Case Study: Numerical Groundwater flow modeling for Water Resources Management of Murunkan Water Supply Well field

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Abstract

The numerical groundwater flow model for Murunkan area was developed to determine the flow regime and impacts on the Murunkan water supply well field under different stress conditions including the water balance. The extent of the model area is approximately 1,050 km^2 and model boundaries were set as Nay Aru (Eastern boundary), Malwathu Oya (Southern boundary) and Western coastal line (Western boundary). The eastern boundary was taken as the lithological boundary between limestone and granitic basement rock. The simplified hydro-stratigraphy is approximated to alluvial deposit underlain by unconformity surface of Limestone followed by unconformity massif granite basement which is almost impermeable. The area was conceptualized in Visual MODFLOW as three layered structure with upper layer of alluvium and middle layer of limestone followed by the basement rock. The limestone layer simulate as unconfined to confined condition depending on the hydraulic conductivity values assigned in the top layer.

Recharge was assessed by well hydrograph technique and transmissivity values were obtained from the previous studies. The hydraulic head data was utilized as calibration target for model calibration. The model was calibrated under well field stress (3.90 MCM per annum) of the Giant's Tank area at steady state condition and it indicated a drawdown of 1.5-2.0 m which is feasible under regular groundwater head and quality monitoring. The calibrated model run under higher level of abstractions (13 MCM per annum) declines the groundwater level by 3 to 4 m in which the aquifer is stressed maximally thus requires a stringent quality monitoring. The sustainability is in doubt under this level since the deeper groundwater of limestone aquifer indicated high salinity which might result upconing.

The water budget of the model is indicated groundwater outflow of approximately 202 MCM annually to the sea which is 20 % of the annual rainfall. The Giant tank is contributed 5.75 MCM for groundwater recharge while tank receives 35.65 MCM from the tank watershed annually. The annual groundwater recharge from rainfall is approximately 78.7 MCM (9.5 % of annual rainfall).

Key Words: Modeling, Groundwater, Murunkan, Nay Aru, Malwathu Oya

1. Introduction

The Murunkan area is located towards the inland of NW coast of Sri Lanka and comes under Mannar District. The study area covers by several large villages such as Nandan, Adampan, Uyilankulam and Murunkan. The southern boundary is demarcated along the Aruvi Aru (Malwathu Oya) flow and northern is bounded by the Nay Aru. The west is defined by the country's NW coastal line while the Eastern boundary defined along the Madhu road and Palampiddi road (as shown in Fig.01).

The area is identified as one of the potential groundwater bearing aquifers which are already exploited for drinking water supply schemes and irrigation practices in Maha season to overcome the water deficit. Despite the water quality in certain areas is not favorable for drinking purposes, there are some remedial options to overcome this, for instances supply of water after mixing these waters with treated surface water or simply pretreatment where it could be applicable.

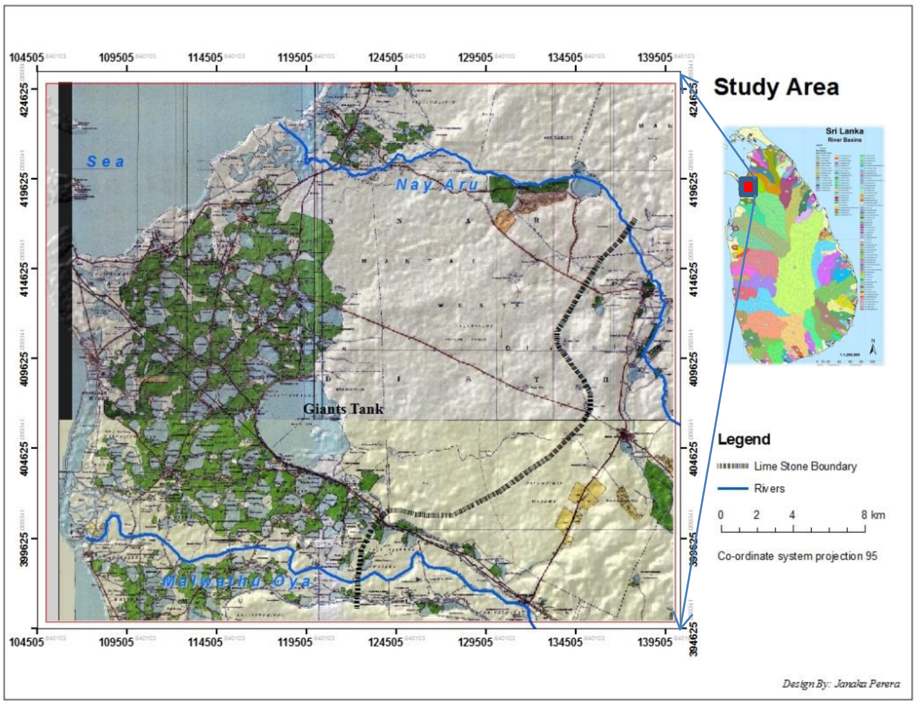


Fig. 01: Murunkan Study Area (extracted from 1: 50,000 scale Topographic Map of Mannar)

Geomorphologically the area is a flat terrain at regional scale except minor local undulations. The elevation varies 0-50 masl range and annual rainfall is approximately 950 mm/yr with temperature fluctuates within the range of 25-33 ^{0} C. The landuse is mostly of paddy cultivation and scattered coconut lands. The tanks are released the water for paddy culitvation through a network of irrigation canals existed specially at abandance in the command area of Giant's Tank. There are series of minor tanks could be observed area below the Giant's Tank which are mainly fed by excess irrigation waters.

This study mainly focused to setup and calibrate regional scale steady state flow model thus identifying of groundwater flow regime at steady state condition under water supply well field stress at Murunkan area and assessment of the groundwater balance.

2. Hydrogeology

The study area comes under Nay Aru basin and the major groundwater bearing zones are alluvium & limestone aquifers. The limestone stratum is underlain by massive and impermeable granitic gneiss basement where the outcrops are visible at the eastern part of the Murunkan area (Davis and Selvaratnam, 1982). The limestone thickens towards the west and tectonically disturbed faulting has produced some facies within the entire limestone formation resulting different hydrogeology and geochemistry within the limestone layer. This Miocene limestone composition is highly varied spatially which determines the aquifer properties (Land Resources Development Centre of UK and Water Resources Board, 1982).

Most of the limestone layer is covered by Post Miocene alluvial deposits which cover later by thin clay layer at the top (Water Resources Board and exploration team of Chinese Government, 1982). This overburden layer is a mixture of clay, sand and gravel at varying proportion which subsequently responsible for the type of aquifer condition to be appear in the limestone bed whether it is unconfined to confined condition.

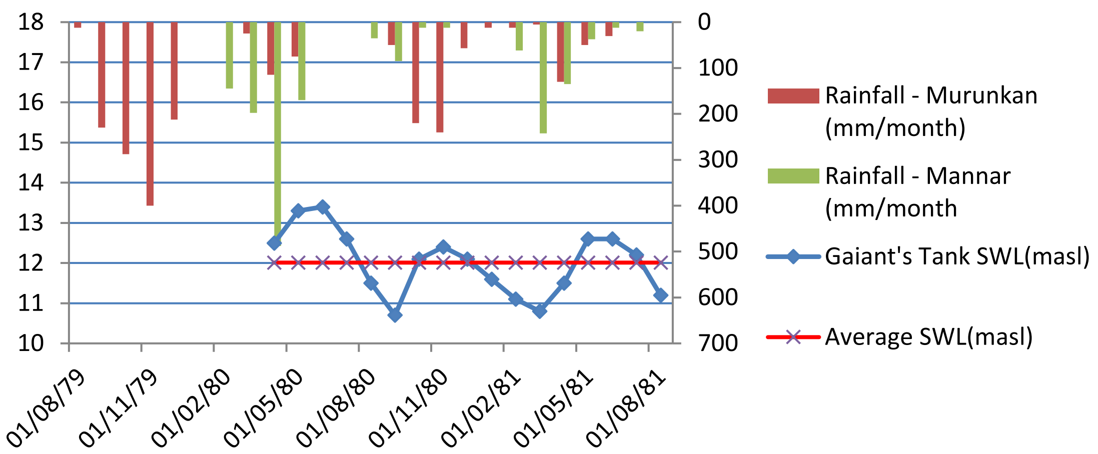


Fig. 02: Annual rainfall distribution and variation of Giant's Tank SWL

3. Model Development

The reliability of the numerical model solution depends on number of criteria: code selection, implications of simplifying assumptions in conceptualization, spatio-temporal resolution and accuracy of data and fluxes (Anderson and Woessner, 1992).

In quantitative groundwater modeling, the model algorithm is based on groundwater flow equation developed with combination of Darcy's law and continuity of mass equation (Anderson and Woessner, 1992). In MODFLOW (Harbaugh and Mc Donald, 1988), this is simulated by finite difference method. The governing equation for groundwater flow in two dimensionally in this numerical modeling code is given by the below partial differential equation.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = W + S_s \frac{\partial h}{\partial t}$$

Where K_x and K_y are hydraulic conductivity components along x and y directions respectively; *W* is source or sink; S_s is specific storage; *h* and *t* are head and time respectively. The equivalent porous media (EPM) concept (Anderson and Woessner, 1992) applies for weathered and fractured limestone in Murunkan area. Model development was involved with series of processes such as conceptualization of the area, model fluxes and model parameters assessment etc. Once these steps fulfilled, the numerical flow model was simulated in the Visual MODFLOW, Version 2011.1.

This model was performed in steady state condition where long term average fluxes used as constants over the period of simulation. This calibrated steady state model could be utilized later for fully transient modeling once the spatio-temporal fluxes are available.

3.1 Model Area

Eastern, southern and western geographical boundaries of Murunkan area are demarcated by Nay Aru, Aruvi Aru (Malwathu Oya) and western coastal line of the country respectively. These boundaries were taken as model boundaries. The eastern boundary was taken as the lithological boundary between limestone and granitic basement rock (Fig. 01). The total extent of the model area is approximately 1050 km^2. The selected study area is bounded in the SLD95 coordinates of (105000, 395000) m in X direction and (140000, 425000) m in Y direction.

3.2 Hydrostratigraphic units (Conceptual model)

The conceptual model is schematized as a cross section or block diagram which reflects the system behaviors and it leads to determine numerical model characteristics. The closer the conceptual model to reality, the numerical model will be more accurate (Anderson and Woessner, 1992).

The hydro-stratigraphy is simply of top soil underlain by unconformity surface of Limestone following the unconformity massif granite basement which is almost impermeable. These simplified three layered structure was approximated and assigned in the conceptual model (Fig. 03). However, the lateral and depth-wise high heterogeneity in composition and hydrogeological properties within a same layer creates a difficulty to represent in the conceptual model since no detail assessment has performed to identify these properties. The thickness of the topmost layer is varied from 0.0 to 30-40 m while the limestone layer thickness varies from 10 m to extreme levels of 130 m towards the coastal belt. The conceptual model was developed as shown below based on the information.

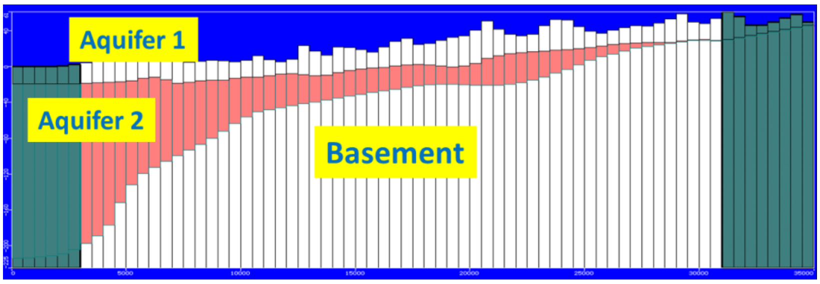


Fig. 03: Simplified conceptual model with the use of hydro-stratigraphy and Geology/ structure of the area

3.3 Model setup and model boundaries

The developed conceptual model was simulated in Visual MODFLOW to construct the numerical model. The area was simulated as three layered structure with upper layer representing the latosol overburden and the middle layer of limestone followed by the impermeable basement granitic rock. The model surfaces elevation of these layers i.e. top surface of overburden, upper and bottom surfaces of limestone were processed in ArcGIS 10.2 Software using the Digital Elevation Model (DEM) of Aster and SRTM with the support of field measured elevation data of the observation wells (Water Resources Board and exploration team of Chinese Government, 1982) and technical & logging data of boreholes (Land Resources Development Centre of UK & Water Resources Board, 1982).

The limestone layer is simulated as unconfined to confined condition depending on the hydraulic conductivity values assigned in the top layer. This model covers 30 by 35 km area with a cell size of 250 m covering the Murunkan area. The grid cells outside the model area were assigned inactive while the cells within the model domain defined active. The two streams Aruvi Aru and Nay Aru were simulated in stream package while of the Giant's Tank is simulated by tank package in Visual MODFLOW (Chiang and Kinzelbach, 2001).

3.4 Boundary conditions

Boundary conditions are mathematical statements which specify the head or fluxes at the boundaries of the model domain. The correct assign of boundary condition is important since it controls the flow regime of the numerical model (Cook, P.G., 2003). The North and south model boundaries along the rivers of Nay Aru and Aruvi Aru were assigned as general head boundary condition. The western boundary is demarcated by the coastal line which was simulated as constant head boundary condition and specified the hydraulic head as sea level. The eastern model boundary was assigned no flow boundary condition considering the topography, groundwater flow, hydrogeology of the site.

The applied boundary conditions and model grid of the numerical model is shown in Fig. 04. The bottom of the second layer is impervious hard massif granite simulated by very low vertical hydraulic conductivity in the model.

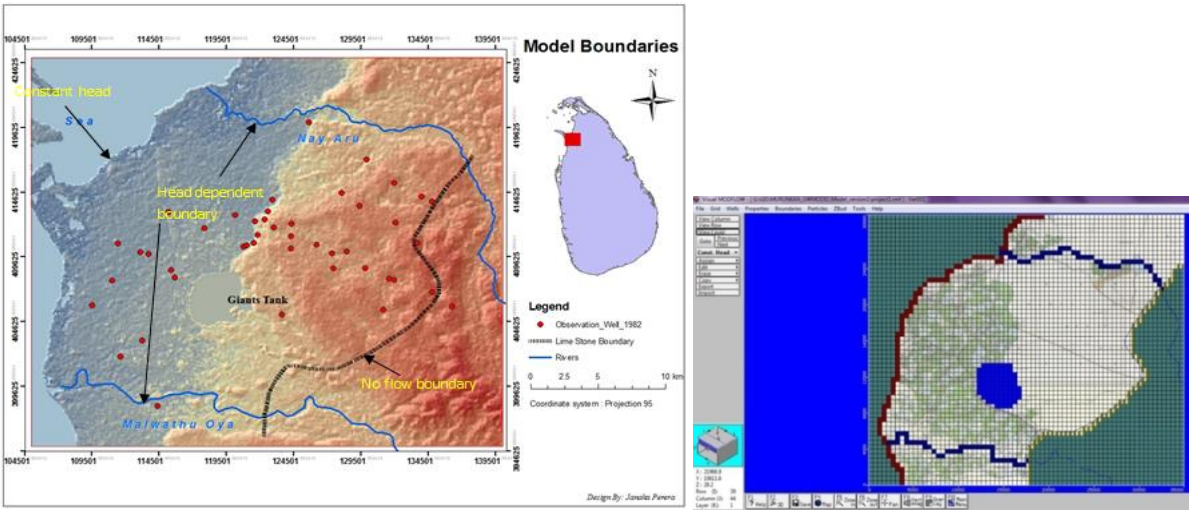


Fig. 04: The boundary condition applied in the numerical model and final model setup of the Murunkan area

3.4 Model fluxes and parameters assessment

The proper model parameters and fluxes evaluation by integration of data sources with different methods is essential to select an appropriate method and to develop a reliably calibrated model (Lubczynski and Gurwin, 2005). Extensive data is required to accurately characterize a hydrogeologic system for the groundwater model setup design. During the calibration stage of the model, more data of hydraulic heads are important to improve the model calibrations. The following temporal, spatio-temporal and spatial data was reviewed and processed.

i.) Groundwater Recharge

The main influx of groundwater is recharge from rainfall, irrigation tanks, Aruvi aru diversion canal, irrigation drains and lateral flow at the defined model boundaries. The groundwater recharge at the higher elevation of the limestone trough toward NE is flow toward the central trough of the limestone and accumulates in the lower limestone karstic features of the Murunkan area (Water Resources Board & exploration team of Chinese Government, 1982). This is evident by large groundwater withdrawal under sustainable condition in an around the Giant's Tank area. The recharge was assessed from the well hydrograph analysis with the use of monthly hydraulic head data monitored in 1979 - 1981 period under the groundwater study performed by water Resources Board. Lateral fluxes on groundwater recharge are assumed negligible in this assessment. The point recharge was deduced from the groundwater level fluctuation as an indirect method (Kruseman, 1997) by following formula.

$$R = \Delta h S_y + Q_{ab} + \Delta Q_{in-out}$$

Where R, Δh, S_y, Q_{ab} and ΔQ_{in-out} are recharge, change in water level elevation, specific yield, groundwater abstraction and difference of lateral inflow-outflow respectively. The total recharge per annum at each well location was assessed by summing up each recharge event determined through the use of hydraulic head variation graph and above formula. The result of the analysis in wells is summarized below. The specific yields of the locations were obtained through available literature and information of groundwater study performed by water Resources Board.

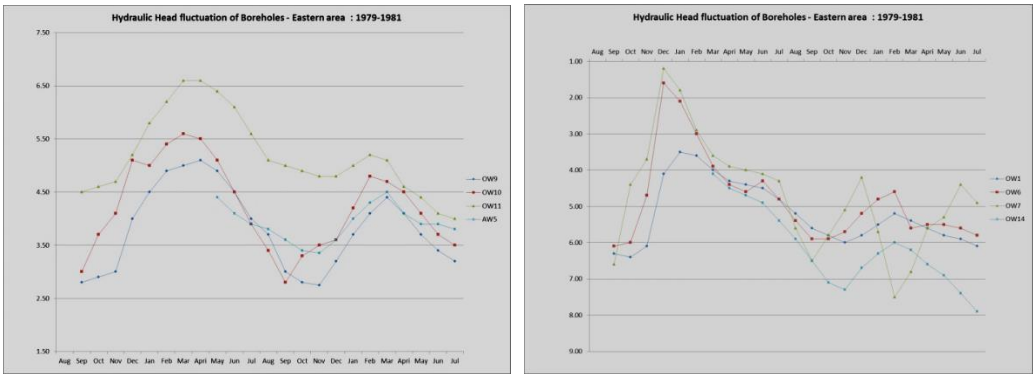


Fig. 05: The monthly hydraulic head data variation at the well locations in Murunkan area monitored in 1979 - 1981 period.

Table 01: The groundwater recharge estimated from well hydrograph analysis at the borehole locations

Well no	Coordinates		Sy	GR mm/yr	GR as % of RF	Hyd. Head (masl)	Well no	Coordinates		Sy	GR mm/yr	GR as % of RF	Hyd. Head (masl)
	X	Y						X	Y				
OW9	120376	402827	0.03	78	8.2	3.81	TW20	131622	407932	0.08	364	38.3	4.44
OW10	118266	400936	0.012	41.7	4.4	4.22	TW25	136264	405792	0.1	275	28.9	10.76
OW11	115431	397891	0.01	30	3.2	5.19	TW50	128472	410078	0.12	96	10.1	21.98
OW12	123672	400219	0.03	75	7.9	11.64	OW1	135064	393714	0.03	67.5	7.1	5.21
AW5	120872	402391	0.03	66	6.9	3.91	OW6	137058	405697	0.03	121.5	12.8	4.83
HD24			0.03	86.3	9.1	4.85	OW7	139147	403849	0.03	128	13.5	4.69
HD11			0.03	108.8	11.4	5.25	OW14	131169	418041	0.085	250.8	26.4	6.14
TW43	115366	408582	0.03	69	7.3	3.02	HD 42			0.03	64.5	6.8	3.9
GA11	116415	405632	0.05	95	10	2.63	HD72			0.03	55.5	5.8	2.83
GA24	113530	407352	0.045	85	8.9	2.43	W122B	121018	410502	0.01	32.5	3.4	6.73
TW16	131984	415284	0.15	330	34.7	13.85	GA10A	115765	402159	0.035	71.8	7.6	2.87
TW18	124284	411229	0.055	98	10.3	13.38							

Note: Sy - specific yield, GR –groundwater recharge, RF –rainfall, Hyd. Head – groundwater head

The evaluated point recharge from the well hydrograph technique was processed in ArcGIS to obtain the spatially distribute recharge map which requires by the model. The transmissivity values were obtained from the available study reports of the area.

ii.) Hydraulic conductivity

Hydraulic conductivity (Kx, Ky, Kz) of the layers were evaluated using the available transmissivity data and the layer thickness data in the report published in 1982 (Davis, J. and Selvaratnam, B., 1982). The point hydraulic conductivity evaluated from the raw data was processed in ArcGIS to obtain spatially distributed in raster format as shown above in Fig. 9. The extent of sea water intrusion under different stress conditions could be simulated and visualize by the transport flow modeling. Transport flow modeling requires dispersivity, effective porosity, seepage velocity through the assessment of pumping test along the coastal belt on the test boreholes or by tracer tests.

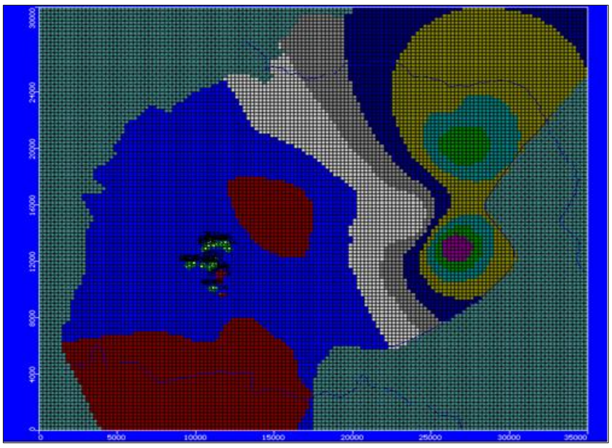


Fig. 06: The Hydraulic conductivity raster map processed in ArcGIS with use of available data

Table 02: Transmissivity data processed using different techniques

TW No	Transmissivity(m2/day)					TW No	Transmissivity(m2/day)				
	Jacobs	Logan	Theim	Theis recovery	Average		Jacobs	Logan	Theim	Theis recovery	Average
MP4	1227	696			962	TW19	7339		962		4151
TW17		13	13.2		13	AW5	568	1313		2334	1405
TW19	600	238	918	247	501	AW9	2939	819			1879
TW20		2.1		0.47	1	GA26		1987			1987
TW39	21	38.75			30	GA41		1870			1870
TW40		42.46			42	GA7		7242			7242
TW42	366	216		313	298	GA23		486			486
TW43	7624	12333			9979	GA42		10381			10381
TW44	890	3294		12455	5546	GA38		9690			9690
TW47		1391		2372	1882	GA72		4848			4848
TW48		453		1581	1017	W117		1920			1920
TW49	376	364		712	484	W127		2001			2001
TW56		154			154	AW6		2596			2596
MH2(A)ODA	650	5996			3323	GA42		5341			5341

iii.) Groundwater abstractions and outflows

The report indicated that the baseflow of Malavi Aru is contributed from shallower sandy alluvium in dry periods and could be well observed in the vicinity of Silavathuri Bridge. Therefore baseflow measurement is important to determine the groundwater outflow in these periods. These outflow components including groundwater abstractions have been not possible to simulate since no data available. The abstractions in 1980's are available approximately for the entire area and no individual withdrawals of the sources (tube wells or dug wells) are existed. All groundwater flows toward westerly and the difference in hydraulic head between limestone and alluvial aquifers also diminishes indicating the unconfined aquifer condition toward westerly.

There are evidences of saline water in many places at deeper levels of the limestone aquifer. However, the freshwater aquifer is been separated in most of the situations by clay rich limestone thin beds encountered within the composite limestone layer. The area is highly utilized the groundwater in Maha season by means of tube wells and also from large agro wells where the alluvium possesses high storage. The agricultural and drinking water supply withdrawals of the area is not yet been assessed. Therefore recent abstraction volumes are not available despite the condition has changed significantly over the few decades. Groundwater outflow is occurred as discharge at the coastal area and flow to Aruvi aru at some places. The basflow measurement has not carried out for Aruvi Aru thus difficulty arises in the simulation of groundwater outflow through these rivers.

Well field abstractions

Table 03: Abstraction data of the supply well field at Murunkan Area - (Source: NWSDB, 2011)

Well number	X	Y	SWL(mbgl)	Ext(m3/d)	Di (inches)	Depth(m)	Remark
4-1539	80.0149	8.8590	6.35	1056	8	30.5	near Giant tank
4-1540	80.0147	8.8600	6.58	1260	8	31	near Giant tank
4-1541	80.0146	8.8607	6.40	1200	8	31	near Giant tank
4-1542	80.0146	8.863	6.47	1404	8	30	near Giant tank
1	80.0158	8.8556	6.7	720	8	35	Vankalai
2	80.0157	8.8556	6.5	2400	8	36	Vankalai
3	80.0158	8.8550	6.38	720	8	34	Vankalai
4	80.0160	8.8544	6.45	720	8	32	Vankalai
5	80.0164	8.8500	6.39	1200	8	32.5	Vankalai

Note: X – Longitude, Y – Latitude, SWL – static groundwater level, Ext – extraction cubic meter per day, Di – diameter of boreholes

Model input data for steady state model

The above determined model fluxes and parameters were utilized as inputs for model parameterization process. The calibration process was performed under steady state condition.

4. Model Calibration

the steady state models have a higher degree of freedom in the calibration process (Lubczynski and Gurwin, 2005). The prameterized model was calibrated in VisualMODFLOW and the calibration target was used as recent hydraulic head data monitored during 2011. The graph below (Fig. 11) indicates the plot of model calculated hydraulic heads vs field measured head data (Table 01).

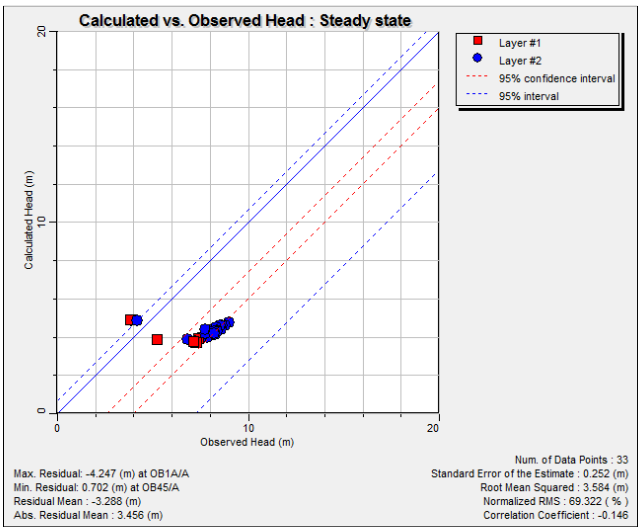
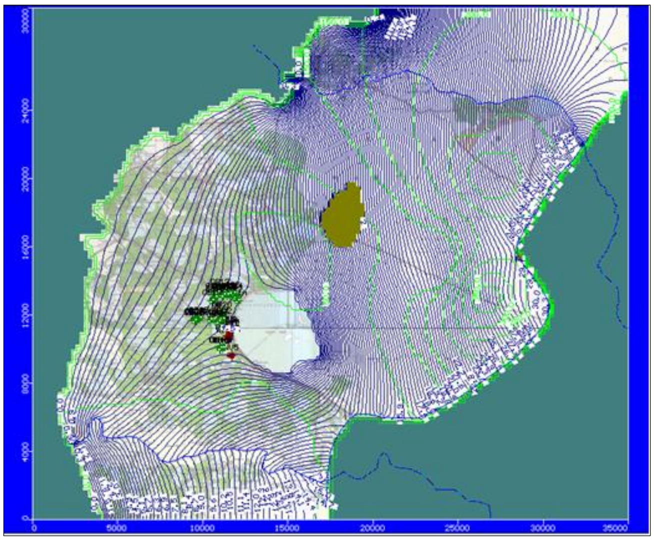


Fig. 07: The plot of calculated vs observed head data of the Murunkan model area.

5. Model output

a.) Under proposed abstraction level

The model was calibrated under well field stress of the Giant's Tank area at steady state condition. The abstraction was simulated in the model as 3 MCM per annum.



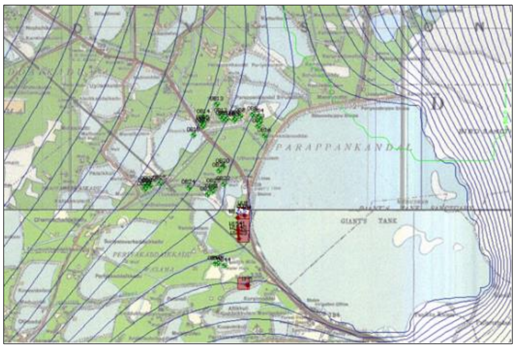


Fig.08: The regional groundwater flow behavior of the Murunkan area and enlarged view of the flow behavior at the Murunkan well field under proposed abstraction level. The production and observation wells are indicated in red and green colors respectively.

The head levels in the well field area near the Giant's tank is 6-8 masl and the model result indicated a drawdown of 1.5-2.0 m with respect to the present static water level at the annual abstraction of 3.90 MCM. This abstraction level is safely obtainable while systematic groundwater head level and quality monitoring is implemented. The model generated water budget is shown in Table 4a.

Component	Amount (MCM per annum)	
	In	Out
Groundwater outflow	0.00	202.29
Well abstractions	0.00	3.90
River leakage	163.89	7.62
Recharge	78.73	0.00
Lake seepage	5.75	34.57
Total	248.38	248.37

Component	Amount (MCM per annum)	
	In	Out
Groundwater outflow	0.00	200.71
Well abstractions	0.00	13.42
River leakage	165.65	7.54
Recharge	78.73	0.00
Lake seepage	11.58	34.30
Total	255.96	255.96

Table. 04: The water budgets under a.) abstraction of 3 MCM per annum and b.) 13 MCM per annum

The major groundwater flow direction is generally S-SW directions and discharges towards the Aruvi Aru(Malwath Oya) and coastal line. The water budget of the model is indicated groundwater outflow of approximately 202 MCM annually to the sea which is 20 % of the annual rainfall. The Giant tank is contributed 5.75 MCM for groundwater recharge while tank receives 35.65 MCM from the tank watershed annually. The annual groundwater recharge from rainfall is approximately 78.7 MCM (9.5 % of annual rainfall).

b.) Under abstraction of 13 MCM per annum

The model run under abstraction of 13 MCM per annum declines the groundwater level 3.0 - 4.0 m with respect to the present levels. This level of exploitation (13 MCM per annum) is stressed the aquifer to a higher degree thus requires a stringent quality monitoring and the sustainability is in doubt since the deeper groundwater of limestone aquifer indicated high salinity which might result upconing. Therefore, the increase of present groundwater exploitation requires further studies on the limestone aquifer in detail.

The steady state flow model could be validated to improve the reliability of flow model. However the limitation of hydraulic head data excludes the possibility of model validation. This steady state flow model could be upgraded to solute transport model where the quality changes could be explored under different scenarios.

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