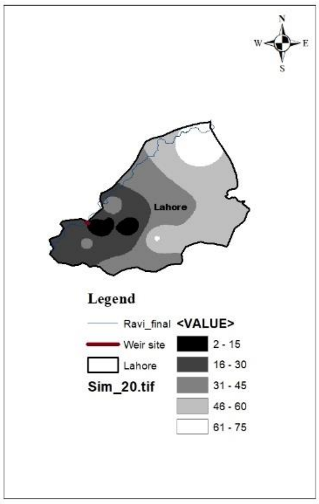

Figure E.34: Simulated WL (ft.) map of Lahore city in year 2020