

Modelling Effects of Val-Bird Weir Height on Water Tables Along the Haughton River (Burdekin Haughton Water Supply System)

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Executive Summary

Extensive irrigation is used for growing sugar cane in the Burdekin-Haughton River floodplain. In order to maintain regular water supply for irrigation, the Val-Bird Weir was built in 1983 on the Haughton River as part of the Burdekin Haughton Water Supply Scheme (BHWSS). This has led to a rise in water tables and potential threat of salinisation of surrounding lands in the region.

In this study a groundwater model (using MODFLOW) has been developed for the area. The model accounts for irrigation, recharge, crop water use, rainfall, constant head in the river, and hydrogeology of the aquifer system. Bore hydrographs for the area were analysed and the model was calibrated against observed data using the parameter optimisation package PEST. The calibrated model was then used to study the effects of lowering Val-Bird Weir height on surrounding water tables. Impacts of lowering the Val-Bird Weir height by 1 and 2 metres on the water tables were simulated. Results suggest that a reduction in weir height lowers the water table in the area closer to the Haughton River. However water tables in the region away from the Haughton River is only marginally affected. Lowering the height of the Val Bird Weir has greater effects on the water tables on the Eastern side of the model area (up to 3 km) due to higher sand content in the aquifer (thus higher hydraulic conductivity) than on the Western side (1.4 km). Results from this study can support analysis of future management options for the Val-Bird Weir and water supply in the area.

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1 Introduction

1.1 History of the Val Bird Weir

The Burdekin Irrigation area is ideal for growing sugar cane. It has warm winters, plenty of sunshine and sugar cane yield is possible throughout the year. In order to maintain a constant water supply for farms in the lower Burdekin region, and to meet urban and industrial needs of Townsville and Thuringowa, the Burdekin River Project was established by the Queensland Parliament in 1980. An expansion of the irrigated cropping became possible due to this scheme and it has contributed a lot to the economical growth in this region.

The Clare Weir along the Burdekin River with its capacity of 15,500 ML functions as a water storage for the irrigation area. This water is mainly needed for irrigation of sugarcane but also for different types of fruit and vegetables. The irrigation area has been developed on both sides of the Burdekin River with each side provided with pumping stations on Clare-Weir. These pumps supply water into the main channels on each bank of the Burdekin River. On the left side, the Haughton main channel diverts water to the Haughton River. There are five stages of the major Haughton Pump Station operating; each stage has a capacity to pump 7000 litres per second. The pumping stations maintain constant water level in the Haughton River all year round.

The Val-Bird Weir on the Haughton River was completed in February 1983, 7.1 km upstream from the Giru-Weir. It was constructed using a combination of sheet piling, reinforced concrete and gabions with a moveable crest. The storage has a capacity of some 2055 MI (Gilbey, 1987). Figure 1.1 shows an overview of the setting of the model area in the Burdekin River Irrigation Area (BRIA) and Figure 1.2 provides details of pump locations and water bodies.

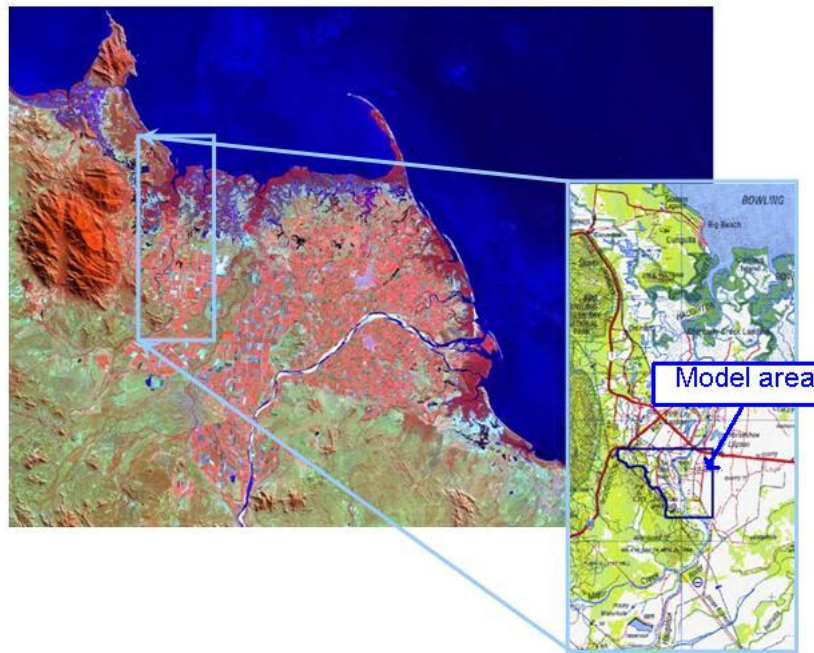


Figure 1.1: Location of the Haughton River and the model area used in this study

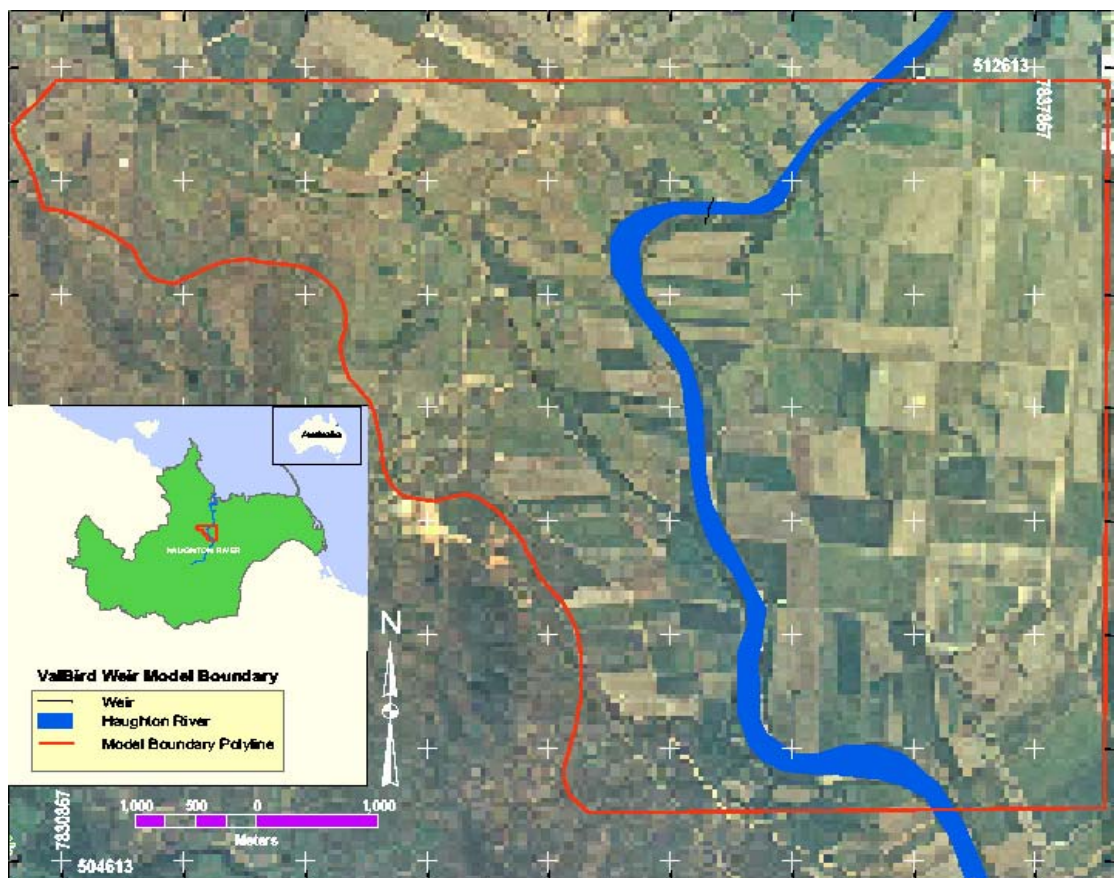


Figure 1.2: Aerial photograph of the model area showing its location in the lower Burdekin and the Haughton River

1.2 Objective of the Study

After construction of the Val-Bird Weir, a gradual increase of water level and salinity (EC) has occurred in the area (Fig. 1.3). A bore near Giru had a constant electrical conductivity of 1dS/m before the start of irrigation in the area in 1987. In 1996 salinity level reached 6 dS/m and has stood at this high level since.

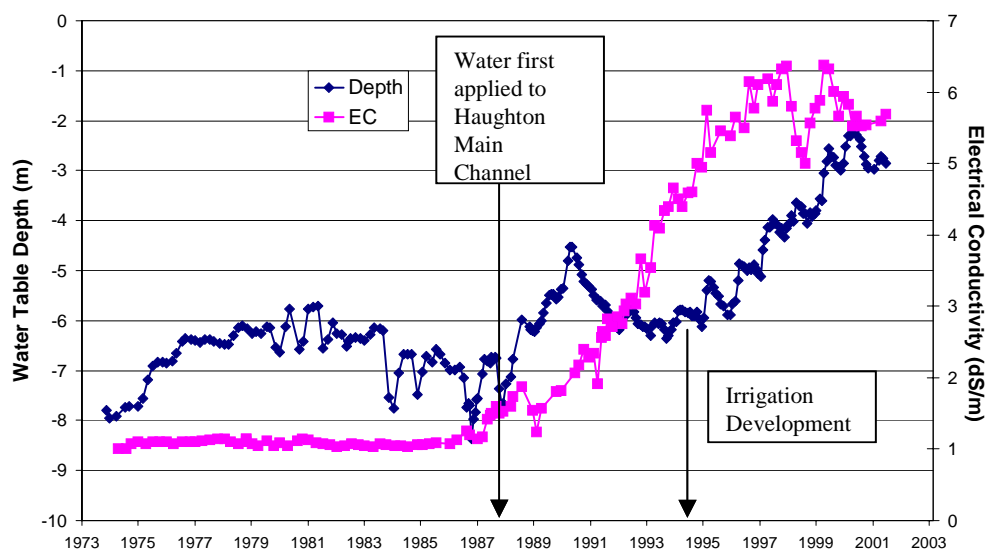


Figure 1.3: Bore 11900089 (Upper Houghton Road, Giru): Watertable and Salinity, 1973-2002 (Charlesworth & Williams, 2002)

Prior to 1987 (i.e. before the commissioning of Burdekin Dam) the average watertable was 8-10 m below ground surface. In 1988 a rapid rise in the water level occurred, and now it is varying between 2-3 m below ground surface. The shallow water table leads to higher capillary connection and salinisation of land. The sugarcane can tolerate salt concentrations up to 2 dS/m. In some areas the soil salinity has already exceeded this value and is a serious threat to the crop. Premature leaf senescence has already been identified on the Upper Houghton Road, Giru as well as leaves with marked margin burning indicating salinity toxicity symptoms (Charlesworth and Williams, 2002).

Another issue is the waterlogging in this area. Due to poor internal drainage, there is not enough applied water travelling below the root zone to leach salts below the root zone (DPI 1993). The main objective of this modelling study was to evaluate the effects of lowering the Val-Bird Weir height on groundwater level in the surrounding area. The modelling was

carried out with MODFLOW model (McDonald and Harbough, 1987), in conjunction with PMWIN pre and post processor.

2 Conceptual Model

2.1 Topography

The Burdekin-Haughton floodplain is bounded by the Burdekin River in the South East and the Haughton River in the North West. It comprises an area of 900 km² which is gently sloping towards the sea with average elevation of approximately 10 meters. In the West and South, steep ranges of outcrops define the borders. Baratta creek, which is situated between the Burdekin and Haughton River, drains the flood plain. Typical natural vegetation is tall woodland, riparian forests and areas of grass land.

2.2 Hydrogeology

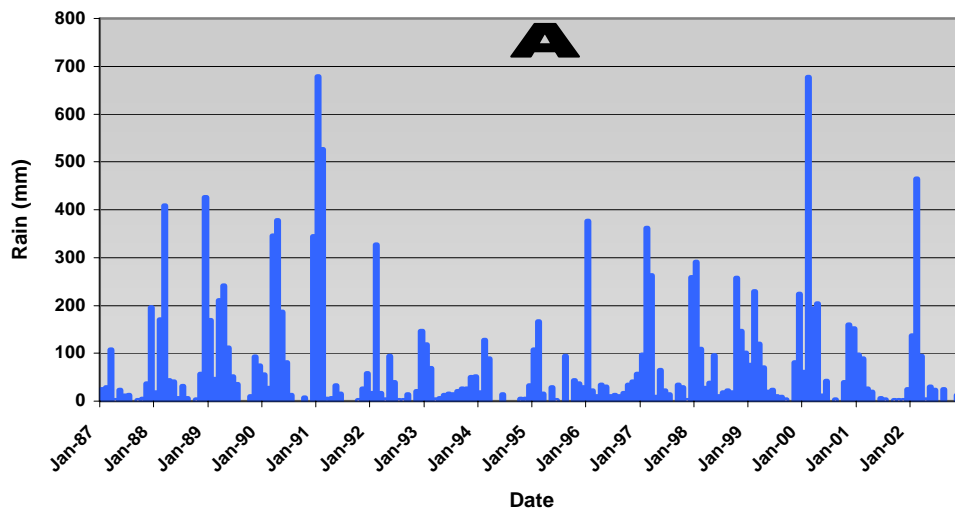
The basement of the area consists of granitic-type rocks. Usually these rocks are weathered at the top to form hard, sometimes sandy clays. River systems have eroded into these rocks and deposited sediments. Surface Geology consists predominantly of fluvial deltaic sediments laid down on a Palaeozoic erosional surface. The sediments form an unconsolidated aquifer comprised of sand, gravel, silt and clay, deposited by river action (see Appendix A). The nature of the sediments depends on the depositional environment, with coarser grained sediments occurring in higher (energy) fluvial environments (eg stream channels) and clays on low (energy) fluvial flood plains. As a consequence, hydraulic conductivity of the aquifer is highly variable. The groundwater flow follows a hydraulic gradient which usually leads to water flowing towards the coast.

Soil properties on the eastern and western side of the Haughton River differ markedly. The western bank soils are mainly grey/black cracking clays with a mixture of sodic duplex soils (DPI, 1993). Unlike the Western bank, there is more sandy clay on the Eastern bank and even gravel can be found in some areas. Clay has the ability to swell and can store a lot of water but the hydraulic conductivity is low as long as no aggregates form. It has a very fine pore space and very often forms confining layers in the subsurface. Porosity of clay can

range from 33 - 60 % depending on the sand content. Specific yield which is the ratio of volume of water that drains from a saturated rock due to gravity to the total volume of rock is always less than porosity. For sandy clay it ranges from 3 – 12 % and for clay from 0 - 5 %. Hydraulic conductivity is dependent upon pore space, the larger the pore space the more permeable the material. The hydraulic conductivity can vary between 0.01 m/d to 10 m/d for clay.

2.3 Rainfall and Evaporation

The data for rainfall and evaporation was obtained from the Kalamia sugar mill site. The rainfall data from 1987-2002 as shown in Figure 2.1(A) has a highly seasonal pattern with rainfall up to 220 mm a month in February, a wet season from December to March and a considerably dry season from June to October with rainfall of 30 mm a month on average.



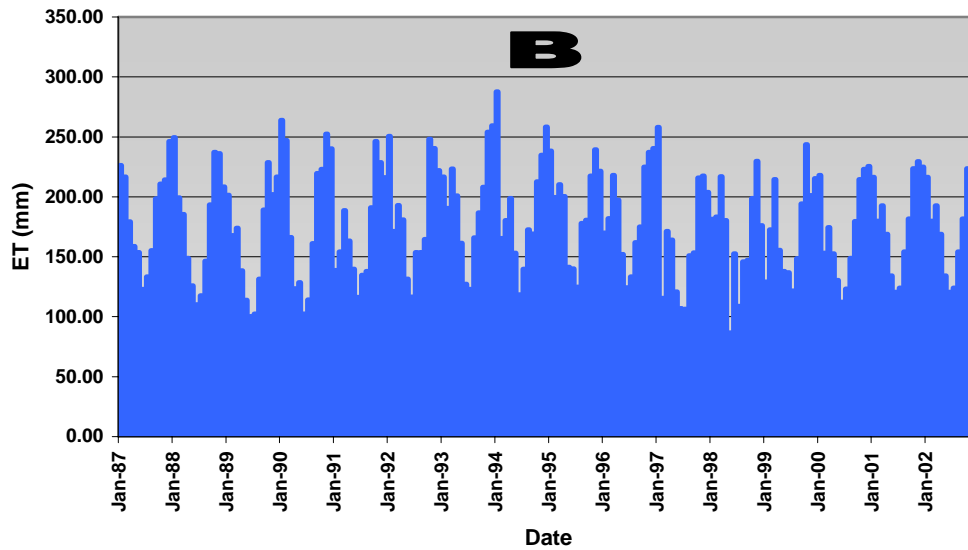


Figure 2.1 (A) Average monthly rainfall and (B) evaporation from 1987-2002 for the Burdekin irrigation

The total annual rainfall is highly variable as well, and ranges from 1540 mm during wet years as for example in 2000 to 260 mm in dry years in 1995. Most of the rainfall however occurs during the wet season from January to March.

The Daily Class A pan evaporation shown in Figure 2.1(B) also has a seasonal pattern whereas the yearly values are more constant. Monthly evaporation values vary from 230 mm during summer in November and December to 120 mm during winter in June and July. The temperature of this area is typical for a tropical region with hot humid summers and mild winters.

3 Groundwater Model

MODFLOW, a three - dimensional finite – difference groundwater flow model (McDonald and Harbaugh, 1987) was used for this study. The simulation involved transient model runs and calibration against measured water levels from November 1995 to March 2002. PMWIN package (Chiang and Kinzelbach, 1998) was used to input model data and process results.

3.1 Boundary Conditions and Discretisation

A regular grid with 100 rows and 119 columns and uniform nodal spacing of 100 m was used to represent the 3917 ha study area (Fig. 3.1). As the aquifer is underlain by basaltic rock and is quite uniform only one layer was considered. The model was only run for the period for which pumping data were available (November 1995 to March 2002). For the transient calibration each month was treated as one stress period (and also as one time step) and 77 stress periods were used in model calibration

In the west with outcrops, a no flow boundary was assumed. To get the exact western boundary, contour lines of the model elevation were drawn using Surfer and the gridding method (Kriging) and the 20 m contour line was used as the boundary for the model. To the north and south, there is almost no change in hydraulic heads over the last 20 years and a constant head boundary was assumed. Analysis of hydraulic heads in the area reveals that there is groundwater flux towards north east. However, it is difficult to quantify this flux. Also there had been relatively minor changes of groundwater level in those bores to the east of the model domain. Therefore it is quite reasonable to assume a no flow boundary for the eastern boundary of the model.

Model elevation relies on measurements of mountain spot heights and measurements at the observation bores. The elevation of the model area was assumed to be the top of the aquifer and an aquifer thickness of 30 m was chosen.

3.2 Initial Hydraulic Heads

The initial hydraulic head is a starting value for the simulation and the simulation period lasts from November 1995 to March 2002. Data for 24 observation bores were used to construct the initial potentiometric surface using the Kriging method of the Field Interpolator built into the PMWIN. However, only a subset of 14 bores with complete water level record/data was used in model calibration.

The cells of the Haughton River in the model domain were treated as constant head due to the Val- Bird Weir. A water level of 6.7 m was used upstream of the Val- Bird Weir and a level of 2.2 m has been applied downstream of the weir. The river heads, both upstream and

downstream were kept constant throughout the simulation and seasonal variations were not accounted for in the model simulations.

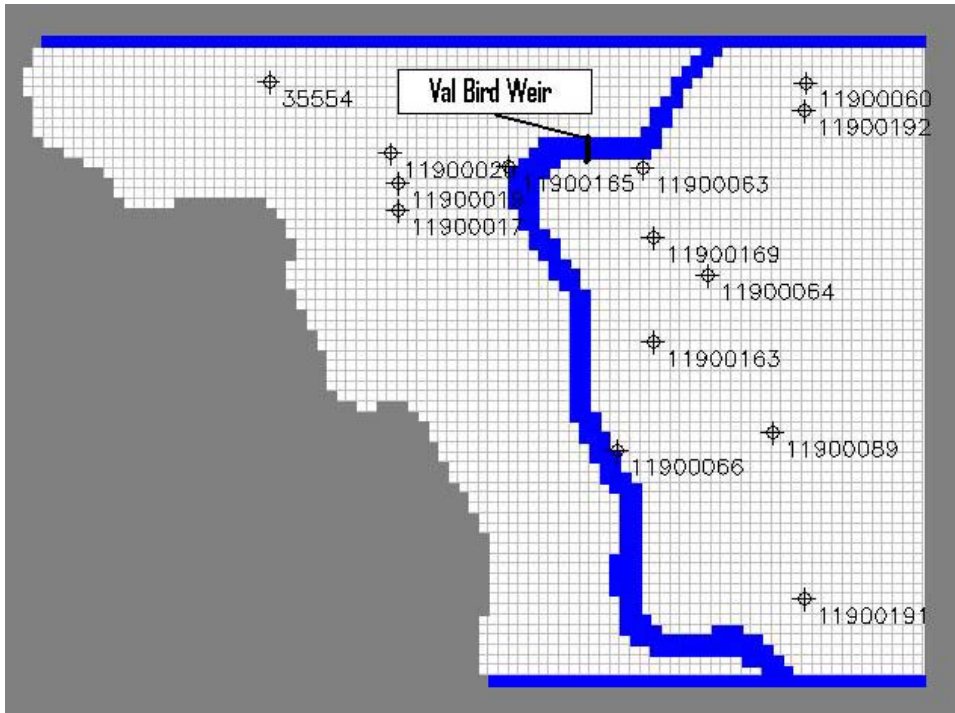


Figure 3.1: Model boundary with square grids (1 ha), Haughton River and observation bores. (Blue cells – constant river heads, grey cells – no flow, and rectangular blocks - active cells)

3.3 Groundwater and Surface Water Pumping

Pumping data from November 1995 until March 2002 was supplied by Sunwater and is shown in Fig. 3.2. Annual pumping varies from 7740 ML in 2000 to 20770 ML in 1996 and an average pumping rate is 13,370 ML/yr. There is no definite correlation between rainfall and pumping.

There are 65 pumping wells and it is assumed that they are contributing the entire pumped water to the model area only which comprises 3917 ha. It is also assumed that the water is uniformly distributed due to the flatness of the landscape. The locations of the pumping wells are shown in Figure 3.3. Of these, 30 bores are open water bores and 35 are groundwater bores extracting water from the aquifer close to the Haughton River and it is assumed that

the interaction between the river and the nearby aquifer layer is instantaneous. Therefore the model assumes that the wells have unlimited source of water available as the water level in the river is kept constant. As a result water level in the aquifer is not affected by the extraction and all pumped water is only used for irrigation and contributes to the recharge in the area. Pumping data was obtained from Sunwater and summed up for the western and eastern part of the model area separately to estimate recharge (See Appendix B)].

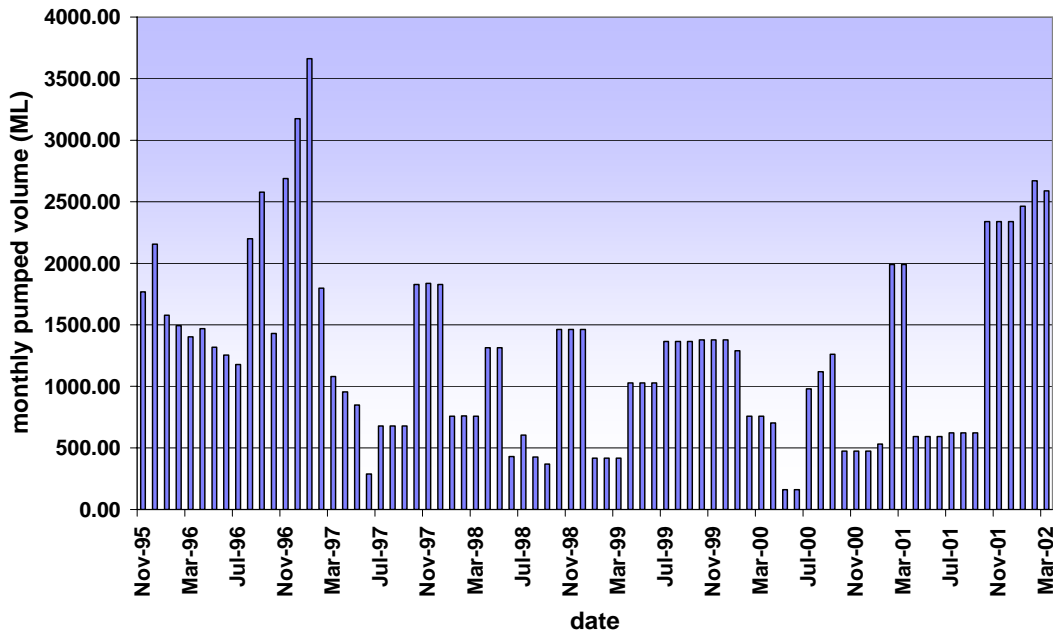
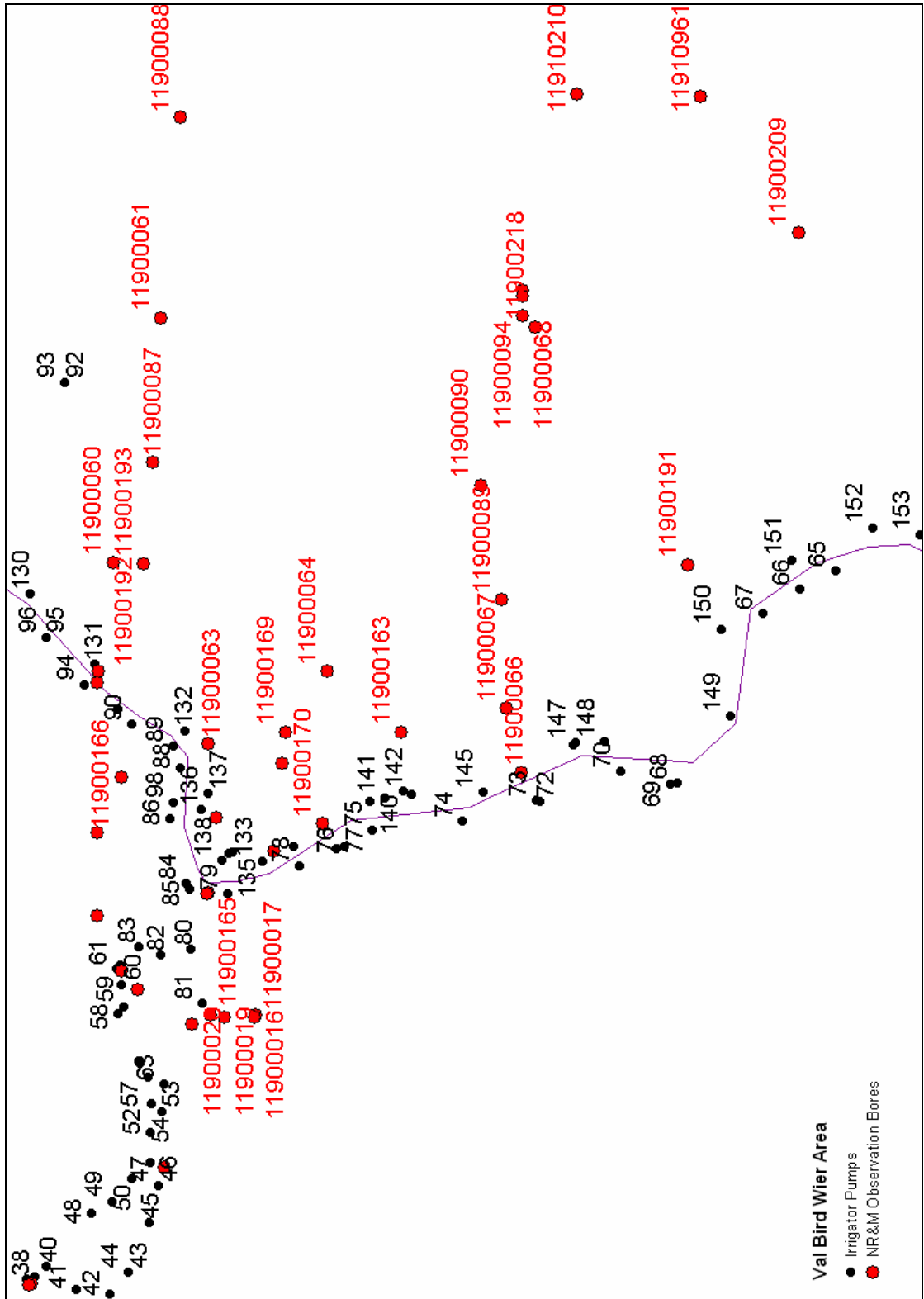


Figure 3.2: Monthly volume (ML) of water pumped (November 1995 to March 2002)

Figure 3.3: Location of pumping wells (black) and observation bores (red)



3.4 Recharge Estimation

Recharge to the groundwater depends on rainfall in the area, irrigation and evapotranspiration. The recharge was estimated using data of the Kalamia sugar mill site for the period November 95 to March 2002. As the pan evaporation data for 2001 and 2002 was missing, the mean monthly pan evaporation values were used in the model. This seemed very reasonable as very little change of pan evaporation occurs over the years.

To estimate net recharge the actual evapotranspiration was needed which was obtained by multiplying the potential evaporation with a crop factor. 25 % of the model area was assumed to be fallow land with a crop factor of 0.2 and 10 % were assumed to be natural vegetation with a crop factor of 0.4 (see equations 1 and 2).

The tree vegetation along the Haughton River was given a crop factor of 1. However, this vegetation is included in the river cells and thus has an unlimited supply of water as the river cells are regarded as constant head cells. There are hardly any other trees in the model area, and the natural vegetation consists of bush and grass, thus a lower crop factor as for sugar cane was chosen for natural vegetation.

The crop factor for sugar cane (which covers 65% of the land area) was derived from CSIRO sustainable ecosystems and relies on measurements. The crop factor is on average 0.61 and shows a high seasonal pattern with maximum values of 0.76 in February and minimum values of 0.49 in August. These monthly values were used for the entire time period.

The recharge area is divided into two regions on each side of the Haughton River. The water from the wells on the eastern side of the river was applied to the eastern area whereas the water from the wells on the western side of the river was applied to the western model area. The pumped water volume on each side of the river was first converted to mm. The irrigation water was then applied to the whole model area (see Equation 3). The recharge was calculated by adding the monthly pumped water of open water bores and groundwater bores plus the monthly rainfall minus the actual monthly evapotranspiration (see Equations 4 and 5). The total monthly recharge (see Figure 3.4) was subsequently converted into recharge rate (m/d) (see Equation 6) as it is required by MODFLOW model.

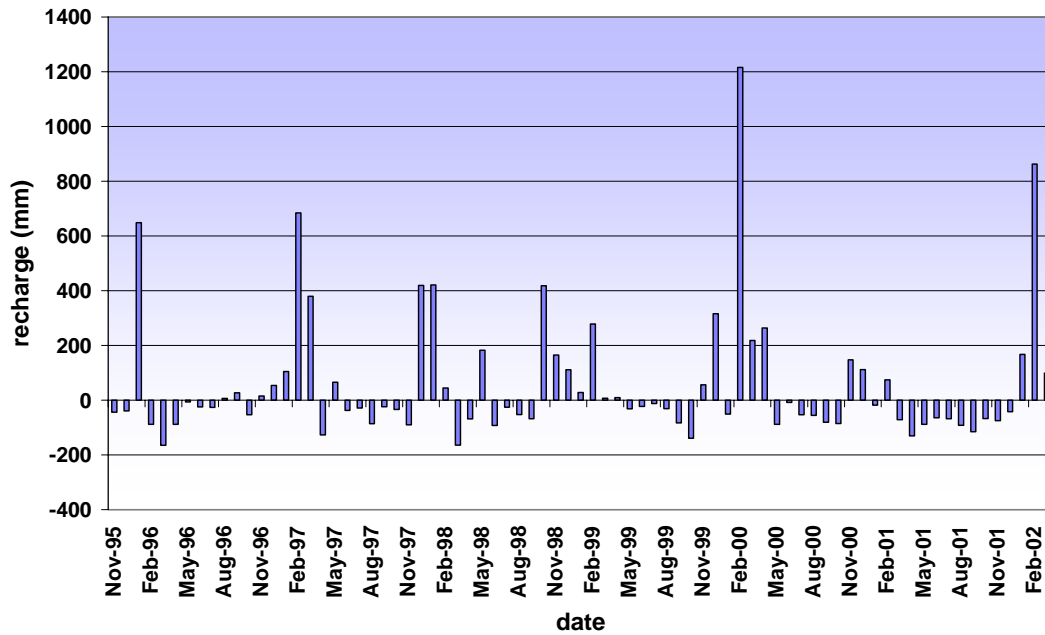


Figure 3.4: Estimated monthly recharge (mm) for the model area from November 1995 to March 2002

Estimation of actual evapotranspiration:

$$ET_o(mm) = ET(mm) * K_c$$

Equation 1

ET_o = Monthly actual evapotranspiration in mm

ET = Monthly pan evaporation in mm

K_c = Crop factor

$$K_c = 0.65 K_{cc} + 0.25 K_{cf} + 0.1 K_{cn}$$

Equation 2

K_{cc} = Crop factor for sugar cane

K_{cf} = Crop factor for fallow land

K_{cn} = Crop factor for natural vegetation

K_c = Overall crop factor used for recharge estimation

Formula for converting MI to mm:

$$\boxed{mm = \frac{MI * 100}{ha}}$$

Equation 3

For the model area:

Western area = 1855 ha

Eastern area = 1867 ha

$$\boxed{recharge\ west = rain(mm) + \frac{irrigation(MI) * 100}{1855(ha)} - ETo(mm)}$$

Equation 4

$$\boxed{recharge\ east = rain(mm) + \frac{irrigation(MI) * 100}{1867(ha)} - ETo(mm)}$$

Equation 5

Rain = Monthly rainfall in mm

ETo = Monthly actual evapotranspiration value in mm

Irrigation = Monthly pumping volume used for irrigation in MI

$$\boxed{recharge\ rate / day = \frac{recharge(mm)}{1000 * 30}}$$

Equation 6

Recharge = Monthly recharge value in mm

4 Model Calibration and Verification

4.1 Trial and Error Calibration

During the trial and error calibration, adjustments were made to the values of hydraulic conductivity and specific yield until simulated and observed hydraulic heads were acceptable. Hydraulic conductivity of 12 m/d, specific yield of 20 % and a porosity value of 30 % were applied to the model area. The trial and error calibration gave useful information on aquifer properties and also provided reasonable trend of the observed and simulated results (see Appendix C). The results are very sensitive to hydraulic conductivity and specific yield values as expected. It is also observed that the boundary conditions applied in the west and east do not affect the results considerably. However, the comparison between the model and observed heads are poor in trial and error calibration. It was therefore necessary to refine the calibration by the use of parameter optimisation package PEST.

The calibration target was set to 1.5 m difference between measured and simulated hydraulic head as a maximum. Subsequently the hydraulic heads at 14 different observations bores were used for calibration with the observed water levels from November 1995 to March 2002 (i.e. a total of 77 stress period).

However, there was ambiguity in a few bore data (e.g. bore 11900066) which needs to be verified in future. Possible causes of error could be either an incorrect recording/entry of surface elevation or water level in the data base. This bore is about 180m away from the Haughton River and it is unlikely that its head will be 2 – 3 m higher than the river.

4.2 Model Calibration using PEST

Several attempts were made using PEST (Doherty, 2000), a model-independent parameter optimiser. The results obtained through trial and error calibration were used as starting values for all parameters. The range of hydraulic conductivity values was 0.01 - 50 m/d and that of specific yield was set between 5 % and 20 %.

During the first attempt, all cells of the model area were given the hydraulic conductivity and specific yield values obtained through trial and error calibration and porosity was set to 30%. The cells of the boreholes were assigned as parameters and thus hydraulic conductivity and specific yield of only these cells were optimized through PEST (Appendix D). A correlation coefficient of 0.83 between observed and calculated hydraulic heads was obtained. These results however don't reflect the heterogeneity of the aquifer and thus a second attempt was undertaken.

In the second attempt, various zones were assigned for calibration. For each observation bore three zones and hence three parameter values were chosen. The zones were chosen based on soil physical properties and bore log data of the aquifer which is an accepted practice while using PEST. Polygons around the observation bores were assigned as one zone; a rectangle of 16 ha around the observation bore and the cell of the observation bore as other zones (Fig. 4.1). The range of parameter values was the same as during the first attempt.

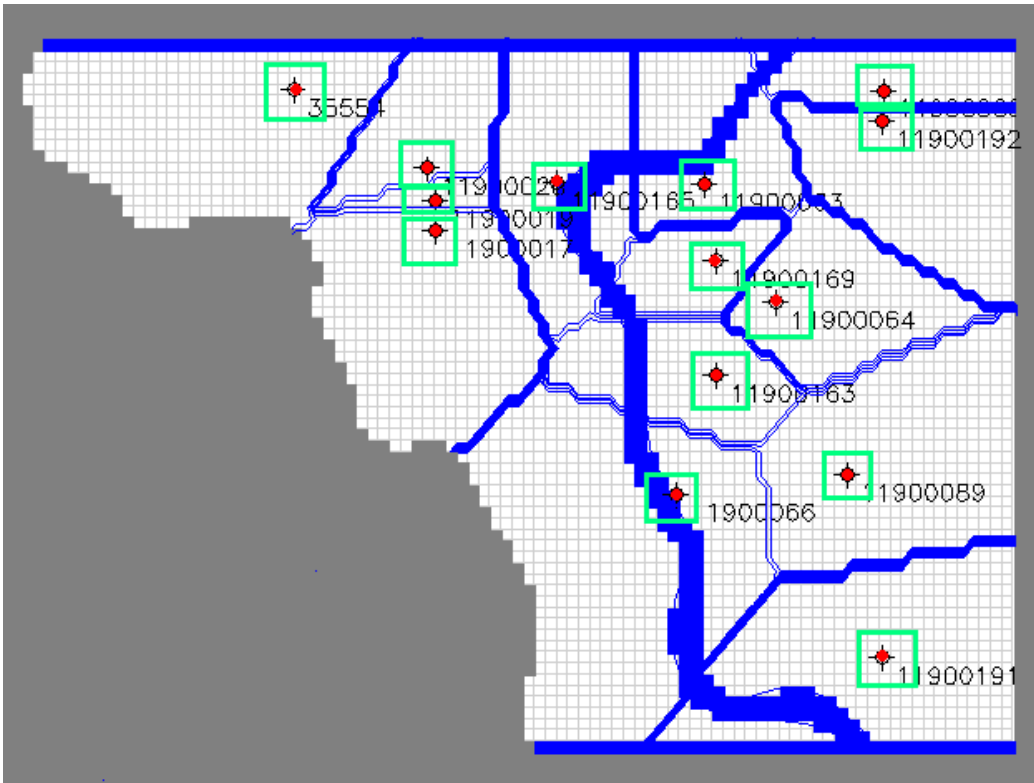
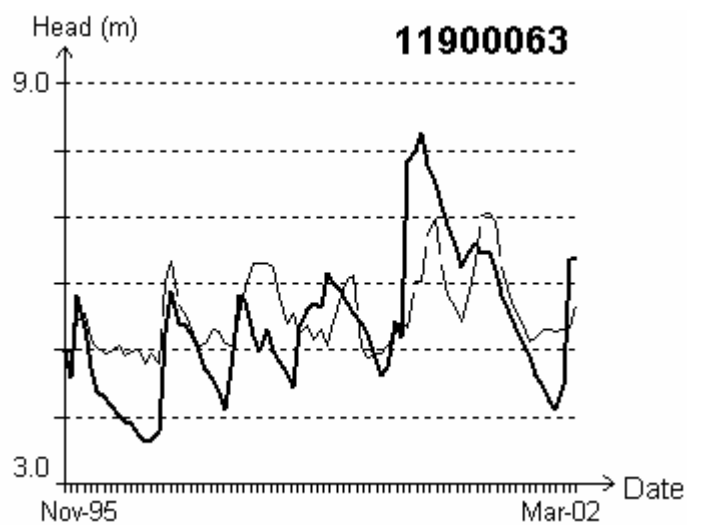
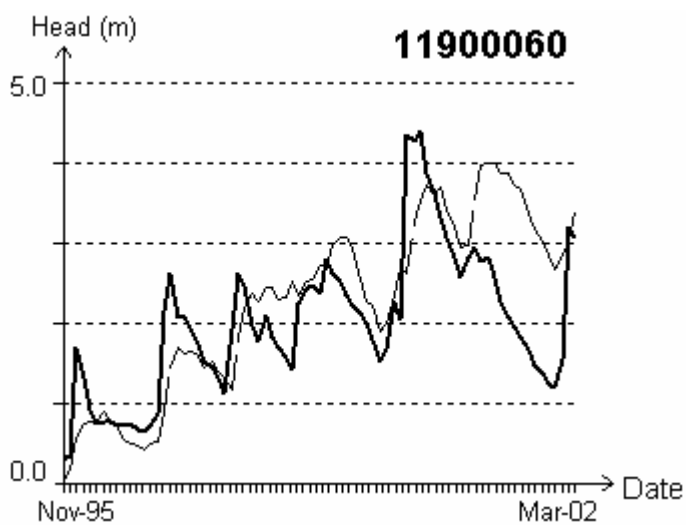
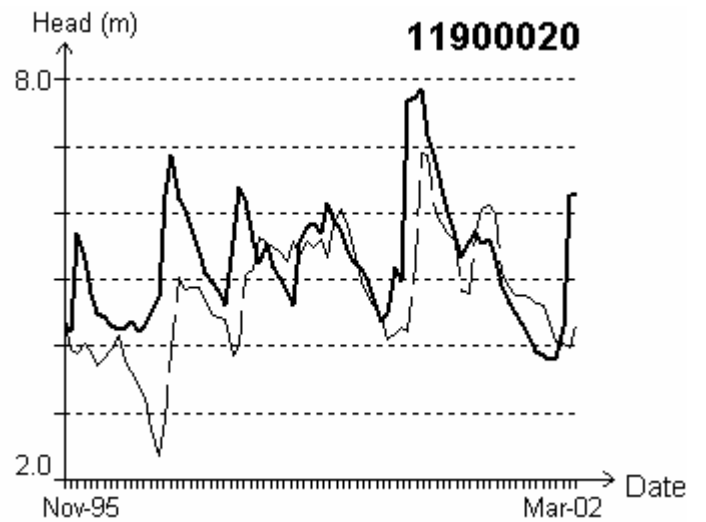
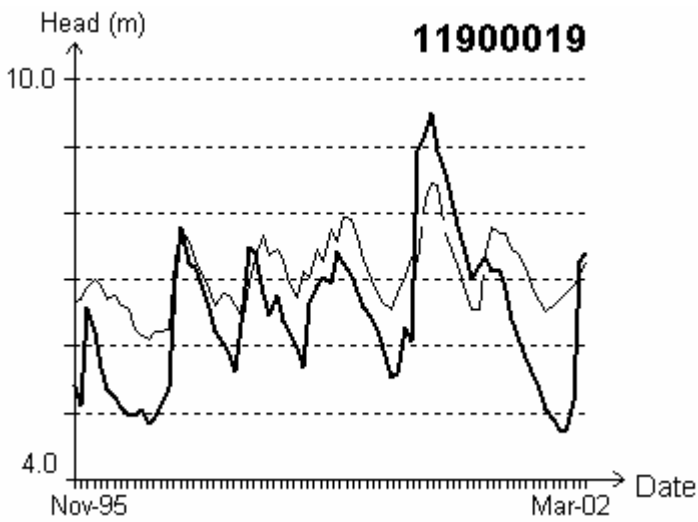
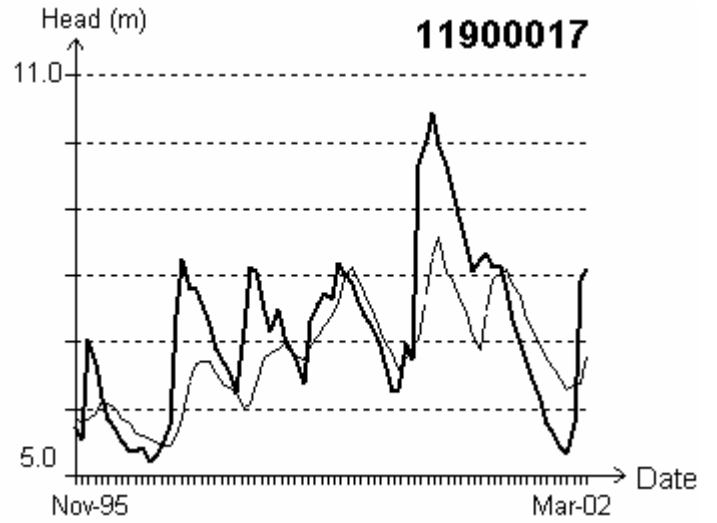
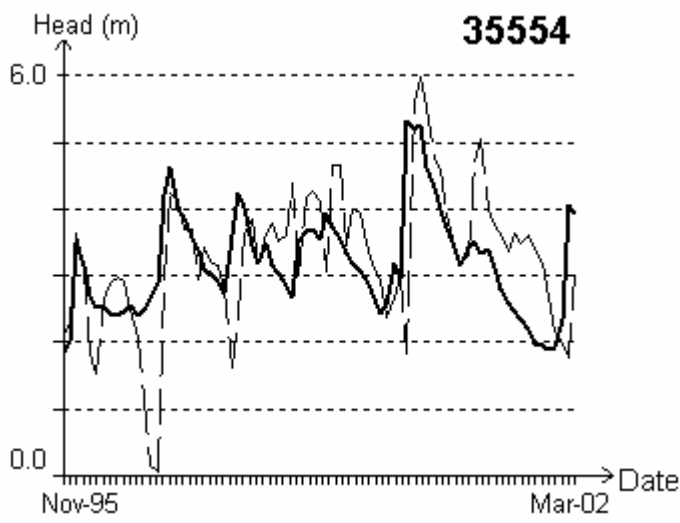
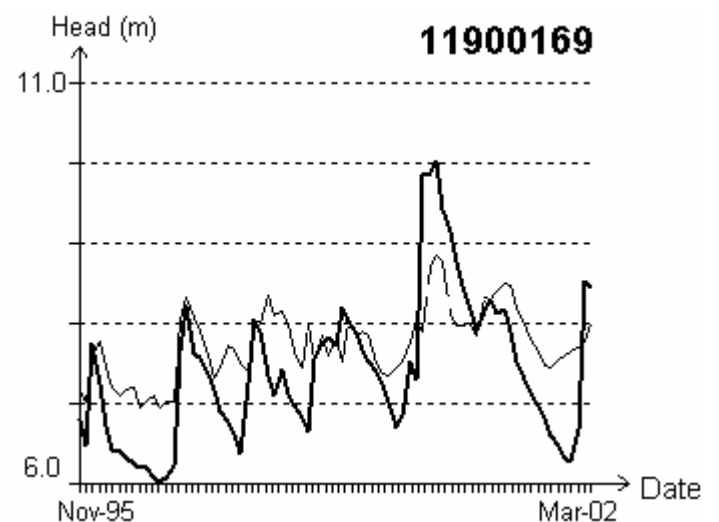
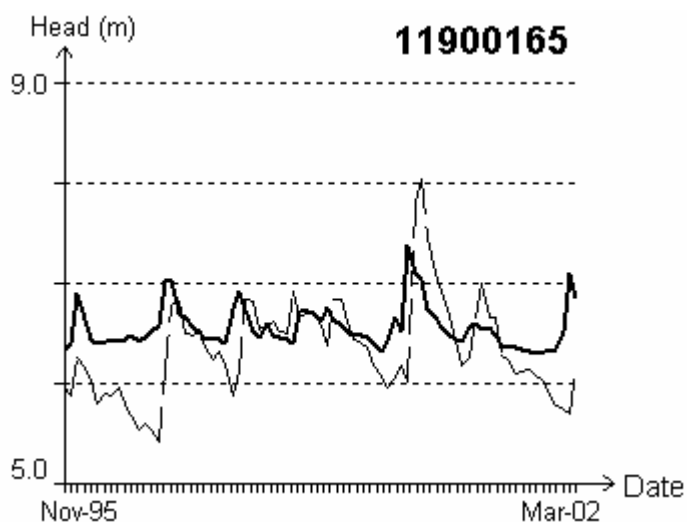
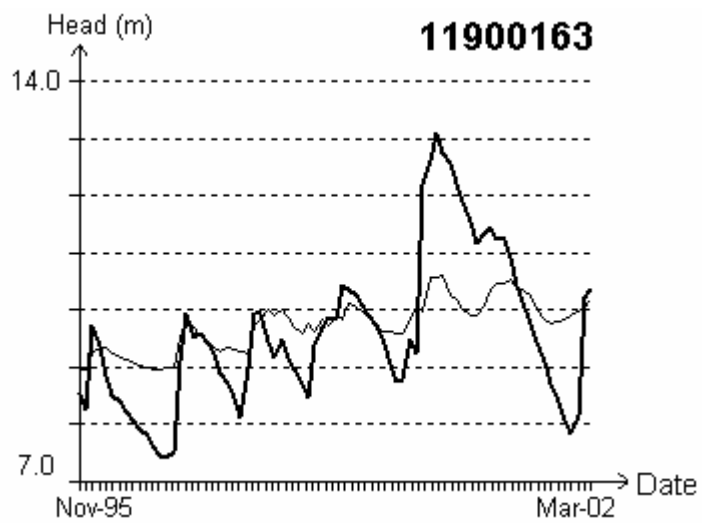
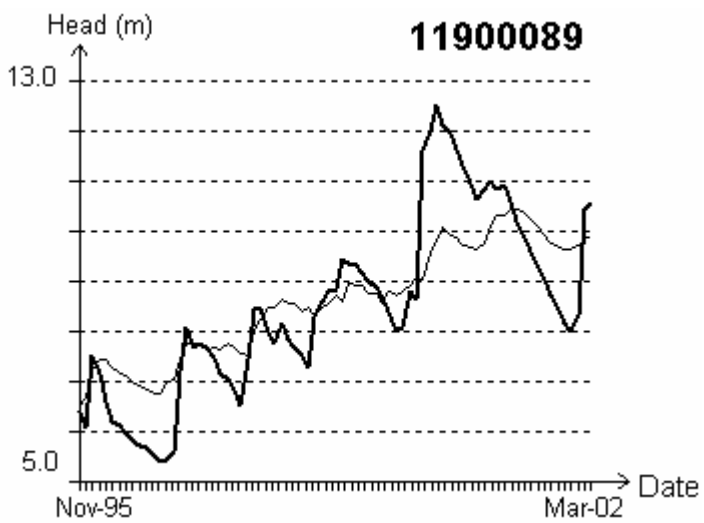
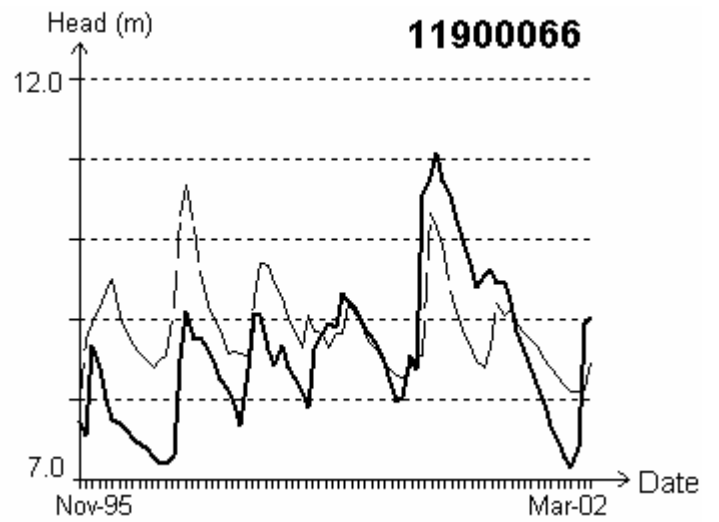
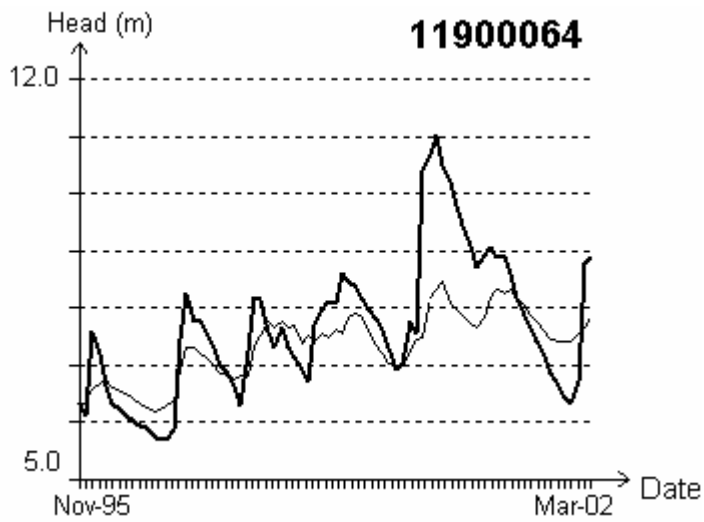


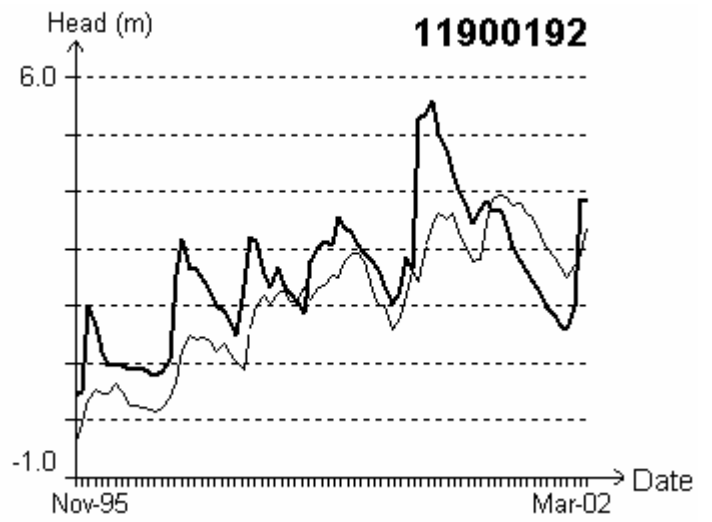
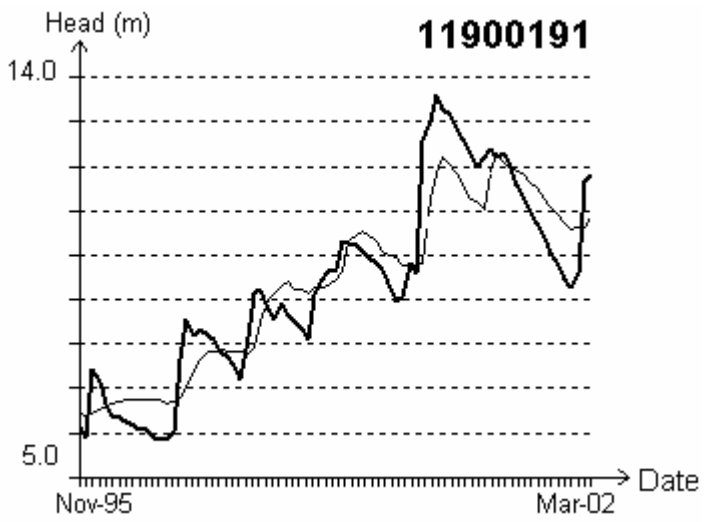
Figure 4.1: Chosen zones and parameter values for the automated calibration using PEST

A hydraulic conductivity range of 0.027 - 50 m/d was computed by PEST, which signifies a heterogeneous aquifer. Specific yield range of 5 to 20 % was used in model calibration. However PEST computed optimum specific yield was 20 % (i.e. upper bound value). Although some pumping data from 1995 to 2000 were missing during the model calibration, correlation coefficient of 0.94 was obtained between observed and calculated heads by subdividing the model area. Results of simulated/modelled and observed hydraulic heads using PEST are shown in Figure 4.2. As can be seen the comparison for all 14 observation bores in the model area is quite reasonable given some uncertainties in pumping data and also the fact that the model does not account for surface runoff.

Figure 4.2: Simulated and observed hydraulic heads for the second attempt using PEST (dark line shows calculated heads and light line shows observed values)







5 Scenario Analysis

The main objective of this work is to model the effects of Val-Bird Weir height on the surrounding water tables. Keeping this in mind, two more simulations were made by lowering the Val-Bird Weir height by 1 m and 2 m respectively. Figure 5.1 shows the initial head distribution of the aquifer in October 1995 and was used for all model calibration runs. Figures 5.2, 5.3 and 5.4 depict the contours of hydraulic heads for the Val-Bird Weir height of 6.7 m, 5.7 m and 4.7 m respectively. Drawdown in heads are shown in Figures 5.5 and 5.6.

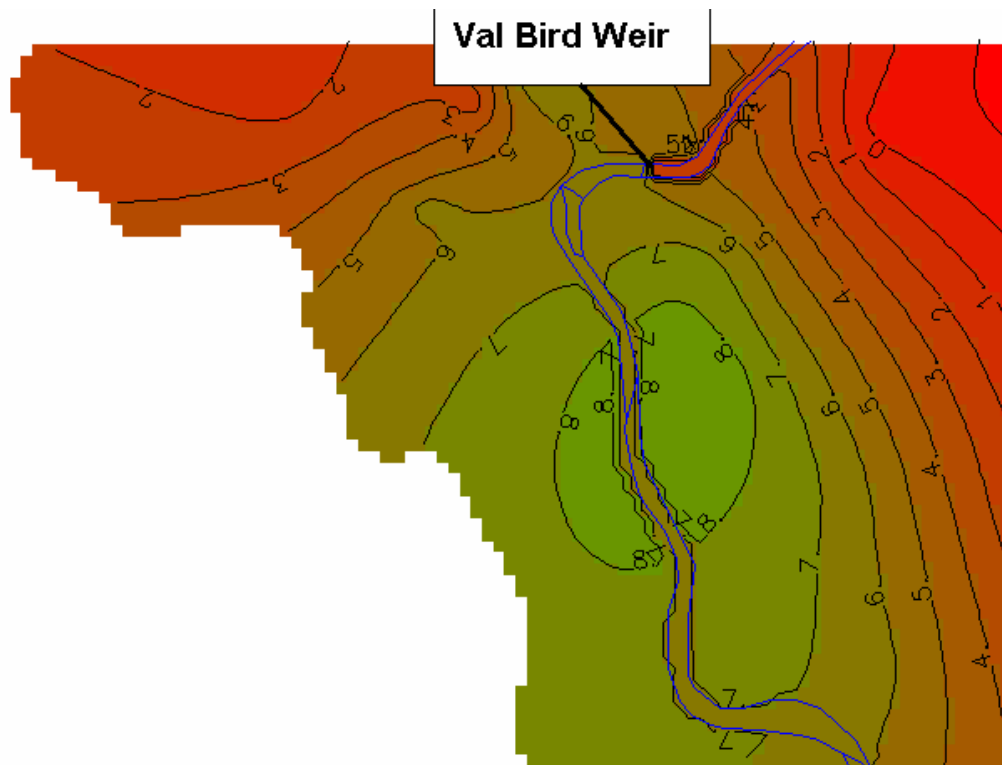


Figure 5.1: Initial hydraulic head in October 1995 (head in the Haughton River upstream of Val-Bird Weir is 6.7m)

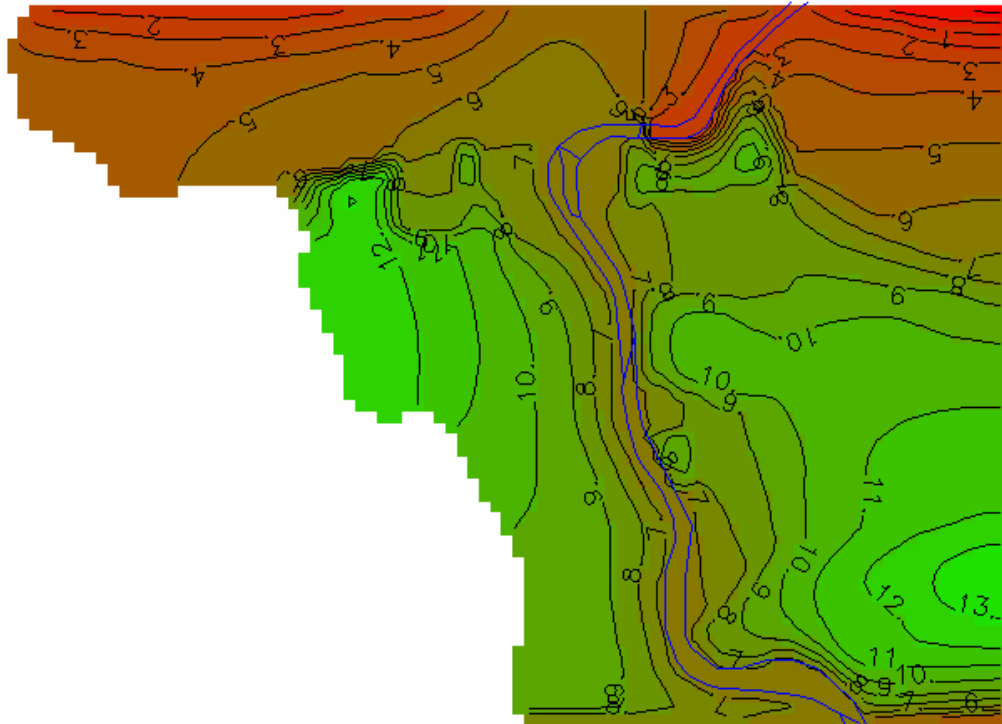


Figure 5.2: Hydraulic head at the end of simulation period in March 2002 (head in the Haughton River upstream of Val-Bird Weir is 6.7m)

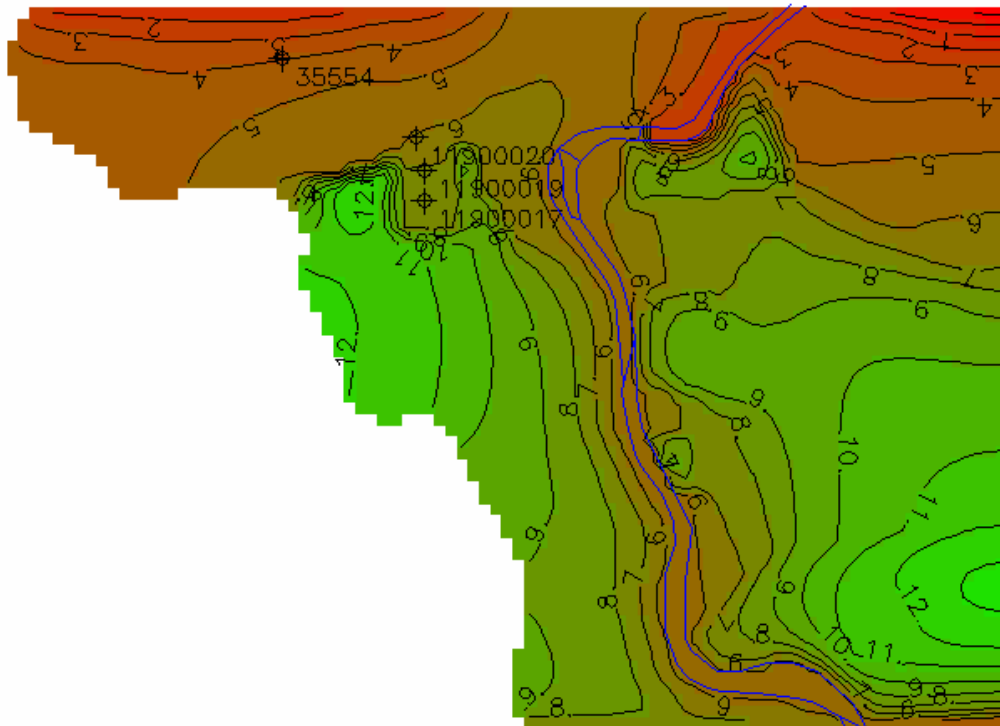


Figure 5.3: Hydraulic head at the end of simulation period in March 2002 (height of Val-Bird Weir is lowered by one meter to 5.7 m)

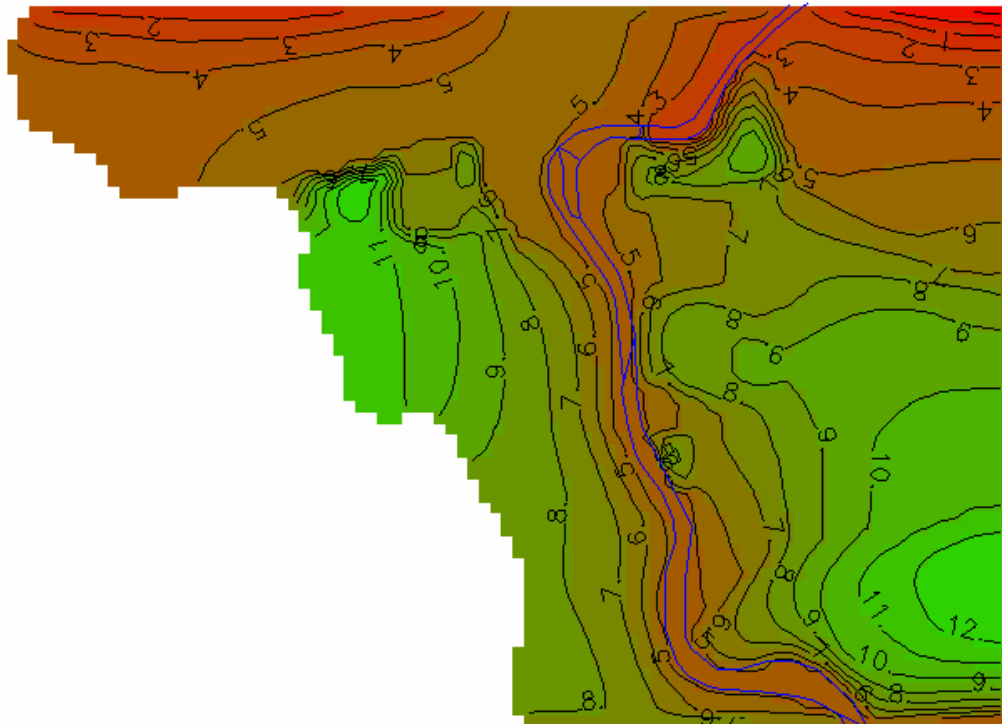


Figure 5.4: Hydraulic head at the end of simulation period in March 2002 ((height of Val-Bird Weir is lowered by two meters to 4.7 m)

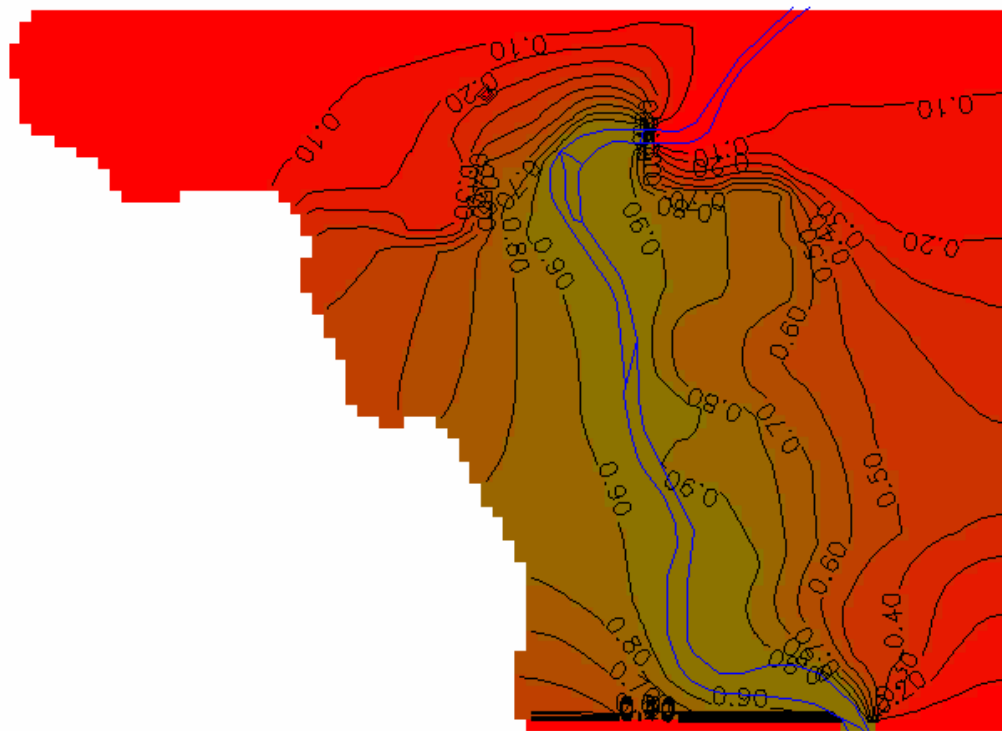


Figure 5.5: Drawdown at the end of simulation period (77 months) (Val-Bird Weir height is lowered by one meter to 5.7 m)

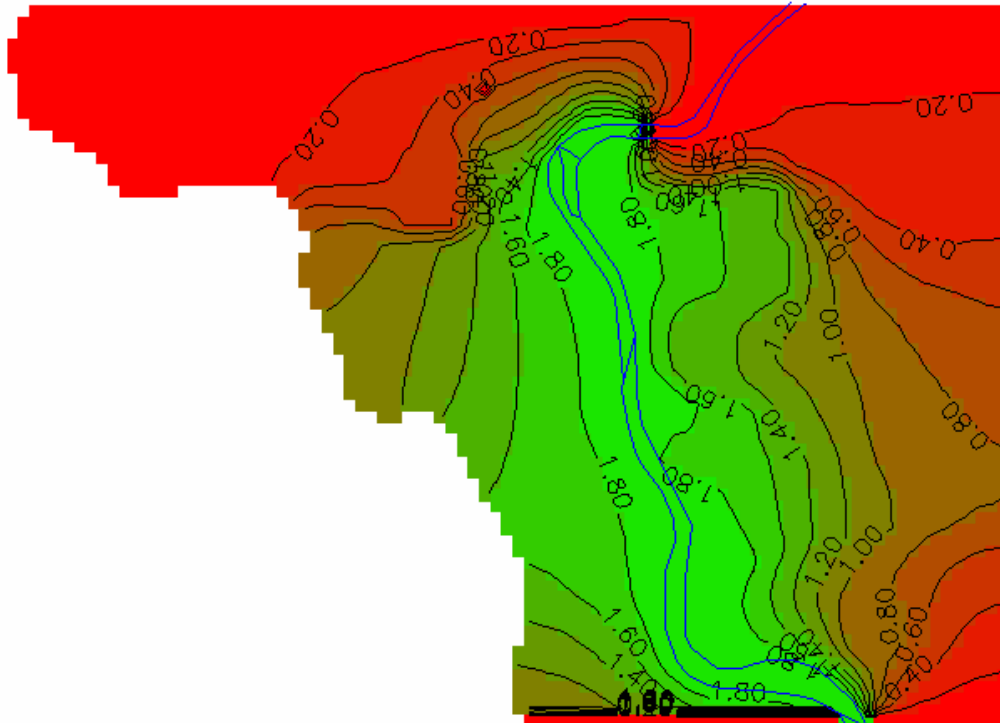


Figure 5.6: Drawdown at the end of simulation period (77 months) (Val-Bird Weir height is lowered by two meters to 4.7 m)

It is important to know the extent and magnitude of drawdowns for the two simulation scenarios. Cross sections were drawn and analysed on both sides of the Haughton River to show the effects of lowering the Val Bird Weir height on water tables (Figure 5.7). These cross sections were drawn from west to east to show the reduction in water level is significant closer to the river and becomes less and less as we move away from the river (Figure 5.8, cross sections 1 & 4, also see Appendix E). Cross section 1 on the western side of the model area (Figure 5.8) clearly shows that the effects of lowering the Val-Bird weir height on water table is felt up to 1.4 km. However, in the eastern part of the model domain, the water table draw down occurs up to 1.3 km. As expected, lowering the weir height by 2 m has greater effects on water table drawdown than by weir height decrease of 1 m.

Figure 5.7: Location and numbering of cross sections

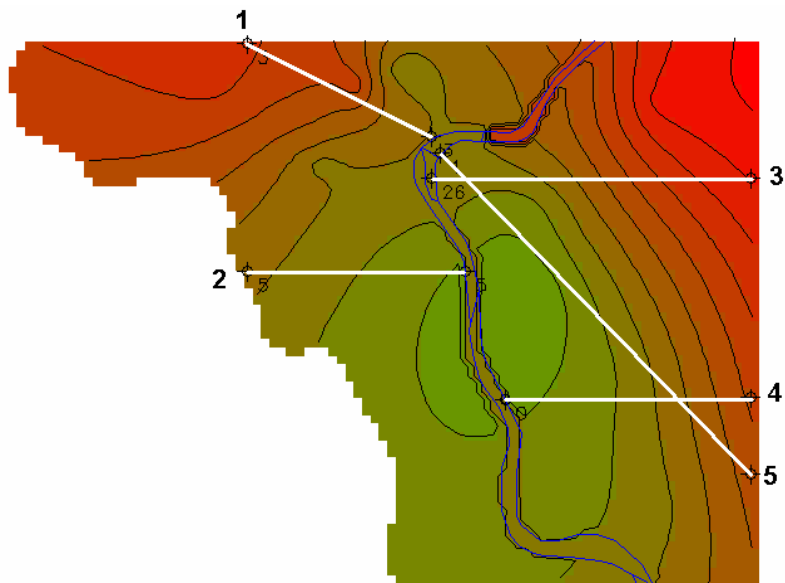
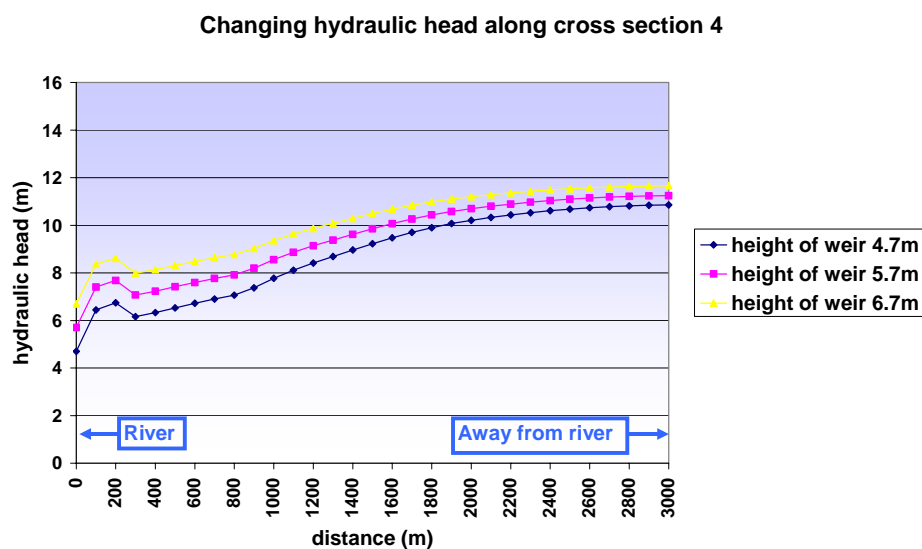
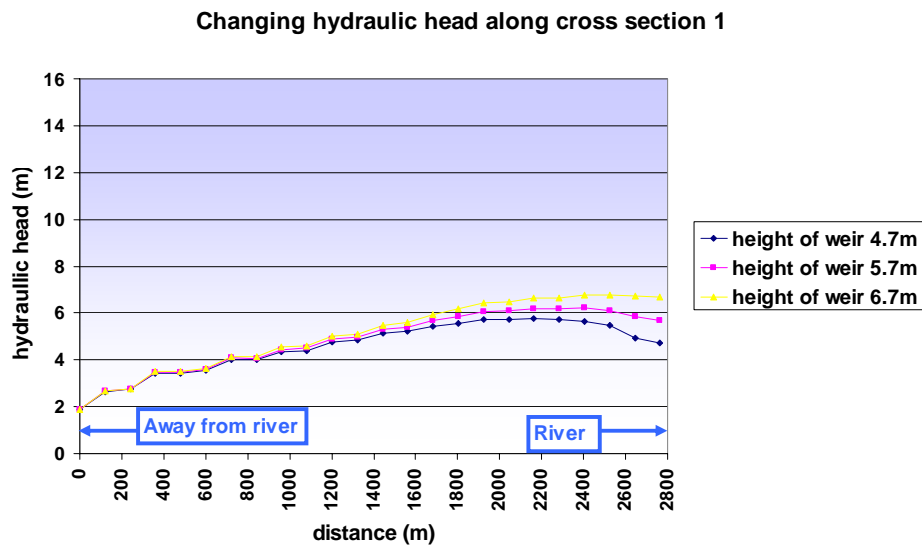


Figure 5.8: Simulated hydraulic head along cross sections 1 and 4 drawn from West to East at the end of simulation period

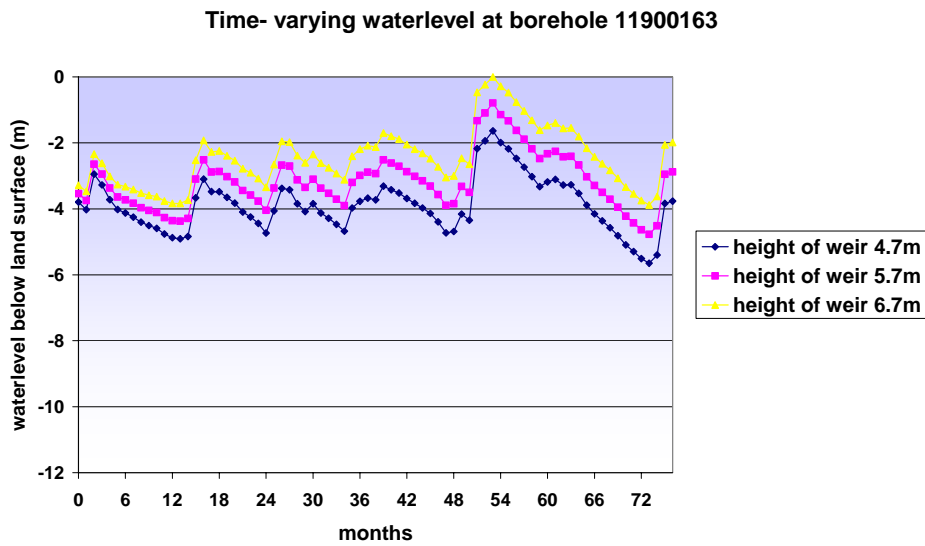
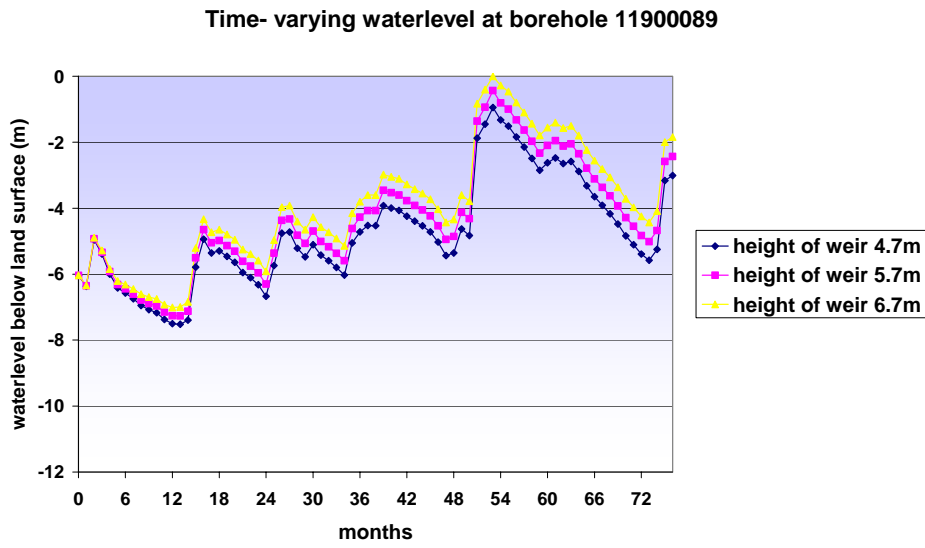


Results were further analysed in detail to look at the effect of decreasing the weir height on the observation bores with time. It showed marginal effects on observation bores on the western side of the Haughton River as 35554, 11900017, 11900019 and 11900020. This is due to the dense brown clay on the western part. Also lowering the Val-Bird weir has small effects on the observation bores away from the river such as bores 11900060, 11900063 and 11900192. The observation bores 11900064, 11900066, 11900089, 11900163, 11900165, 11900169 and 11900191 (Fig. 5.9 and also see Appendix F) has significant effect of lowering the weir height.

5.1 Sensitivity Analysis with Bore 11900066 disabled

Due to uncertainty in 11900066 bore data (as pointed out earlier in section 4.1) it is important to see the effects of disabling this bore on the water tables in the area. It is inconceivable that a bore only ~180m away from the river edge can have a hydraulic head of 9.8m (3.1m higher than the river height). Sensitivity runs were carried out by removing bore 11900066 to see the effects on hydraulic heads and drawdowns in the model area. This process also involved generation of initial hydraulic heads without this bore and rerunning the model simulations for all scenarios. The zone containing bore 11900066 was merged with the neighbouring zone and again PEST was used to optimise heads for the entire model domain. Results from this calibration are shown in Appendix G1, G2 and G3 and drawdown contours clearly highlight slight differences as compared to the initial scenario analyses which included bore 11900066. Analyses of drawdown 2.3 km east of the river shows that the difference in drawdown in the case of lowering the Val-Bird Weir by 1m is 0.13m. However when the Val-Bird Weir height is lowered by 2m, the difference in head drawdown is about 0.17m. Given some uncertainties in aquifer properties and estimation of recharge, these differences are not significant. It is however recommended that the bore 11900066 data be re-examined and verified.

Figure 5.9: Simulated water level at boreholes during simulation period (over 77 months)



6 Conclusion

Rising watertable is a major issue in this area. Groundwater modelling carried out in this study shows that the water tables closer to the Haughton River can be lowered by lowering the Val-Bird weir height.

- Model simulations show that Weir height reduction lowers the water table in the area closer to the Haughton River, whereas away from the river lowering of the water table is marginal.
- Lowering the Val-Bird Weir height has more effect on the water table on the Eastern area (up to 3 km away from the river) due to higher sand content of the aquifer and thus higher hydraulic conductivity than on the Western area (up to 1.4 km away from the river).
- Simulation results show a strong correlation between Val-Bird Weir height and the surrounding water tables. Thus lowering the weir by two metres may result in twice as much drawdown than lowering the weir by one metre.
- Trial and error calibration for bore 11900066 showed a poor comparison between observed and modelled heads. The possible reason for this discrepancy could be an incorrect elevation or water level entry in the database. Due to this uncertainty, sensitivity runs were carried out by disabling this bore and average differences in drawdown 2.3 km east of the river were found to be very small (0.15 m).

Modelling carried out in this study would assist in the future irrigation management of the Haughton river area in the BRIA.

7 Appendices

A. Strata Data for Model Area

11900017	0	0.3	SOIL
	0.3	2.44	HARD CLAY BROWN
	2.44	3.66	HARD CLAY GRITTY BROWN
	3.66	4.88	CREAMY CLAY SANDY BROWN
	4.88	6.4	HARD CREAMY CLAY BROWN WITH BLACK STREAKS
	6.4	7.32	GREY-WHITISH CLAY SILTY-HARD
	7.32	8.38	SAND COARSE WHITE-FAIRLY CLEAN
	8.38	9.3	HARD CLAYBOUND SAND
	9.3	10.06	HARD CREAMY CLAY GRITTY BROWN
	10.06	10.67	BROWN GRANITY CLAY (HARD)
	10.67	13.11	WHITISH CLAY GRITTY BROWN (HARD)
	13.11	15.24	WEATHERED GRANITE
	15.24	18.29	WEATHERED GRANITE AND ROCKS
	18.29	21.34	WEATHERED GRANITE AND WHITE ROCKS
11900019	0	0.46	BROWN SOIL
	0.46	1.22	HARD REDDISH CLAYEY SOIL
	1.22	2.44	HARD BROWN GRAVELLY CLAY
	2.44	4.57	BROWN CREAMY CLAY SANDY
	4.57	5.49	CLAY SILTY BROWN AND GREY
	5.49	8.84	CREAMY CLAY BROWN WITH BLACK STREAKS
	8.84	9.75	FINE CLAYBOUND SAND-SOFT
	9.75	11.28	HARD CLAY SANDY
	11.28	15.24	GREY AND CLAY GRITTY BROWN (HARD)
	15.24	16.46	WEATHERED GRANITE
			SWL 15FT 4-12-69
11900020	0	0.91	TOPSOIL
	0.91	3.96	CLAY SANDY
	3.96	7.01	SPOTTY RED CLAY
	7.01	10.06	BLUE CLAY AND DECOMP ROCK
	10.06	13.11	BLACK AND GREY SPOTTED CLAY
	13.11	16.15	SANDSTONE
	16.15	22.56	WEATHERED GRANITE
	22.56	23.47	GRANITE ROCK
			00/00/0000 SWL -5.20 M TMP NUL C
	16	22	QUALITY DESCRIPT/CONDUCT: 6250
11900060	0	0.46	ROAD FORMATION

	0.46	3.66	CLAY BROWN
	3.66	4.88	CLAY SANDY BROWN
	4.88	6.1	SPOTTY RED CLAY
	6.1	10.67	CLAYBOUND GRAVEL AND SAND
	10.67	15.85	CLAY BROWN
	15.85	23.47	CLAY SANDY BROWN
	23.47	29.87	CLAYBOUND CG SAND AND GRAVEL
	29.87	32.31	RED CLAY GRITTY
	32.31	38.71	WEATHERED GRANITE
11900063	0	0.61	TOPSOIL
	0.61	3.66	LOAM
	3.66	6.71	CLAY BROWN
	6.71	9.75	SPOTTY RED CLAY
	9.75	12.8	CLAY AND STONES
	12.8	15.85	CLAY SANDY
	15.85	18.9	CLAY AND STONES
	18.9	21.95	BROWN SPOTTY CLAY AND SAND
	21.95	27.74	RED SPOTTY CLAY AND SAND
	27.74	32.31	CLAY BROWN
	32.31	33.83	WEATHERED GRANITE
	33.83	35.05	GRANITE ROCK
			WATER STRUCK 42FT SWL28FT 14.12.64
11910064	0	15.24	MAINLY CLAY SWL 36FT
	15.24	18.29	BROWN SAND COARSE WITH
			10 PERCENT OF 1IN GRAVEL
			REASONABLY CLEAN
	18.29	20.73	CREAM SAND COARSE WITH
			25 PERCENT OF 2IN GRAVEL
	20.73	21.95	CREAM SAND COARSE WITH
			25 PERCENT OF 2IN GRAVEL
			V CLEAN
	21.95	22.86	CLAY BROWN
	22.86	25.3	BROWN SAND COARSE SOMEWHAT DIRTY
	17	25	QUALITY DESCRIP/CONDUCT: 850
11900066	0	0.3	TOPSOIL
	0.3	2.44	CLAY SILTY BROWN
	2.44	3.66	CLAY BROWN
	3.66	5.49	CLAY SILTY BROWN
	5.49	6.4	CLAY COLOURED
	6.4	7.32	CLAY SAND

	7.32	12.19	CLAY SANDY
	12.19	13.72	SAND EMBEDDED IN CLAY
	13.72	18.59	CLAY COLOURED
	18.59	19.81	CLAY BROWN
			19/01/1971 SWL -8.20 M TMP NUL C
11900089			DRILLER BLIESNER ROTARY SWL 8.06M
	0	0.2	GREY SILTY TOPSOIL
	0.2	0.5	CLAY GRITTY BROWN
	0.5	1.1	LIGHT BROWN FINE SANDY CLAY SILTY
			WITH TRACES OF LIME
	1.1	7.2	VERY CLAY SILTY BROWN
	7.2	7.9	CLAYEY FINE - MEDIUM SAND
	7.9	8	CLAY GREY
	8	8.7	CLAYBOUND SAND AND GRAVEL
	8.7	9.7	LIGHT CLAY SILTY BROWN
	9.7	10	CLAYEY FINE SAND
	10	11.5	LIGHT CLAY SILTY BROWN
	11.5	13	LIGHT BROWN SANDY CLAY SILTY
	13	13.8	CEMENTED SAND FINE SILTY
	13.8	14.8	GREY AND CLAY SILTY BROWN
	14.8	16.5	GREY AND BROWN FINE SANDY CLAY SILTY
	16.5	16.7	LAYER OF FRACTURED LIME
	16.7	18.3	CLAY GREY AND BROWN
	18.3	20.3	LIGHT CLAY SILTY BROWN
	20.3	22.9	CLAY SILTY BROWN
	22.9	25.7	BROWN FINE SANDY CLAY SILTY
	25.7	26.9	CLAYEY SAND COARSE AND GRAVEL
	26.9	27.3	COMPLETELY ROCK WEATHERED
	27.3	27.6	HIGHLY ROCK WEATHERED
	27.6	28.4	COMPLETELY ROCK WEATHERED
	28.4	33	COMPLETELY HIGHLY ROCK WEATHERED
	33	33.6	HIGHLY ROCK WEATHERED
	33.6	33.65	FRESH ROCK
	27	33	QUALITY DESCRIP/CONDUCT: 1060
11900165	0	2.5	CLAY FINE SANDY BROWN
	2.5	2.8	CLAY BROWN
	2.8	3.8	CLAY SANDY
	3.8	5.4	SAND FINE
	5.4	13	GRAVEL SANDY WATER LOSS
	13	14	GRAVEL SANDY LOOSE
	14	14.2	GRAVEL CLAYBD GREY VALCANIC WEATH/RK

	14.2	15	GRAVEL CLAYBD BRN VALCANIC WEATH/ROCK
	15	19.2	BROWN NEAR TOP BECOMING LIGHT GREY/ REDDISH BROWN WITH DEPTH THIS WAS ORIGINALLY A COARSE SEDIMENT THAT HAS DECOMPOSED
	19.2	21.3	SAND SAND CLAYEY IS WHITE FELDSPAR AND GREY QUARTZ CLAY IS LIGHT GREY PUGGY DECOMPOSED ALLUVIUM
	21.3	25.4	CLAY SILTY LIGHT GREY STIFF
	25.4	28.8	GRANITE WEATHERED GEOLOGIST COX BP76 ROTARY
	0	1	SOIL
	1	2	CLAY SILTY REDDISH BROWN
	2	3.8	CLAY SANDY FINE REDDISH BROWN
	3.8	13.5	SAND AND GRAVEL 10MM CLEAN FRESH
	13.5	14	CLAY BLUISH GREY
	14	19	CLAY MOTTLED TO LIGHT GREY/LIGHT
11900169	0	1.9	CLAY BROWN
	1.9	2.3	CLAY BROWN SANDY
	2.3	3	CLAY BROWN SANDY ROCK WEATHERED
	3	4	CLAYEY GRAVEL HARD CEMENTED SAND
	4	4.8	CLAY FIRM GREY COURSE SANDY
	4.8	5	CLAYEY GRAVEL H/CEMENTED COURSE SAND
	5	8.6	CLAYEY GRAVEL FIRM SANDY
	8.6	9	CLAY FIRM SANDY
	9	14.1	CLAY GREY FIRM
	14.1	20.2	CLAYEY GRAVEL WHITE
	20.2	22	CLAY SANDY GREY/BROWN BOULDERS 21.00
	22	25.2	CLAY SANDY MOTTLED HARD CEMENTED SAND
	25.2	27	CLAY SANDY/GRANITY HARD CEMENTED SAND
	27	31.2	CLAY SOFTER MOTTLED GRANTIIY AND SANDY
	31.2	33.4	CLAY GRANTIIY WEATHERED
11900191	0	1.6	CLAY SANDY BROWN FINE GRAINED.
	1.6	2.8	SAND ORANGE/BROWN V/FINE GRAINED GRADING TO MED GRAINED WITH DEPTH.
	2.8	11.8	CLAY SANDY L/GREY/BROWN WITH MINOR GREEN/BLUE CLAY MED GR. SAND MINOR MNO2 NODULES TO 6MM V/MINOR COARSE GRAVEL.
	11.8	16.5	CLAY SANDY L/GREY/BROWN WITH L/GREY AND YELLOW MOTTLE WITH LAYERS OF V/

			SILT.
	16.5	26	SAND CLAYEY/CLAY SANDY L/CREAM AND
			FLESH COLOURED MOTTLE SAND MED GR.
			WITH V/MINOR SUBROUNDED GRAVEL.
	26	27.1	SAND SL/CLAYEY L/CREAM COLOURED V/
			COARSE SOME COBBLE/GRAVEL BANDS.
	27.1	30.6	CLAY SANDY L/CREAM COLOURED WITH
			FLESH PINK COLOURED MOTTLE AND MINOR
			FRIABLE INDURATED SAND CLAYEY
			FRAGMENTS.
	30.6	33.3	GRANITE EXTREMELY WEATHERED SL/CLAYEY
			MINOR CALCRETE MUCH MICA.
			33.3 END OF BORE - REFUSAL.
11900192	0	1	CLAY BROWN
	1	4	CLAY SANDY BROWN/SAND GREY PARTICLES
			ARE MED GRAINED.
	4	5.5	CLAY SANDY BRN SAND IS MED TO COARSE.
	5.5	9	CLAY SL/SANDY GREY/BLUE/GREY WITH
			EXTENSIVE BRICK RED MOTTLE.
	9	12	CLAY L/GREY/BROWN SL/SANDY SOME RED
			MOTTLE.
	12	13	SAND CLAYEY/ CLAY SANDY L/GREY/BROWN
			SAND COARSE IS SUBROUNDED.
	13	16.3	CLAY L/GREY/BROWN.
	16.3	20	CLAY REDDISH/BROWN WITH L/GREY/BROWN
			MOTTLE.
	20	24	CLAY L/GREY/BROWN WITH REDDISH
			BROWN MOTTLE.
	24	25	SAND ORANGE/BROWN MED TO COARSE GR.
			SUBROUNDED.
	25	27	SAND L/GREY COARSE SL/CLAYEY.
	27	30.2	SAND COARSE L/ORANGE/BROWN.
	30.2	33.6	SAND CLAYEY L/GREY WITH REDDISH
			MOTTLE MED TO COARSE GR. COARSER WITH
			DEPTH HARDER DRILLING.
	33.6	38.1	GRANODIORITE EXTREMELY WEATHERED
			K-FELDSPAR RICH WITH DEPTH ALTERED.
			38.1 END OF BORE
			NOT REFUSAL.

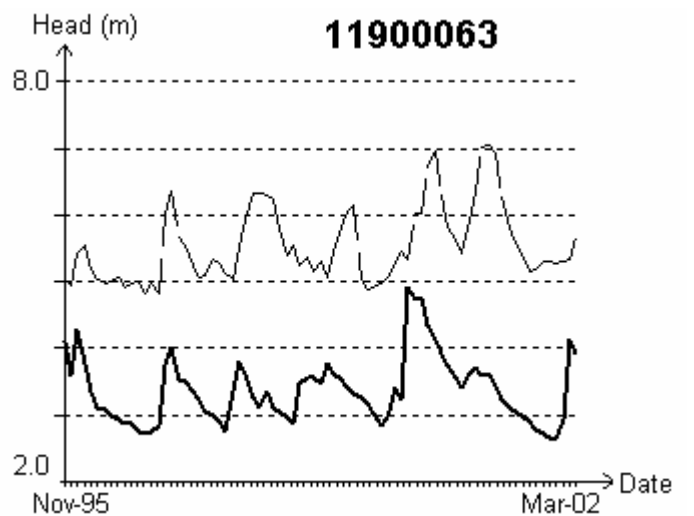
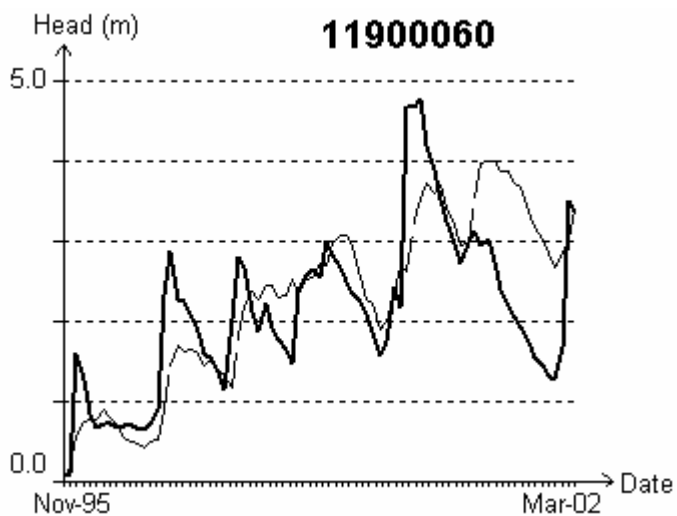
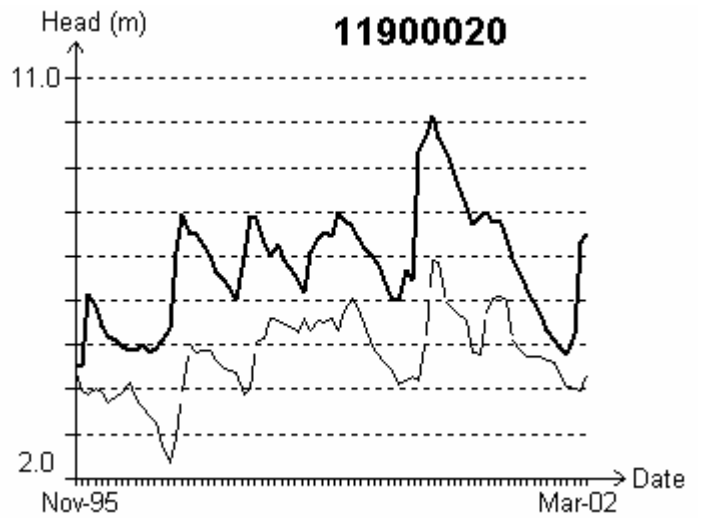
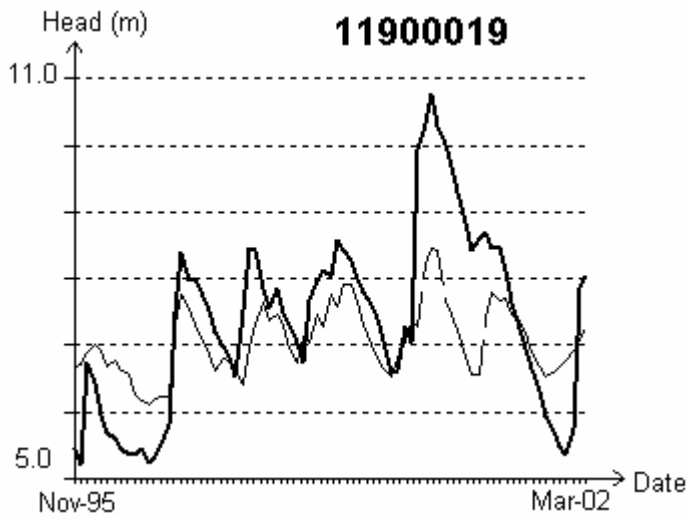
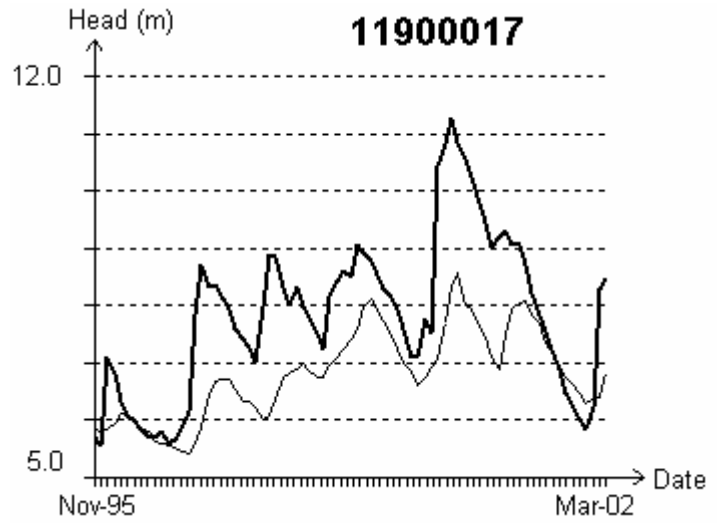
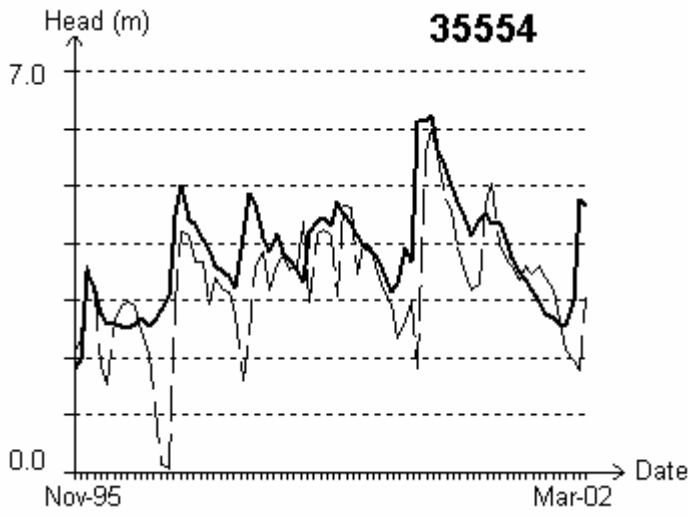
B. Pumping Data for Model Area in ML

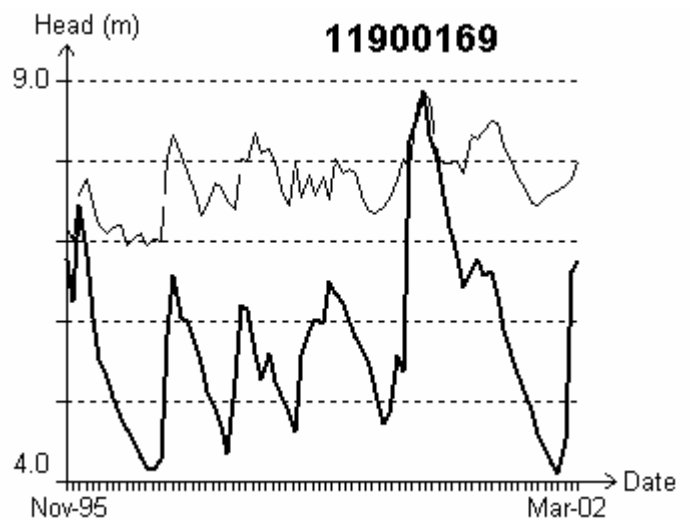
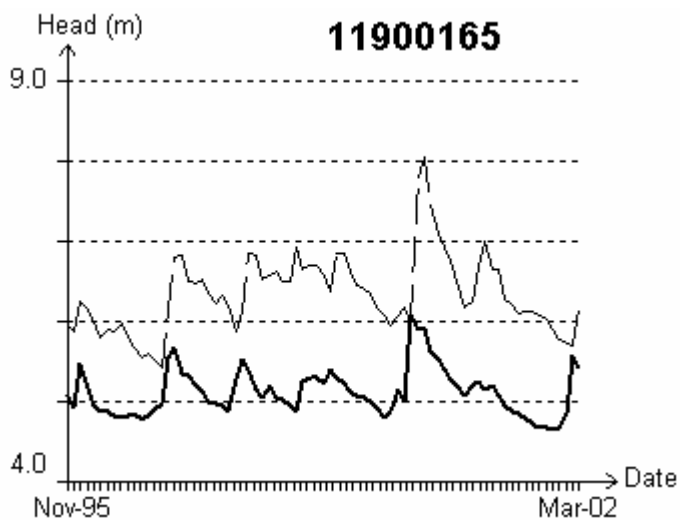
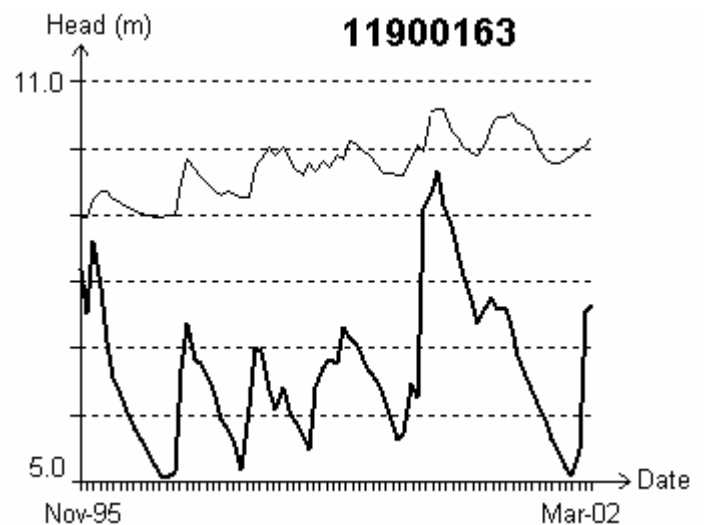
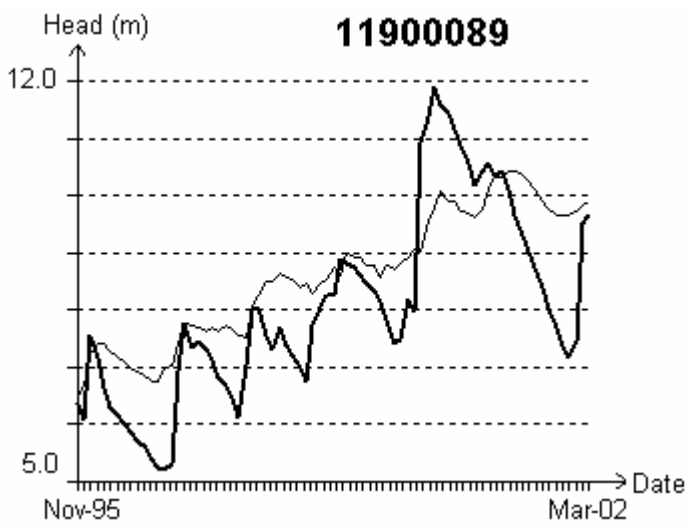
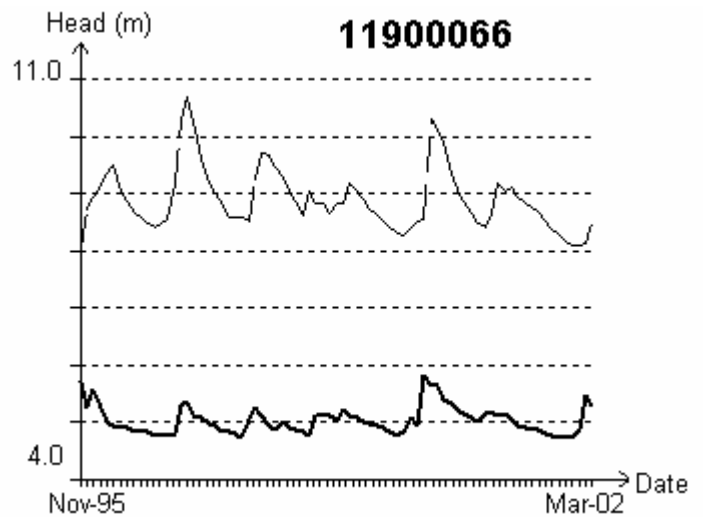
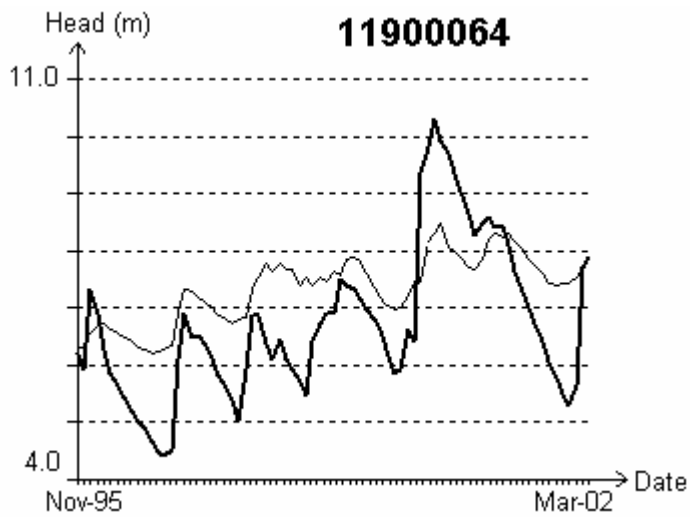
	total (ML)	pumping west (ML)	pumping east (ML)
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1/01/1996	1578.75	1022.00	556.75
1/02/1996	1492.75	936.00	556.75
1/03/1996	1402.75	846.00	556.75
1/04/1996	1469.75	913.00	556.75
1/05/1996	1317.50	683.50	634.00
1/06/1996	1254.50	620.50	634.00
1/07/1996	1178.00	706.00	472.00
1/08/1996	2200.00	1305.00	895.00
1/09/1996	2578.00	1592.00	986.00
1/10/1996	1430.00	732.00	698.00
1/11/1996	2688.00	1727.00	961.00
1/12/1996	3175.00	1959.00	1216.00
1/01/1997	3662.00	2166.00	1496.00
1/02/1997	1799.00	1098.00	701.00
1/03/1997	1080.50	683.50	397.00
1/04/1996	956.50	559.50	397.00
31/05/1997	848.00	474.00	374.00
30/06/1997	289.00	82.00	207.00
1/07/1997	679.00	402.00	277.00
1/08/1996	678.00	401.00	277.00
1/09/1996	678.00	401.00	277.00
1/10/1996	1828.33	1135.67	692.67
1/11/1997	1837.33	1144.67	692.67
1/12/1997	1828.33	1135.67	692.67
1/01/1998	759.00	404.00	355.00
1/02/1998	760.00	405.00	355.00
1/03/1998	759.00	404.00	355.00
1/04/1998	1315.00	696.00	619.00
1/05/1998	1314.00	695.00	619.00
1/06/1998	431.25	244.50	186.75
1/07/1998	605.25	418.50	186.75
1/08/1998	426.67	239.92	186.75
1/09/1998	369.25	182.50	186.75
1/10/1998	1462.00	767.67	694.33
1/11/1998	1462.00	767.67	694.33
1/12/1998	1462.00	767.67	694.33
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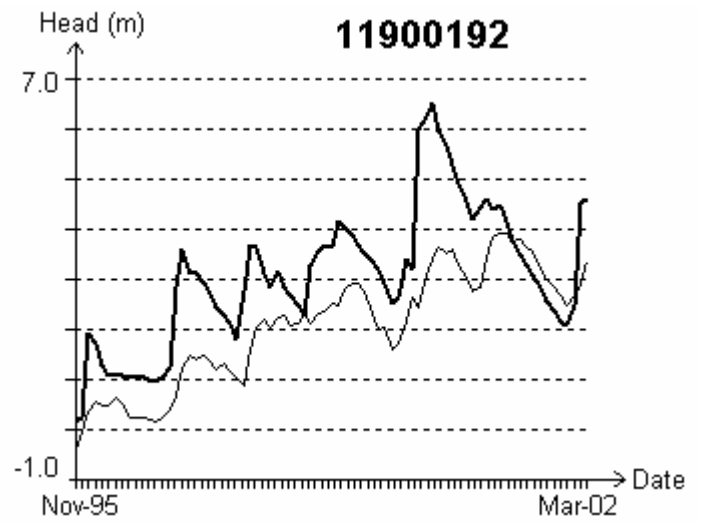
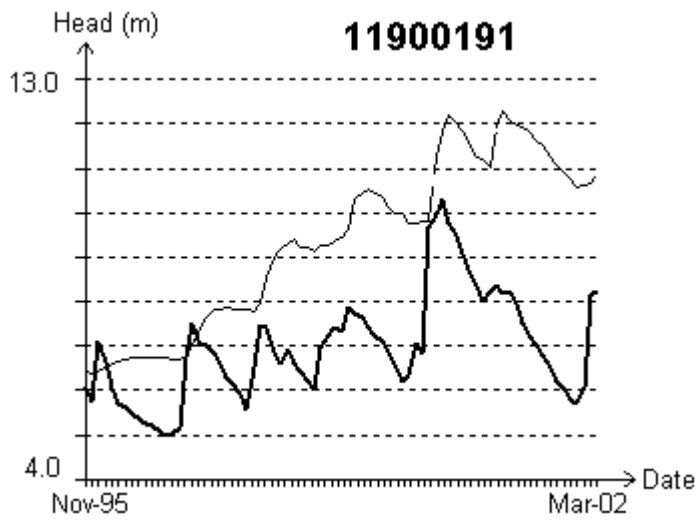
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1/05/1999	946.00	497.33	530.67
1/06/1999	946.00	497.33	530.67
1/07/1999	1275.67	746.33	618.33
1/08/1999	1275.67	746.33	618.33
1/09/1999	1275.67	746.33	618.33
1/10/1999	1204.75	657.75	720.67
1/11/1999	1204.75	657.75	720.67
1/12/1999	1204.75	657.75	720.67
1/01/2000	1204.75	657.75	631.67
1/02/2000	674.00	372.33	386.33
1/03/2000	674.00	372.33	386.33
1/04/2000	674.00	372.33	331.00
1/05/2000	132.00	54.50	106.83
1/06/2000	132.00	54.50	106.83
1/07/2000	979.33	580.00	399.33
1/08/2000	979.33	580.00	540.33
1/09/2000	979.33	580.00	681.33
1/10/2000	437.50	259.75	215.08
1/11/2000	437.50	259.75	215.08
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1/10/2001	2165.33	1296.00	1043.00
1/11/2001	2165.33	1296.00	1043.00
1/12/2001	2165.33	1296.00	1043.00
1/01/2002	2258.33	1358.33	1106.00
1/02/2002	2258.33	1358.33	1313.00
1/03/2002	2258.33	1358.33	1230.00

C. Results of the Trial and Error Calibration

Dark line shows calculated heads and grey line shows observed values

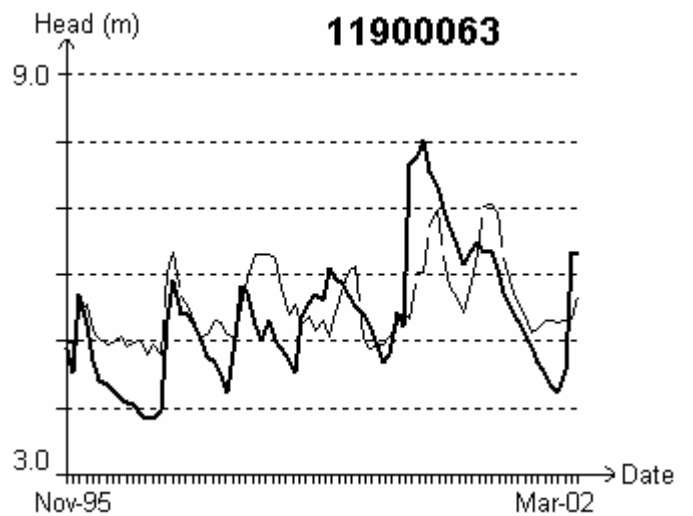
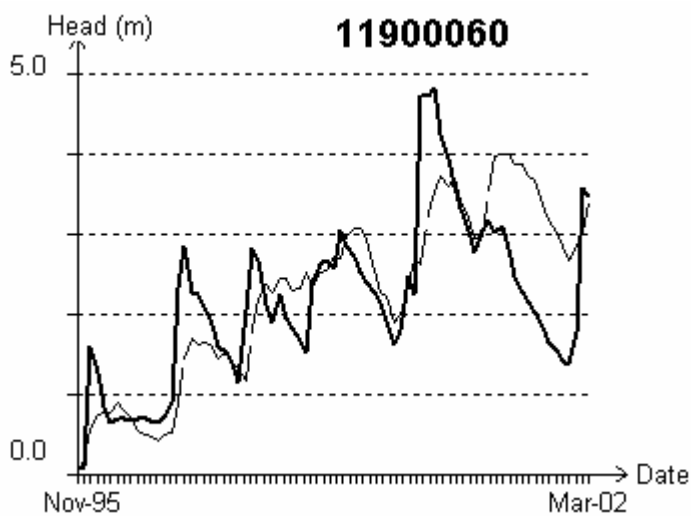
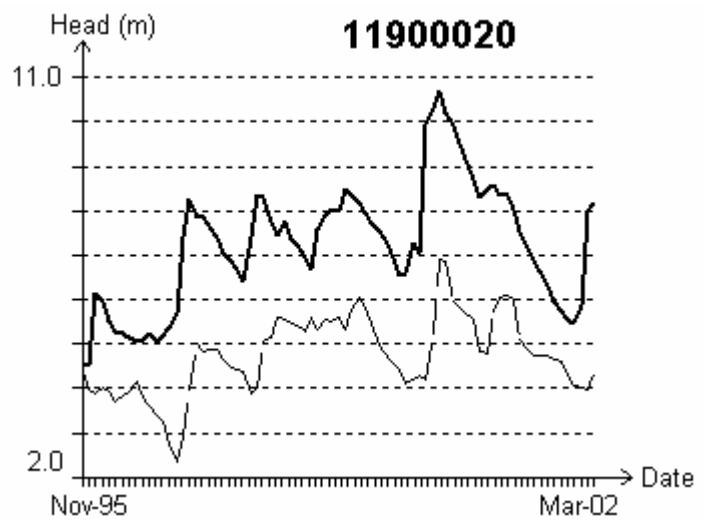
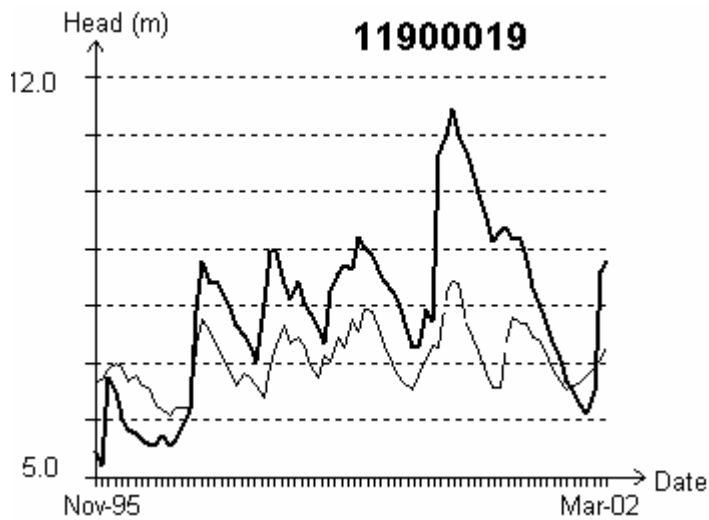
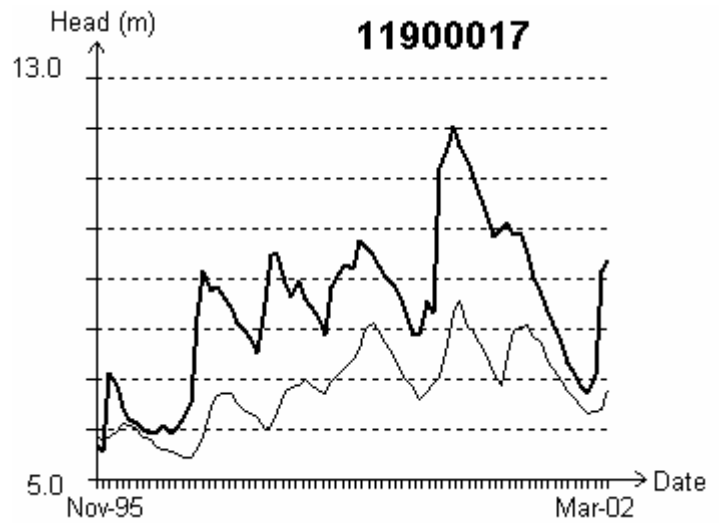
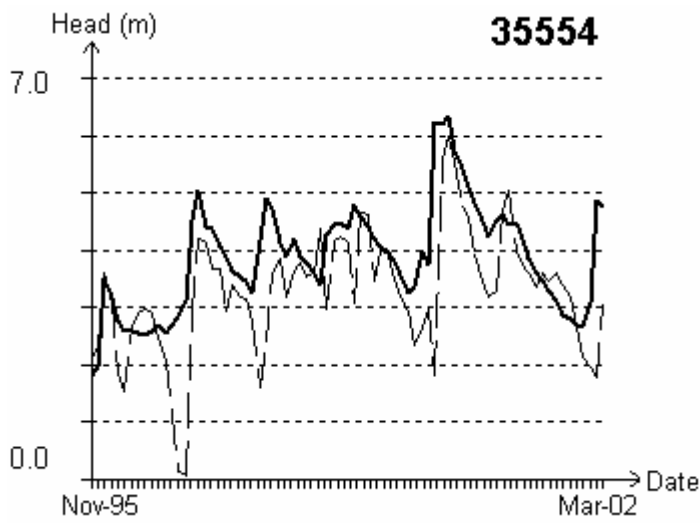


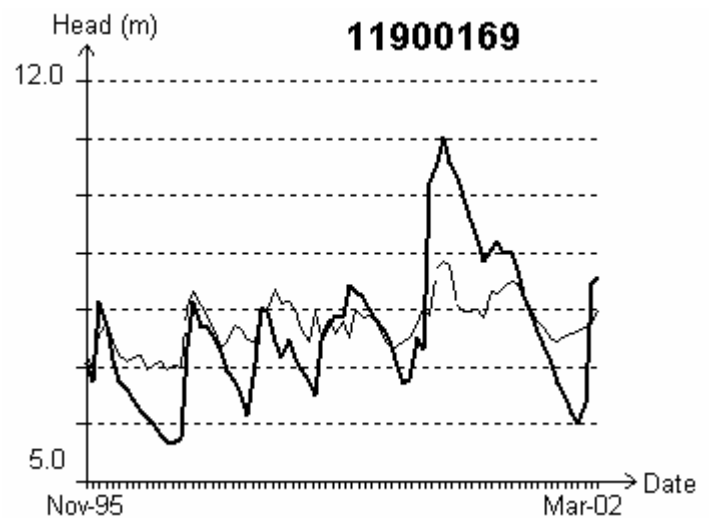
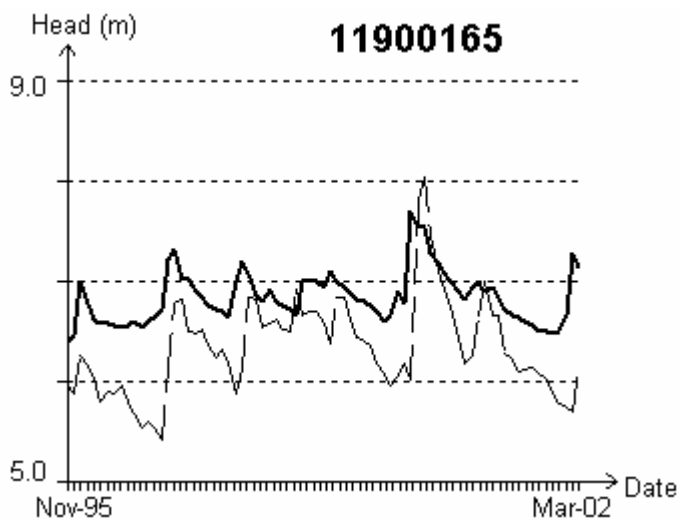
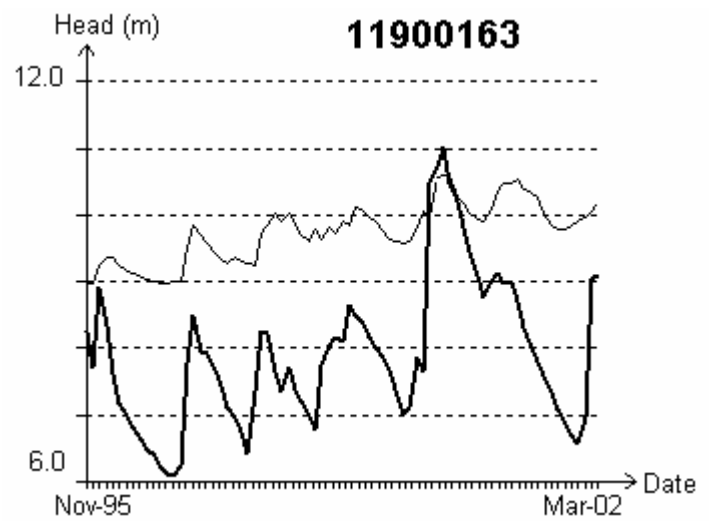
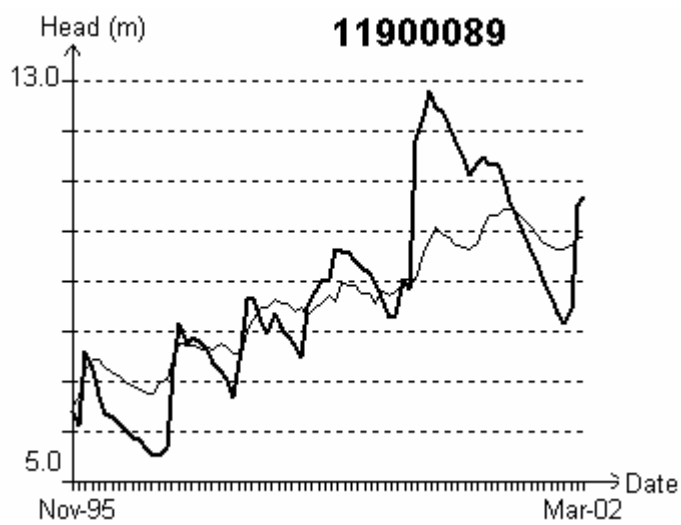
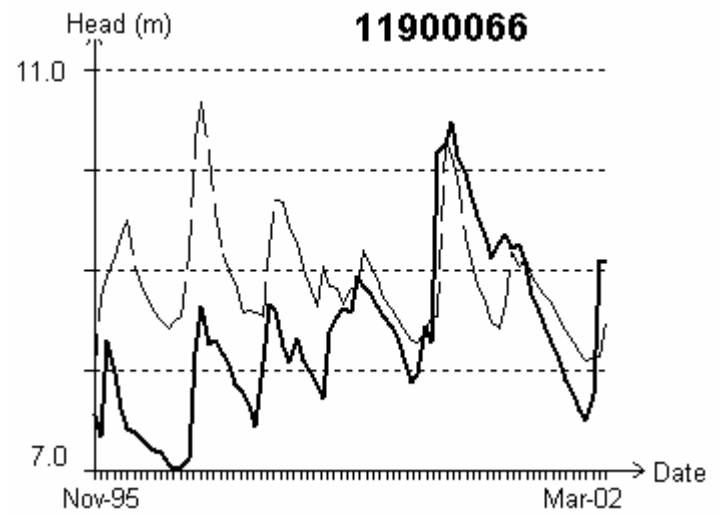
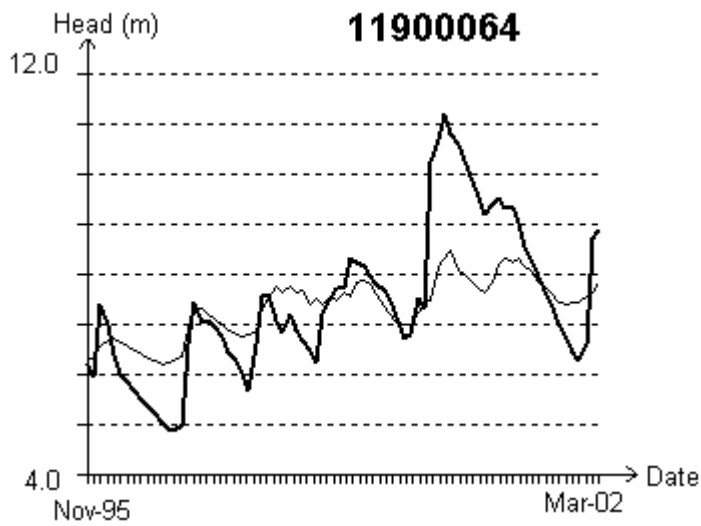


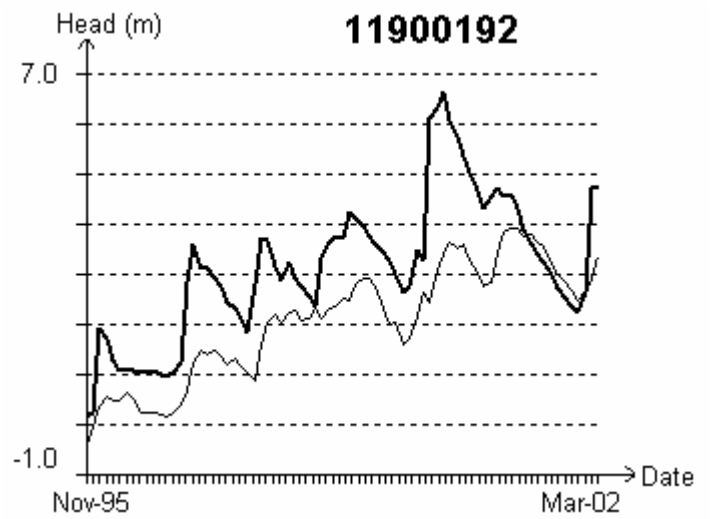
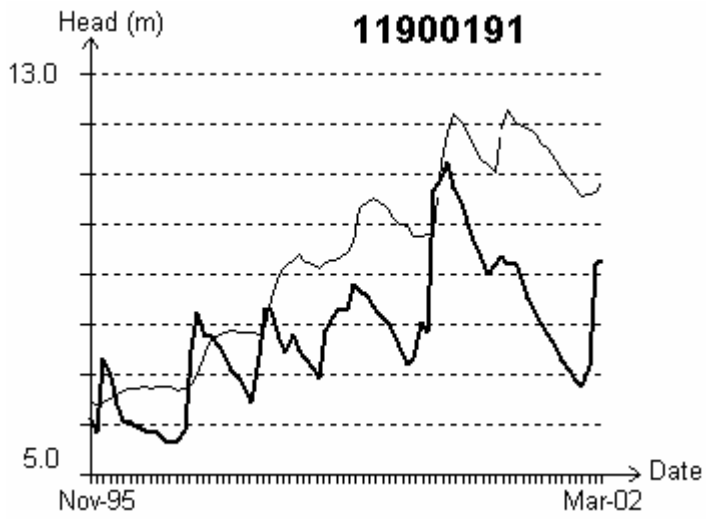


D. Results of the first Attempt using PEST

Dark line shows calculated heads and grey line shows observed values

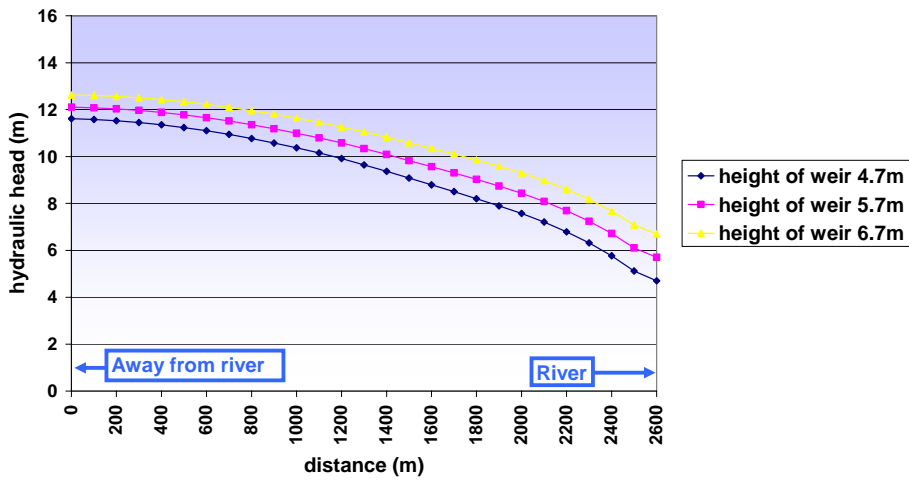




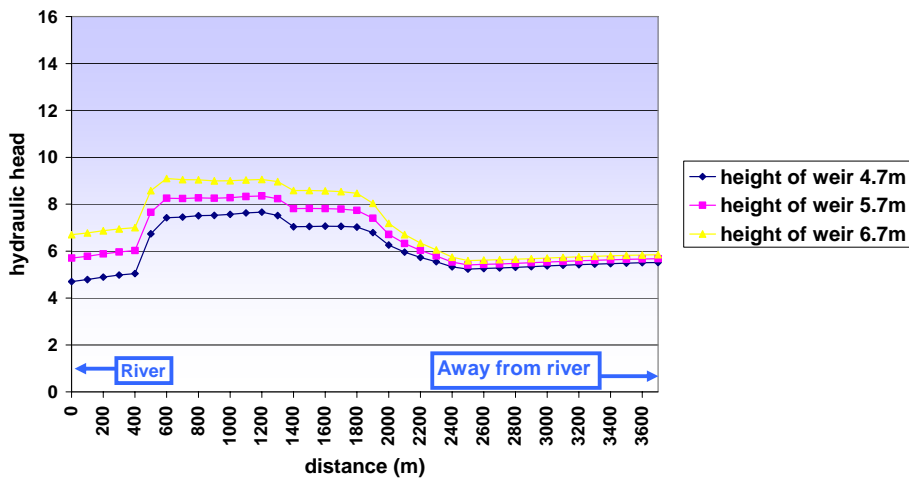


E. Cross Sections at End of Simulation Period

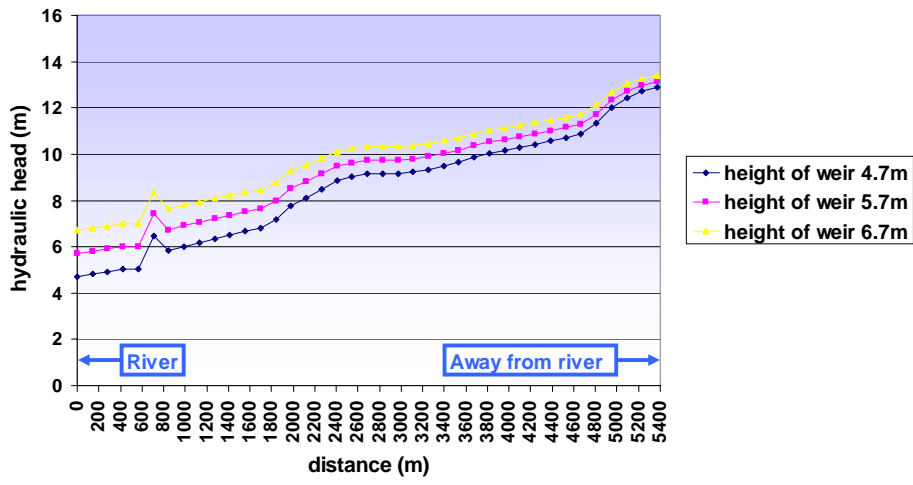
Changing hydraulic head along cross section 2



Changing hydraulic head along cross section 3

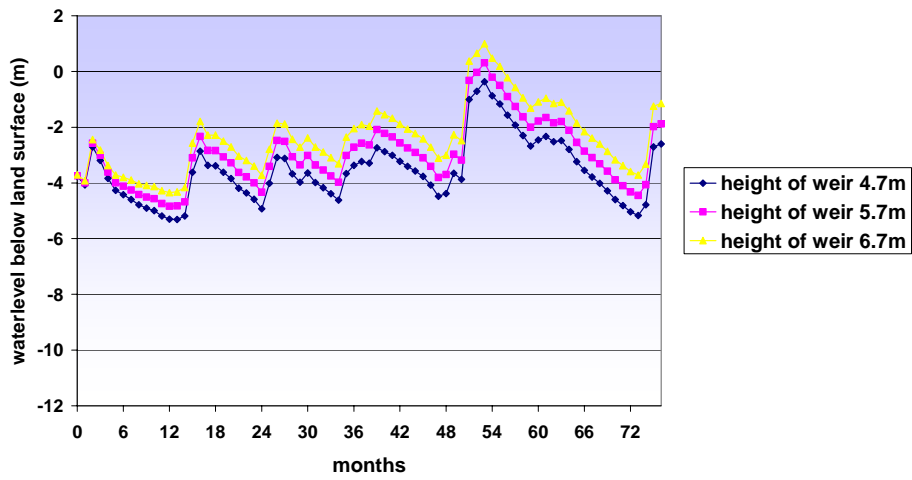


Changing hydraulic head along cross section 5

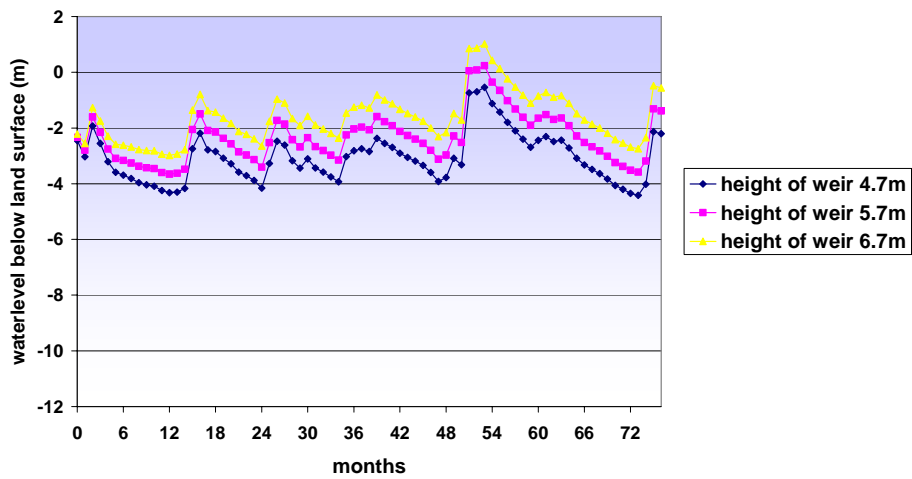


F. Watertable Behaviour at Boreholes

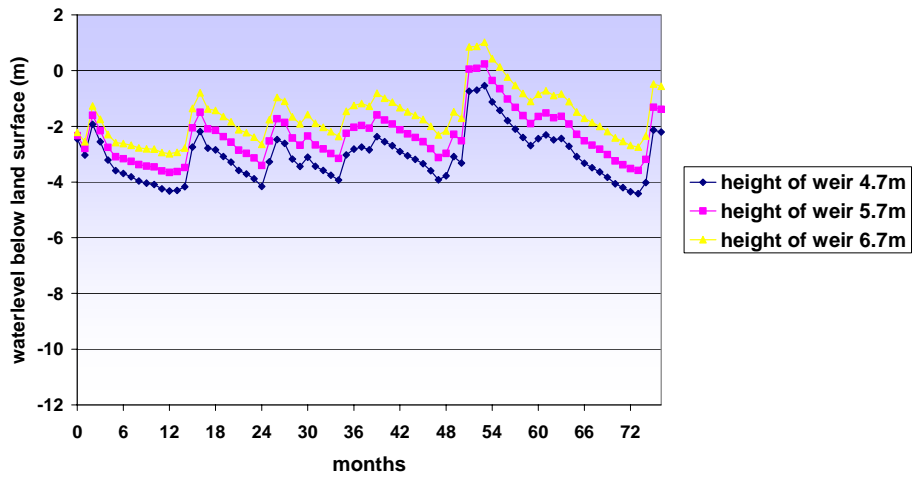
Time- varying waterlevel at borehole 11900064



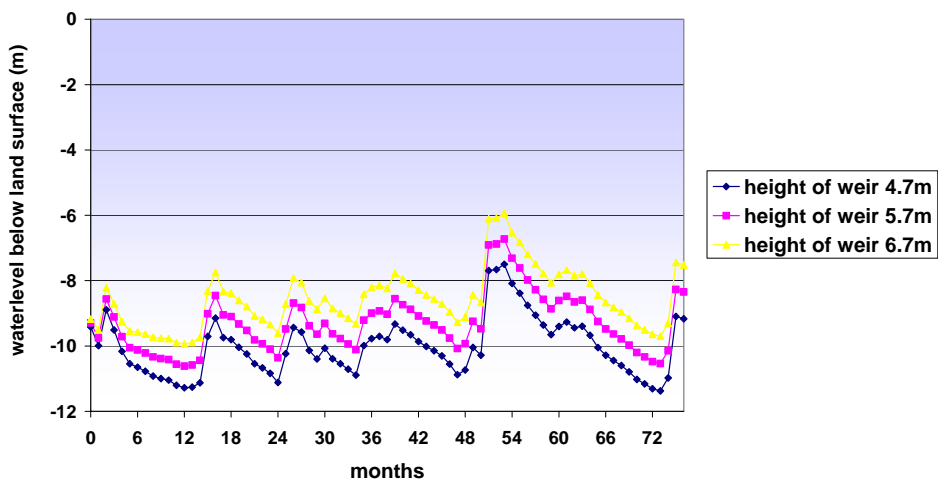
Time- varying waterlevel at borehole 11900169



Time- varying waterlevel at borehole 11900169



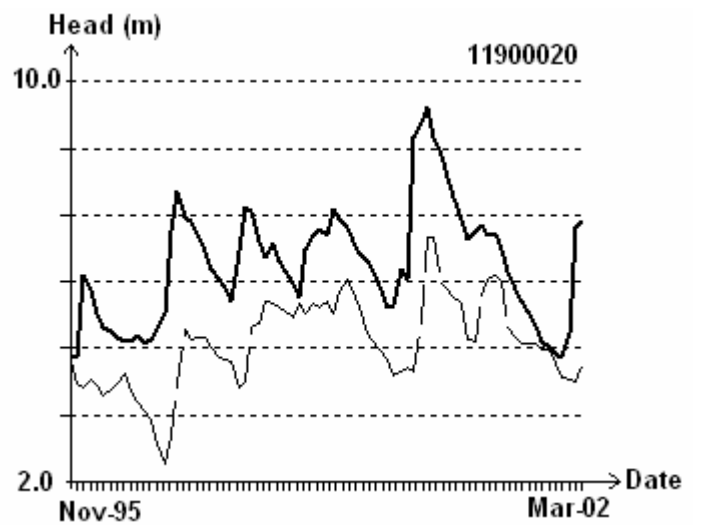
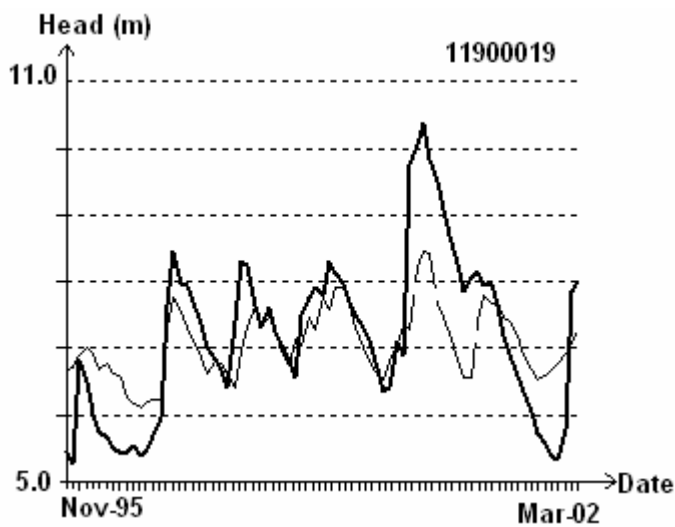
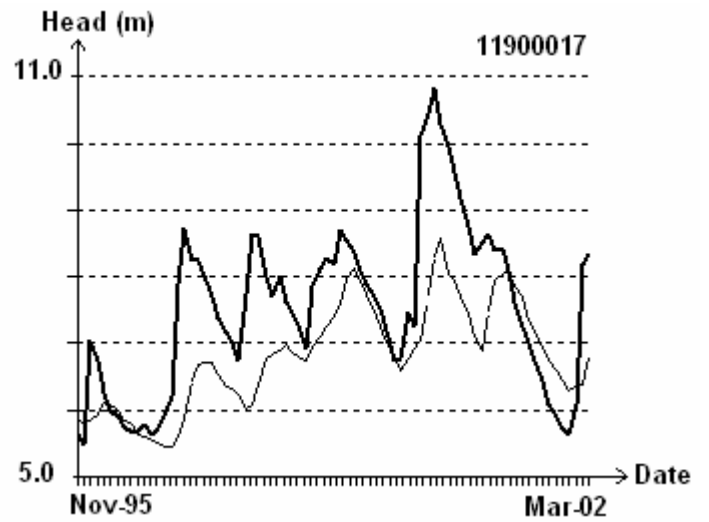
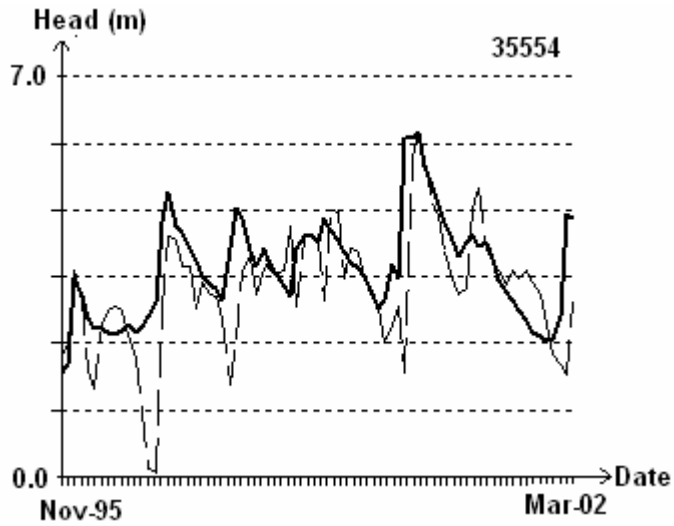
Time- varying waterlevel at borehole 11900191

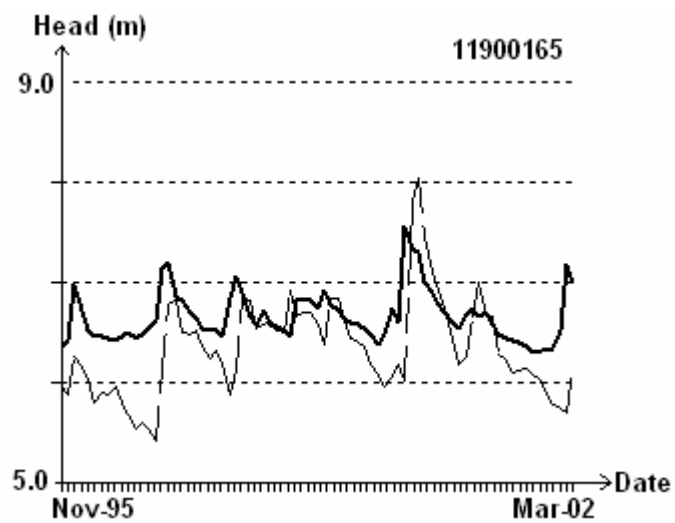
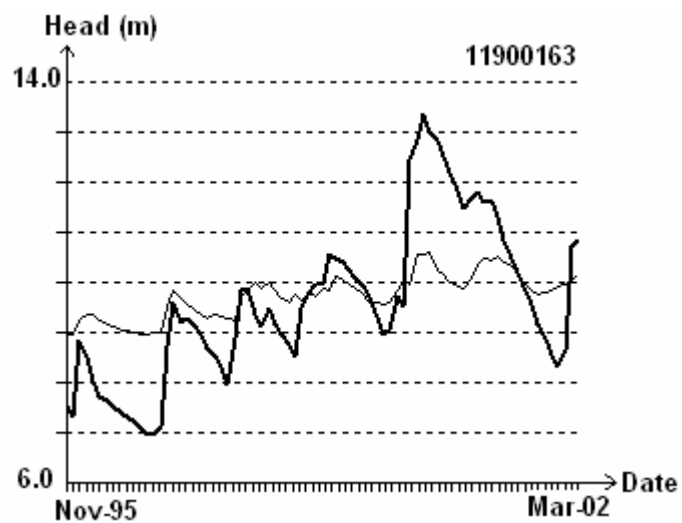
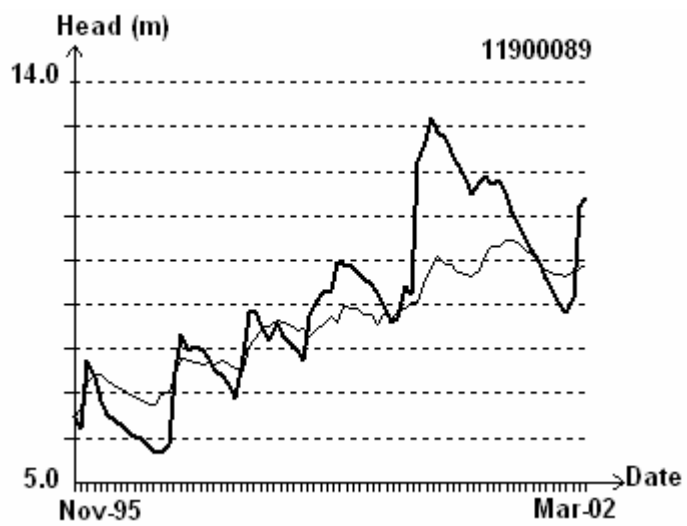
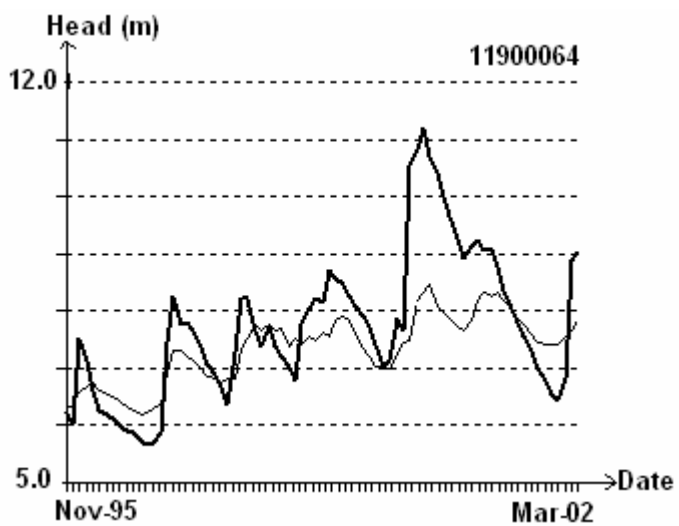
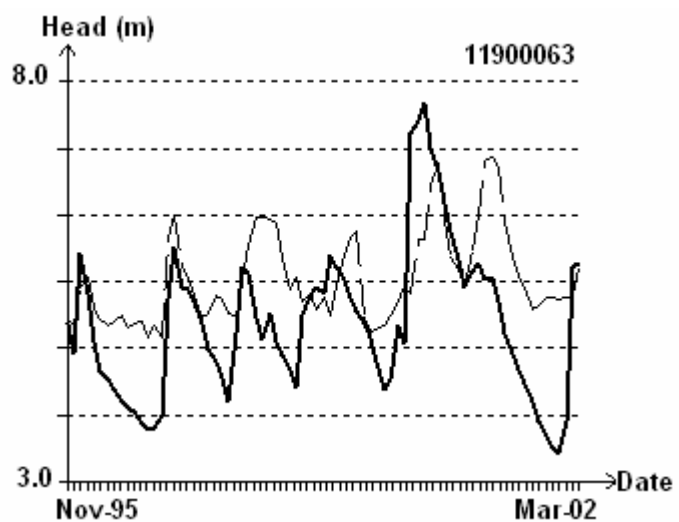
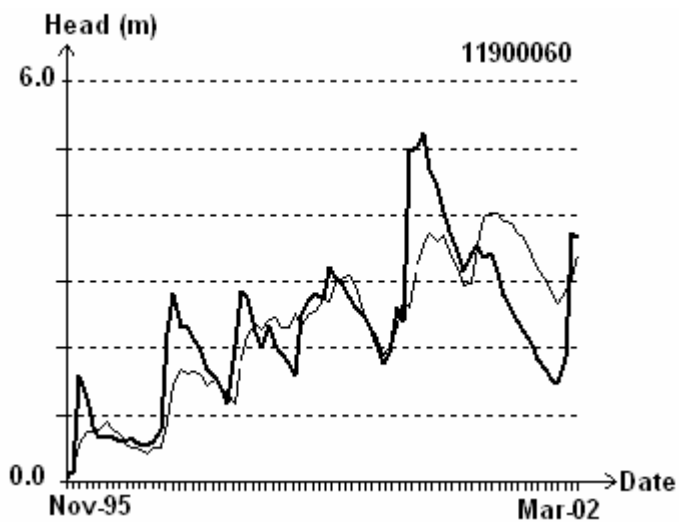


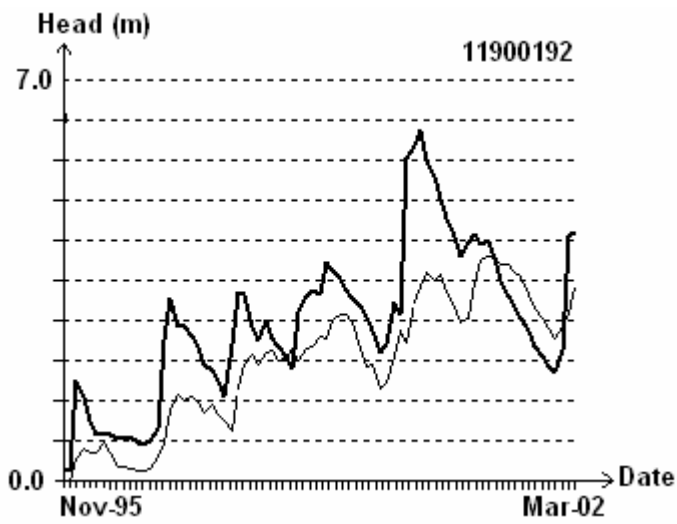
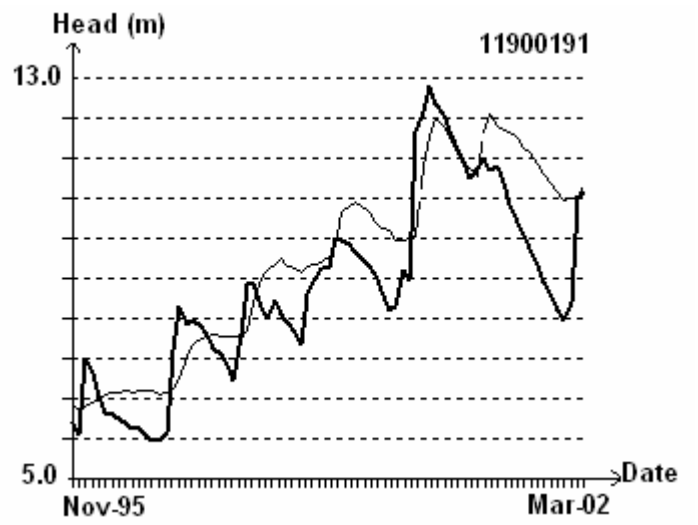
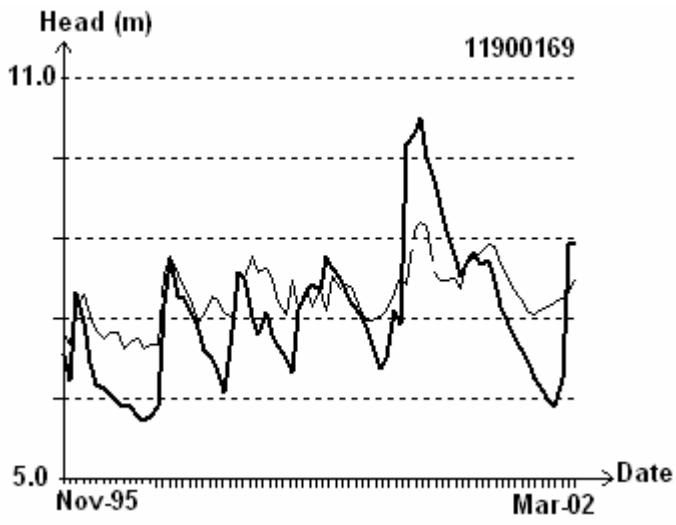
G. Sensitivity Analysis with Bore 11900066 disabled

G1: Model calibration (Bore 11900066 disabled)

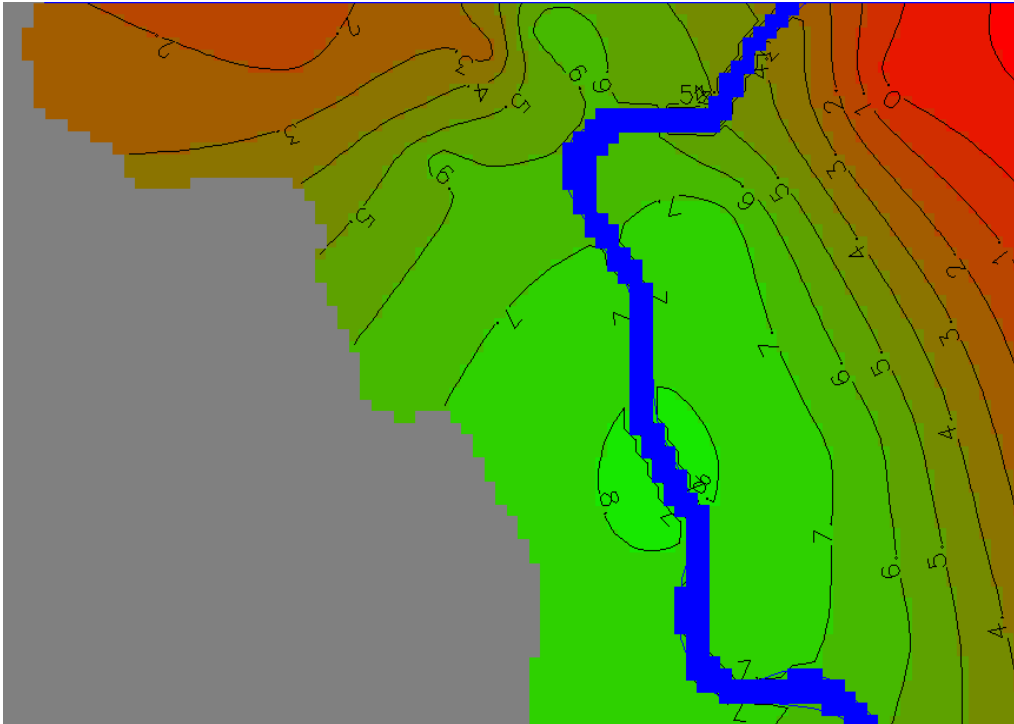
(Dark line shows calculated heads and grey line shows observed values)



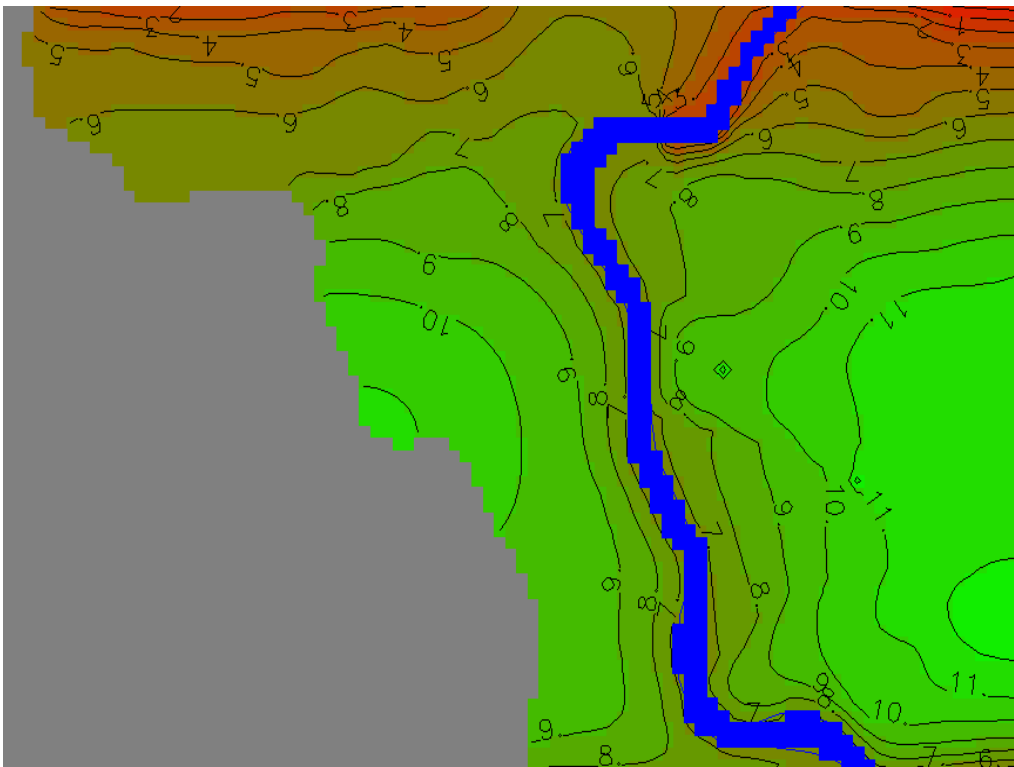




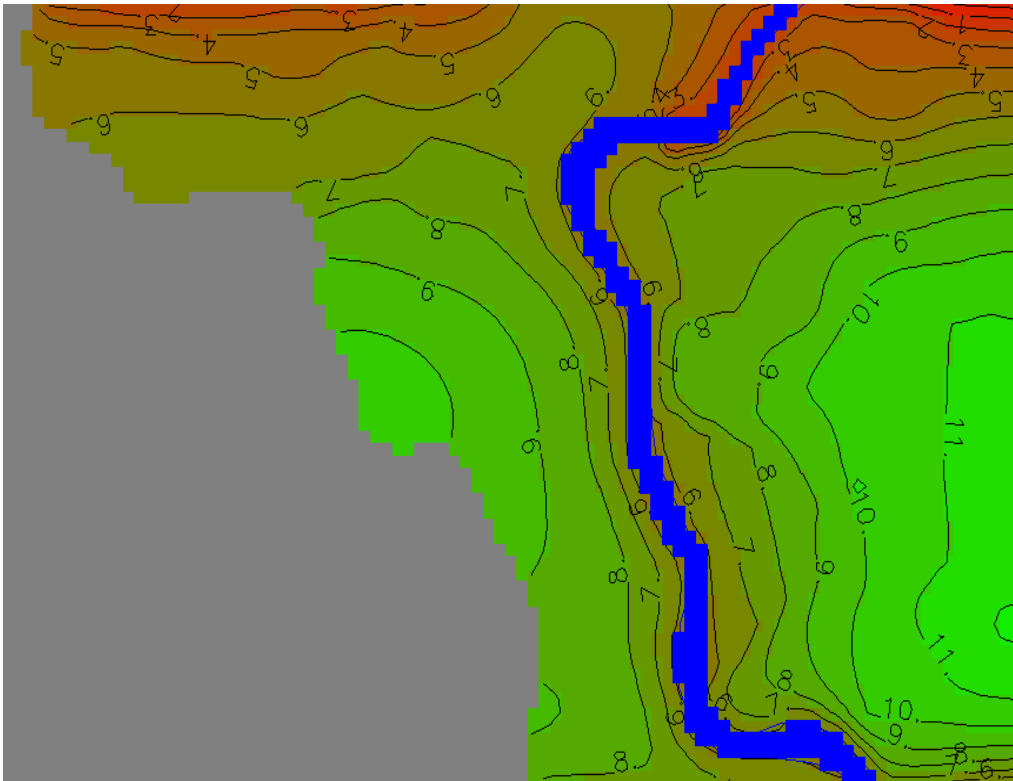
G2: Hydraulic heads and drawdowns (Bore 11900066 disabled)



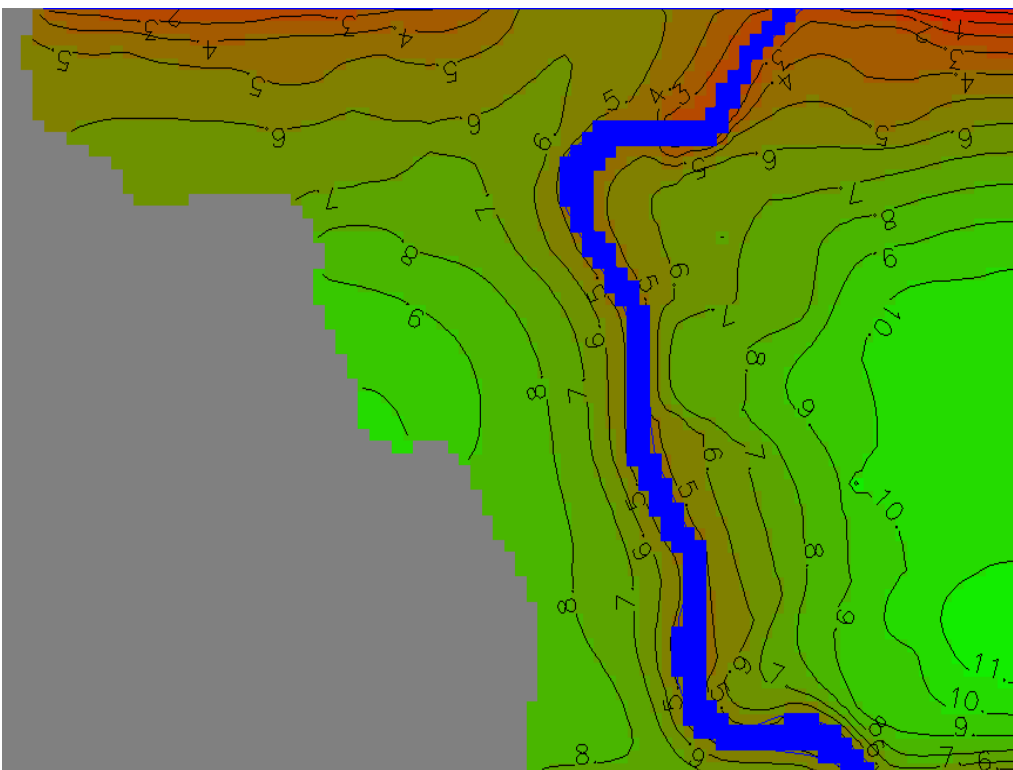
Initial hydraulic head in October 1995 without bore 11900066. Head in Haughton River upstream of Val-Bird Weir is 6.7m.



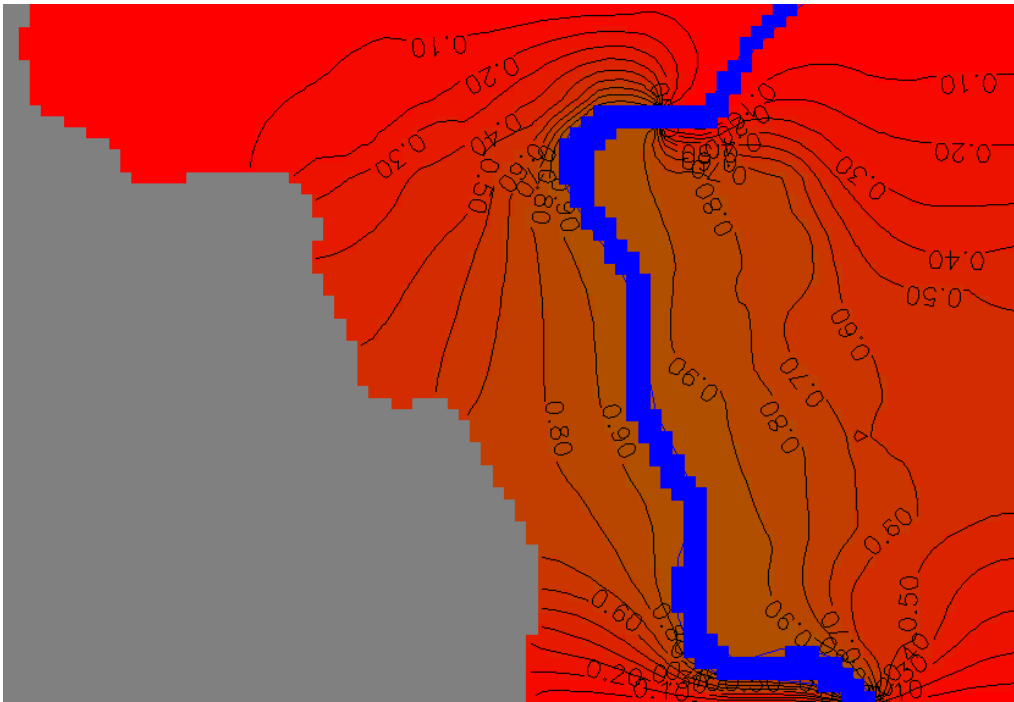
Hydraulic head at the end of simulation period in March 2002 without bore 11900066. Head in Haughton River upstream of Val-Bird Weir is 6.7m.



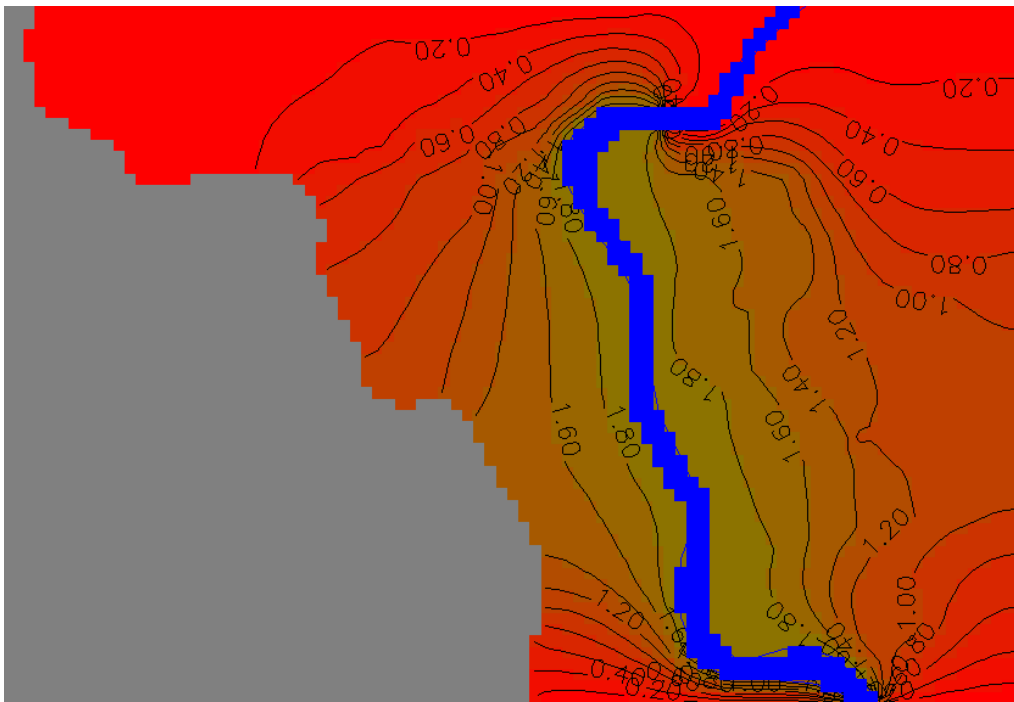
Hydraulic head at the end of simulation period in March 2002 without bore 11900066. Head in Haughton River upstream of Val-Bird Weir is 5.7m



Hydraulic head at the end of simulation period in March 2002 without bore 11900066. Head in Haughton River upstream of Val-Bird Weir is 4.7m

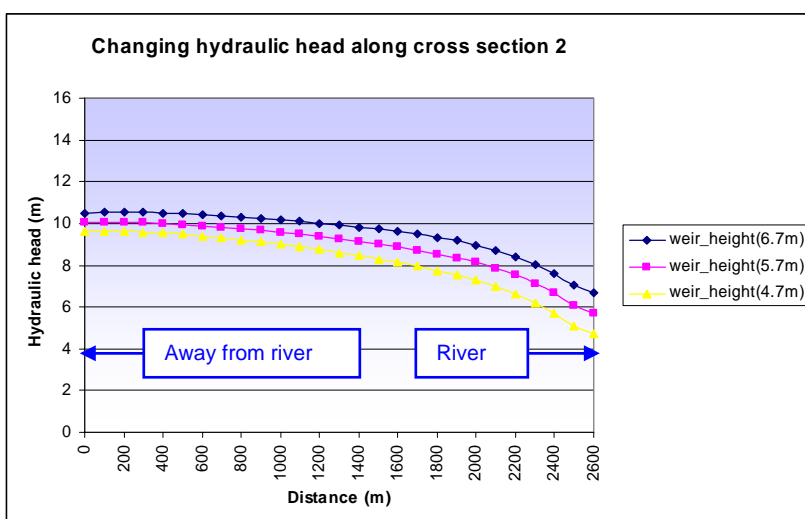
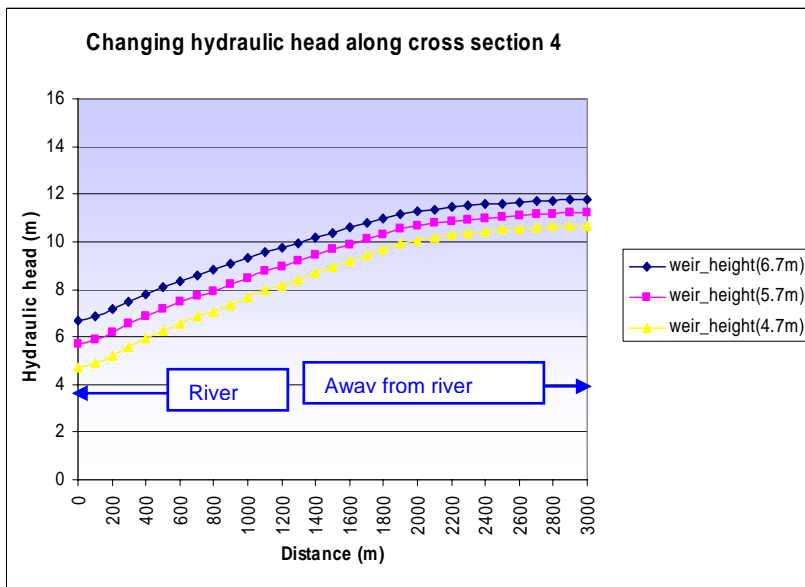
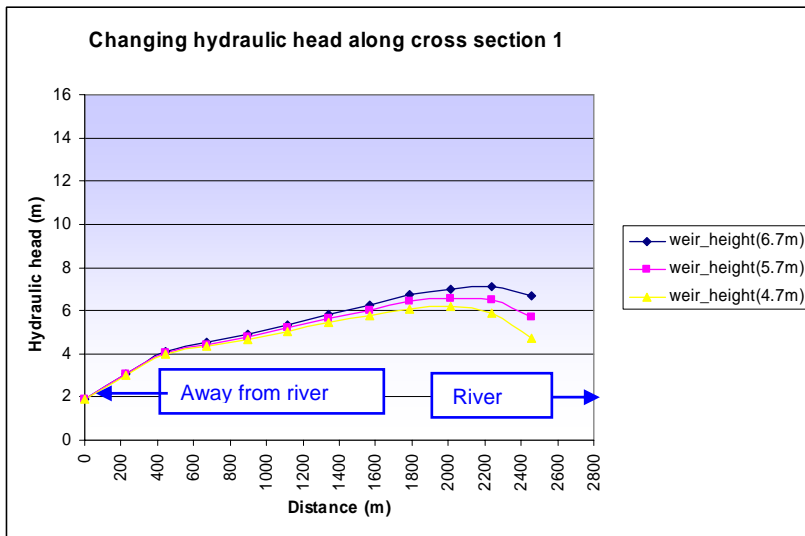


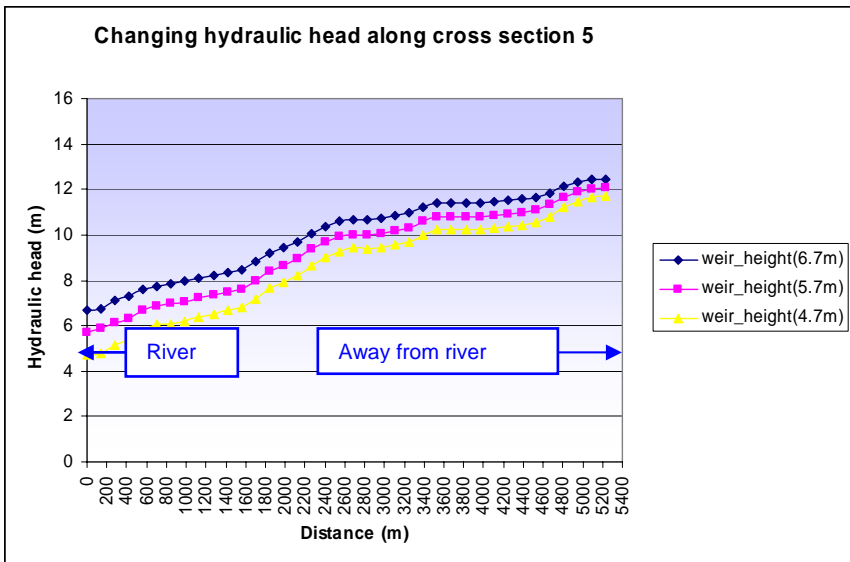
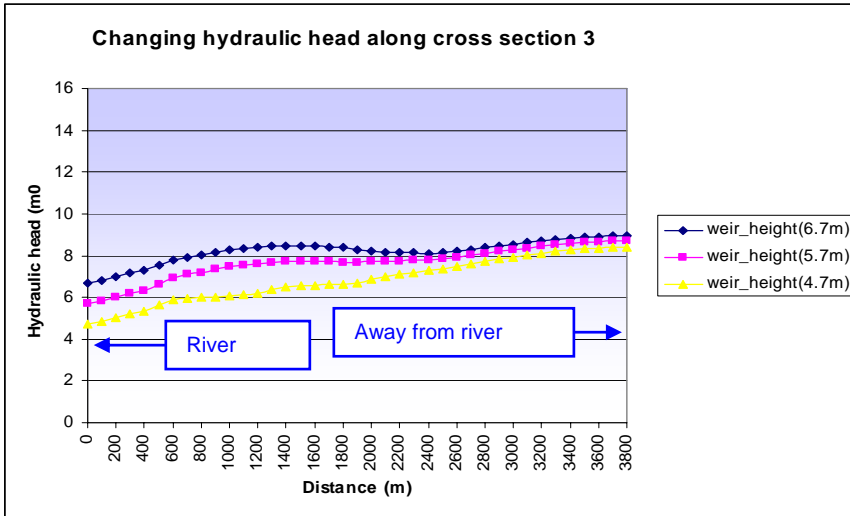
Drawdown at the end of simulation period (77 months). (Val-Bird Weir height is lowered by two metres to 5.7m)



Drawdown at the end of simulation period (77 months). (Val-Bird Weir height is lowered by two metres to 4.7m)

G3: Hydraulic heads along various cross sections (Bore 11900066 disabled)





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