

Simulation of the groundwater flow model of the Western Aquifer of Mauritius

Manta Devi Nowbuth *
*Faculty of Engineering,
University of Mauritius*
Email: mnowbuth@uom.ac.mu

Fabrice Feliciane
Mauritius

Nihaad Hosany
Mauritius

Paper Accepted on 06 October 2009

Abstract

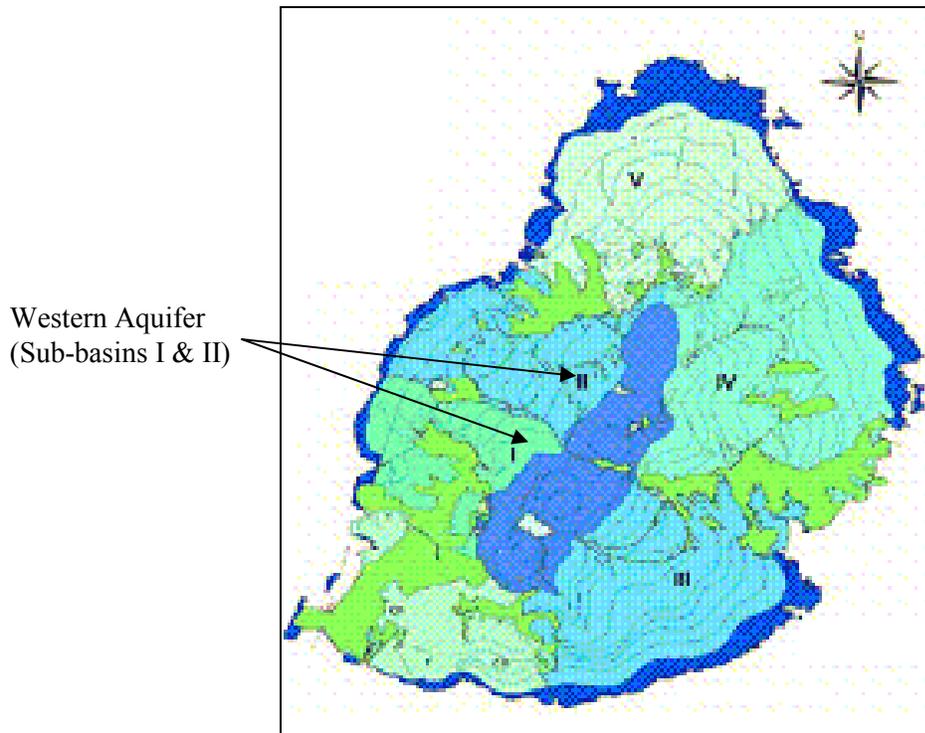
The Western Aquifer is the largest aquifer of the island of Mauritius, and it is heavily exploited to cater for domestic and industrial water demand. This is mainly because it is situated in an urbanised region where water demand is high. This aquifer covers a major part of the districts of Plaines-Wilhems, Moka and Black-River. According to recent hydrogeological studies, the Western Aquifer is made up of two sub-aquifers, the aquifer of Curepipe and the aquifer of Phoenix. The aquifer of Curepipe has been the subject of several hydrogeological studies in the past. These studies have significantly helped in the understanding of the nature of this subsurface basin, and have to a large extent helped towards a safe exploitation of the aquifer. Several exploration techniques, ranging from geophysical surveys, drilling of coreholes and monitoring of groundwater levels have been carried out. The present study aims at improving the understanding of the hydrogeology of the Western Aquifer through the use of a numerical groundwater flow model. The findings of the study show that the intra-calderic borders act as groundwater divides within the system, controlling the flow characteristics within the aquifer and significant flow paths actually connect the two sub aquifers.

Keywords: Hydrogeology, Western Aquifer, Groundwater flow model, Conceptual model

**For correspondences and reprints*

INTRODUCTION

As the pace of socio-economic development keeps on increasing, the groundwater resources of the island of Mauritius are being subject to higher stresses. In order to avoid depletion of this precious resource, its effective management is required. Several hydrogeological studies have been carried out in the past, and these are still widely used to assess the potentially exploitable groundwater resources. Hydrogeological studies supported with both field assessment techniques such as radio-tracers, environmental isotopes, pumping tests, sounding and the neutron probe, have provided hydrogeologists with detailed information regarding the nature of the groundwater bodies. Amongst non-destructive subsurface investigative techniques, are conceptual and numerical groundwater flow models. These mathematical models serve the purpose of improving the understanding of the hydrogeological set up of a subsurface system and can also be used to forecast future development of the resource, without causing any damage to the actual system. Such models are also extensively used to simulate movement of contaminants through groundwater bodies. The Western Aquifer (Figure 1) is currently the most heavily exploited aquifer of the island since it is productive and it is located within a zone with high water demand. The Western Aquifer, like all the aquifers of the island tend to be mostly unconfined in nature, and drought conditions result in severe stress on the productivity of the aquifer. With the findings of the recent hydrogeological studies, there is a need to further improve the understanding of the hydrogeology of the Western Aquifer. Being already heavily exploited, and also located in an urbanised region, this aquifer is therefore under constant threat to surface pollutants. A numerical groundwater flow model of the aquifer was considered as an important tool to get a better understanding of both the hydrogeology of the aquifer and its response to recharge and discharge events. The first step of this study was to develop a conceptual model of the Western Aquifer, based upon the findings of past hydrogeological studies.



Re: Giorgi et al., FAC project (1999)

Figure 1: The Western Aquifer

HYDROGEOLOGY OF THE WESTERN AQUIFER

The hydrogeology of the Curepipe Aquifer has been studied fairly in detail by several past studies (Sentenac, 1963; Fao, 1971; Sigma & Sogreah, 1981; Giorgi *et al.*, 1999). Geophysical investigations carried out by Sentenac (1963) indicated that the aquifer system is governed by three major lava formations, the Trois Mamelles-Mount Rempart, the Candos-Corps de Grade-St-Pierre-Bambous-Medine and the Petit Malabar-Gros Cailloux-Beau-Bassin-Grand Malabar. These sub formations act as geological barriers and control the flow of groundwater in particular pathways. The more recent hydrogeological studies (Giorgi *et al.*, 1999) noted that the Western aquifer consisted of a combination of two interactive sub-aquifer systems, the Curepipe aquifer and the Phoenix aquifer.

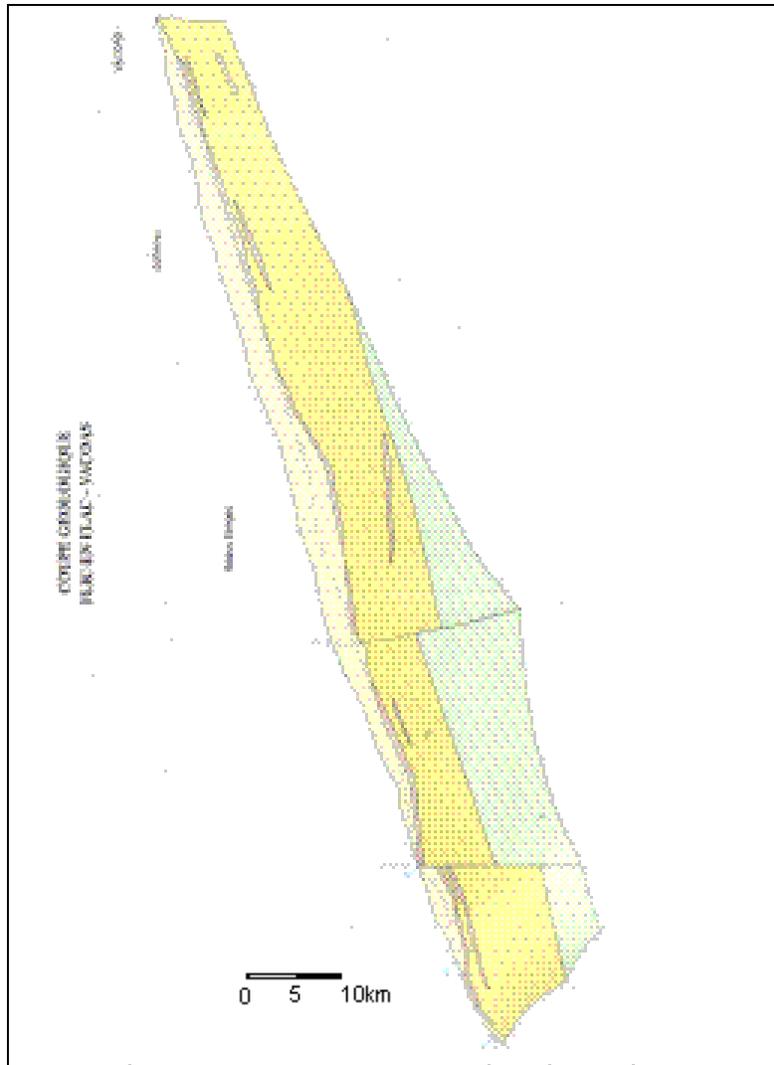


Figure 2: Vertical section across the Western Aquifer (Flic-en-Flac/Vacoas)

According to the master plan by Sigma & Sogreah (1981), the hydrogeology of the Curepipe aquifer is mainly governed by the late lava flows from Trou-Aux-Cerfs and Curepipe Point, with thickness of the order of 60 to 70 metres (Figure 2). In this same respect, the study reported that the aquifer is made up of lava flows from the intermediate lava series. These lava flows are characterised by relatively low coefficient of hydraulic conductivity but with high storage coefficients. This particular aquifer is further described as a closed basin, within which the build-up of water occurs, hence favouring a high water table. French Cooperation (1991) has also mentioned the presence of perched aquifers within this aquifer. The Western aquifer is also characterised by the presence of lava tunnels. These features significantly influence the overall permeability of the aquifer and the

preferential pathways of the groundwater flow within the aquifer. With respect to the overall permeability of the aquifer, Sigma & Sogreah (1981) have reported that the heterogeneity characteristic of the aquifer is also associated to the volume of voids in the recent lava flows and also to the degree of weathering of clays within the intermediate lava flows. The presence of localised fissures and irregular quality of the recent basalts also account for the heterogeneous nature of the aquifer system (French Cooperation, 1991). Another important characteristic associated with the Curepipe aquifer is its high flow gradients, ranging of the order of 2 to 3% (Sigma & Sogreah, 1981). Hydraulic gradients are relatively very steep as compared to normal situation in groundwater basins. In localised areas within the Western Aquifer the hydraulic gradient goes up to 5%. The transmissivity characteristic is also reported as being highly heterogeneous both in space and in time. Pumping tests carried out (Sigma & Sogreah, 1981) have shown that the values are of the order of $10^{-2} \text{m}^2/\text{s}$.

The climate prevailing in this region is classified as being subhumid along the western coast and humid in the upper Central Plateau (French Cooperation, 1991). The Central Plateau of the island is a major recharge zone, receiving on average an annual rainfall of 4m. Rainfall is uneven distributed with a minimum of 800mm along the coast and a maximum of about 4000mm along the Central Plateau. Evaporation is highest in the coastal region (2000mm) and decreases to a minimum (1400mm) towards the Central Plateau. Three major rivers systems are within the boundaries of the aquifer system, they are namely; Grand River North West, River Du Rempart and River Tamarin. These rivers are perennial in nature and are in hydraulic contact with the aquifer system. The Western Aquifer is connected on the eastern side to the major recharge zone, the Central Plateau. Fao (1971) carried out studies on the recharge capacity of the aquifers of the island, and reported that the infiltration factor varied in the order of 5% to 30% for the island of Mauritius. This same study considered the Western Aquifer as being divided into three main sub regions, and reported an infiltration factor around St-Pierre as being 5%, that around Mare-Aux-Vacoas as being 7% and that around Curepipe varying from 10 to 30%.

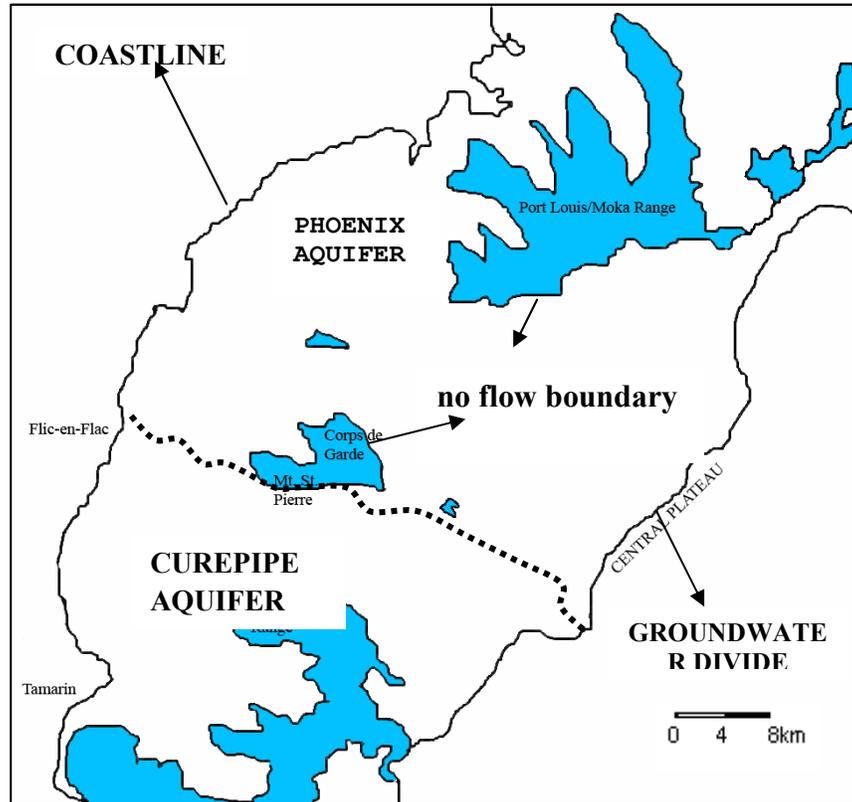
Groundwater is discharged from the Western Aquifer via five potential routes; abstraction of groundwater by pumping, tapping from a natural tunnel, the Pierrefonds tunnel, harnessing of springs, harnessing of rivers and finally outflux of groundwater along the coasts. The exploitation of the Western Aquifer dates back long, since the mid 1960's, when it was exploited to cater for agricultural water demand. Later on exploitation on a much larger scale started to cater for domestic water demand. Sigma & Sogreah (1981) reported that the Western aquifer constantly loses water to the sea at the rate of $3.7 \text{ m}^3/\text{s}$ along zones in hydraulic contact with the sea, based upon an average aquifer thickness of 30m. The Western Aquifer is located within a highly urbanised zone and the resulting ground surface activities constitute potentially polluting sources. In the coastal region, irrigation is practiced on a relatively large scale. Seawater intrusion is also a threat to the aquifer along the coastal zones.

CONCEPTUAL MODEL OF THE WESTERN AQUIFER

A conceptual model is a simplified representation of the complex real system. A conceptual model tends to provide the qualitative description of the real aquifer system. According to Samper et al. (1990), developing a conceptual model is the most important and difficult step to be completed in the eventual development of a numerical groundwater flow model. A good conceptual model helps a modeller to understand how an aquifer system responds to recharge and discharge events and what geological barriers control these movements. The development of a conceptual model is carried out in 3 stages; the hydrogeology of the system, the recharge and discharge events, and the physical parameters describing the permeability and storage characteristics of the aquifer. The conceptual model of the Western Aquifer was developed based upon past hydrogeological studies and also by using recently compiled hydrogeological information and climatic information from the local water institutions, Meteorological Office and the Water Resources Unit.

Boundaries of the aquifer system

The Western Aquifer, is made up of two sub aquifer systems, the Curepipe Aquifer and the Phoenix Aquifer, but since these two sub aquifers are in hydraulic contact with each other, the Western Aquifer is analysed as one main aquifer. The Curepipe Aquifer is bounded to the south by the Black River mountain ranges and to the west by the sea (Figure 3). The northern boundaries of the system include mainly the old remnants of Mount Corps De Garde/Mount St Pierre and Candos Hill, as well as the borders of the intra-caldera centered on Arnaud. Giorgi et al. (1999) noted that this particular boundary is discontinuous since the fresh basalts of the recent series allows the transfer of groundwater towards the Phoenix Aquifer, between Corps De Garde and Candos Hill. The system is connected to a major recharge area, the Central Plateau, along the eastern side (groundwater divide). The second sub aquifer, the Phoenix Aquifer is limited to the north by the Port-Louis/Moka Mountain Ranges, and is bounded by the sea (coastline) along the western area. This aquifer is bounded by Corps De Garde mountain to the south and by the limits of the caldera centred on Valetta and Montagne La Terre. This second sub aquifer is also in hydraulic contact with the major recharge area, the Central Plateau.



*Figure 3: Boundaries of the Western Aquifer
(Giorgi et al., 1999)*

Bedrock elevation

The bedrock (Figure 4) of the Western Aquifer constitutes the bottom boundary of the Western Aquifer and was derived by Giorgi et al. (1999). This impermeable boundary is made up of lava flows from the older volcanic series. The bedrock has a valley shape and it coincides with mean sea level at a distance of approximately 2 km from the coast. The bedrock map of the aquifer indicates the presence of two valleys and these would therefore constitute a route for groundwater flow. The valleys tend to converge in the central region of the aquifer and then extend laterally to reach the sea.

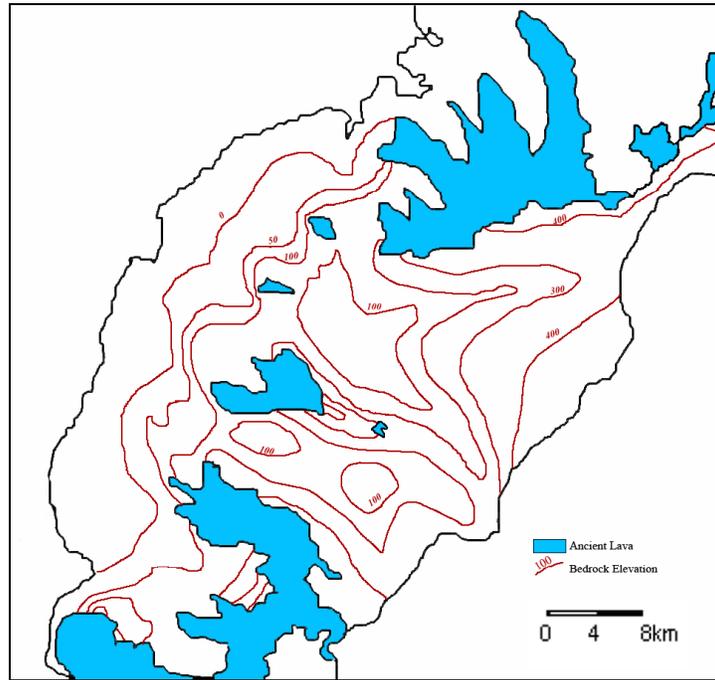


Figure 4: Bedrock elevation map
(Giorgi et al., 1999)

Geological structure

Curepipe aquifer is made up mainly from the lava flows of the recent basaltic formations. The source of these fresh basalts is the crater of Trou-Aux-Cerfs which has been very active in the final phase of the formation of the island. Closer to the coast however, lava flows from the intermediate lava series are also present. These are characterised by low permeability. Intermediate lava flows are quite pronounced in the south western area, and the height of these formations attain up to 500 metres near the zone of recharge. Phoenix aquifer is more complex, and is characterised by a relatively minor proportion of the recent basaltic flows. The fan-like shape of the recent basalts which also emanated from Trou-Aux-Cerfs, does not reach the coast. The remaining area is dominated by lava flows from the intermediate series, except for a narrow strip of recent lava flows. The height of the recent formations varies from 150 metres to about 500 metres near the zone of recharge. Lava tunnels present within the subsurface significantly influence the flow of groundwater both in terms of direction and magnitude. Proag (1995) reported that the existing lava tunnels can reach as long as 600 metres length and are concentrated in particular areas, Petite Rivière, Beaux Songes and La Caverne. The lava tunnels also act as a channel for polluted to reach the aquifer system at a relatively very fast rate.

Hydrological Information

On average the precipitation of Mauritius is about 2000mm annually. The Western Aquifer receives an annual rainfall which varies from 800mm along the coast to 4000mm (Padya, 1984) at its highest elevation region, the Central Plateau. This region is the main recharge zone of the Western Aquifer.

Hydraulic head distribution

The local water authority has established a well-organised groundwater monitoring network. Groundwater levels are taken once every week at small diameter holes, commonly referred to as coreholes. Graphical plots of hydraulic heads indicate a variation of potential head values from 450m around the Central Plateau to almost 0 metres along the coast at sea level (Figure 5).

Transmissivity characteristics

Studies carried out by the French Cooperation (1991) and Ramroop (1987) established detailed information as to the variation of transmissivity characteristics of the study area. Transmissivity values were found to vary from 10^{-3} m²/s to values greater than 5×10^{-2} m²/s.

Layering of the aquifer system

Boreholes logs obtained from the Water Resources Unit were used to get information about the vertical structure of the aquifers. The aquifer being basaltic in nature, it is best characterised as a multilayered aquifer. The layers are connected to each other via layers of lower permeability. However, these low permeability layers at times also act as geological barriers restricting the groundwater flow in a lateral path.

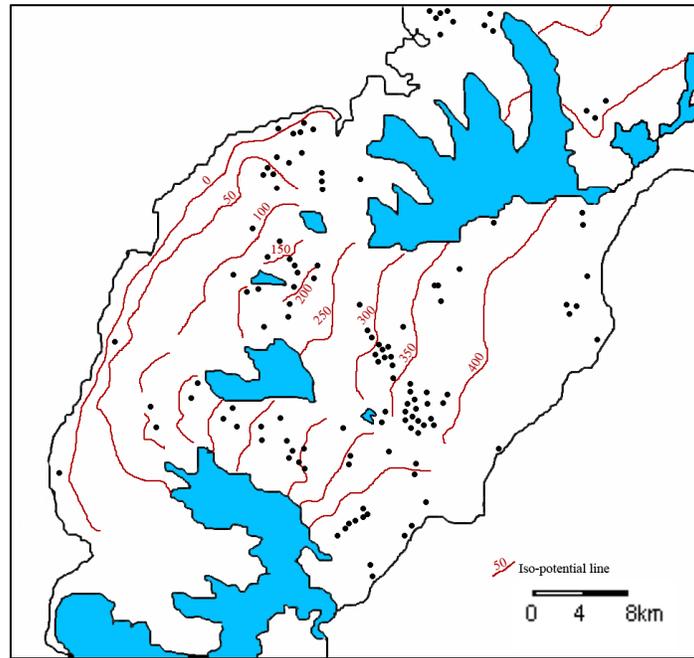


Figure 5: Hydraulic head distribution

(Giorgi et al., 1999)

NUMERICAL GROUNDWATER FLOW MODEL OF THE WESTERN AQUIFER

Any modelling study must follow a modelling protocol. This protocol may not be identical for all studies, but it has many common points. A typical modelling protocol has been described by Anderson & Woessner (1992). The first step is to define the purpose for which a numerical model is required, this is then followed by the development of a detailed conceptual model, based on the understanding derived a numerical groundwater flow model is developed, this model has first to be calibrated, and verified. The calibrated model can then be used for predicting purposes. The software Visual Modflow was used to develop the numerical model. This software uses the finite difference method as numerical method, and the convergence was determined using the difference criterion less than 0.005m between successive hydraulic head values.

A numerical groundwater flow model of the Western Aquifer was being developed to get further insight into the hydrogeology of the aquifer and also to test the response of the aquifer to various stress conditions.

Grid Design

Grid design is a very important step in numerical modelling, the finer the grid the better the simulated system. However, a very fine grid also requires much more detailed field information, which may not always be available. The best advisable approach is to start with a relatively coarse grid and to refine the mesh as the process of modelling goes on. For the purpose of this study, a grid cell of size 1km by 1km was initially selected. This was later on refined to a grid cell size of 200m by 200m.

Boundary conditions

The boundaries of the aquifer were identified during the conceptualisation stage, so the following made up the boundaries of the numerical model:

1. A constant head of 0m represented the coastal zone – Western boundary
2. The mountain ranges making up the northern and southern boundaries were represented by as a no-flow boundary.
3. The eastern boundary which is the connection between the Central Plateau to the Western Aquifer was represented by a groundwater divide, as a recharge constant flux boundary. This flux value was computed using Darcy's law and using the measured hydraulic heads at coreholes located within the Central Plateau.
4. The groundwater divide separating the sub aquifers, was simulated for the most part as no-flow boundary, with connecting zone close to the Central Plateau region.

Physical Parameters

The main physical parameters that were used in this model were, coefficient of hydraulic conductivity, storage coefficients, and the recharge distribution over the study area. Initially a single value of hydraulic conductivity was assigned to the numerical model. This value was then modified stepwise based upon the zoning concept (Peck *et al.*, 1987). Bhaghirutty (1995) used storage coefficient values ranging from 10% to 30%. For specific yield a value of 0.01 per m was used as a starting value. Recharge to the aquifer was assumed to be a percentage of rainfall, using the infiltration factor of 0.3 as specified in the Fao (1970) study. As for the river/aquifer interaction, a conductance value had to be specified. This was obtained from assuming a value for the permeability of the river bed, and the conductance value specified was 34.56m²/day. Transmissivity values for the intermittent lava series range from 10⁻⁵ to 10⁻³ m²/s and those for the recent lava series range from 10⁻³ to 10⁻² m²/s, according to French Cooperation (1991).

Layering of the aquifer

Initially the aquifer was simulated in terms of only one layer, but this was then changed to cater for the multilayered characteristic of the real aquifer system.

Calibration and Verification Criteria

Historical groundwater levels at observation wells and the piezometric map (Figure 4) was used to calibrate the model. Part of the data was used during the calibration stage and part of it was used during the verification stage.

RESULTS & DISCUSSIONS

The numerical model for the Western Aquifer was calibrated using the available data. With more detailed information, a more representative model would have been obtained. The numerical model was initially a simple one for which the predicted groundwater levels did not perfectly match the observed ones (Table 1), owing to the constraints in data used to develop the numerical model.

Observation Well	Observed heads (m)	Calculated head (m)	Difference (m)
F4 Hollyrood	415	432	17
B25 Pierrefonds	254	325	71
F2 Petite Rivere Village	57	133	76
CH150 Beaux Songes	208	252	44
CH151 La Louise	268	368	100
CH159 Rose Hill	253	325	72
CH200 Le Bousquet	92	203	111
CH216 Bambous	123	143	20
CH221 Pte aux Sables	25	61	36
CH245 Ebene	240	316	76

Table 1: Comparison table – Observed and simulated hydraulic head values at observation wells

The complexity of the model was incorporated in a stepwise manner and to be able to understand the response of the aquifer by matching predicted and observed groundwater levels. The physical parameters such as coefficient of permeability and recharge were modified to improve the fit between the predicted and observed groundwater levels. The model was initially calibrated under steady state conditions and then under dynamic conditions.

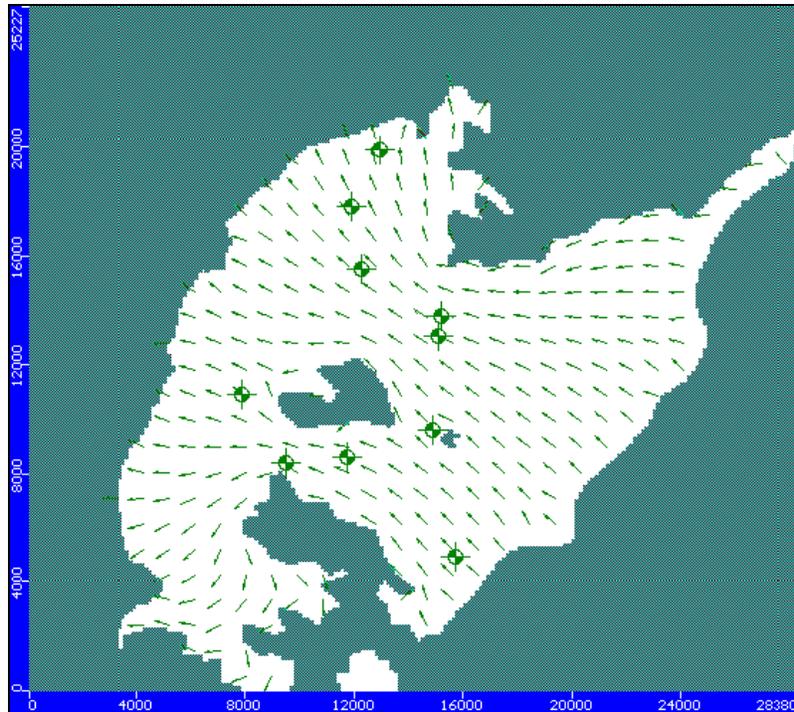


Figure 6: Simulated groundwater flow direction

The calibrated numerical model obtained was however quite useful in providing more insight into the hydrogeology of the system. The coarse model simulated the groundwater flow direction (Figure 6). During the calibration stage, the following key features were noted:

1. The Western Aquifer should be described as partly confined in some regions and partly unconfined in others, and not as entirely unconfined as past hydrogeological studies have demonstrated. This conclusion was drawn based upon the simulation of the hydraulic head at the observation wells. Even with detailed zoning to cater for variation of hydraulic conductivity, it was not possible to simulate the hydraulic heads at some observation wells to match field observations.
2. The remnants of the old volcanic series that formed the island, still visible in the form of outcrops of mountains Mount Corps de Garde and Mount Rempart, actually act as geological barriers, governing flow direction (Figure 5) within the aquifer system.
3. The numerical model confirmed the connection between the recent lava and the intermediate lava series with significant lateral flows taking place in between these two lava flows.

4. The groundwater flow velocity with the aquifer is of the order of 4×10^{-3} m/s.
5. The system loses groundwater to the sea at the rate of $4.65\text{m}^3/\text{s}$ and this is a very high value as compared to what had been reported by past studies.
6. Though there is surface and groundwater interaction within this aquifer system, there is a very small contribution of surface water to the groundwater, and this is confirmed by the relatively small dry flow rates of rivers.

CONCLUSION

This present study has illustrated how a reliable numerical groundwater flow model has been constructed and how it has provided further insight into the aquifer system, supporting past findings and also providing further insight into an aquifer system. The reliability of the model is associated with the detailed conceptual model and also with a good understanding of the physical characteristics of a basaltic aquifer in terms of coefficient of hydraulic conductivity and storage capacity. A numerical model is therefore an additional support to hydrogeological site investigations, and the accuracy of such a tool is very much dependent on the experience of the modeller. The Western Aquifer model developed has helped in getting a better understanding on the hydrogeological conditions prevailing within the aquifer. So, it can be concluded that a numerical groundwater flow model can be used as a supporting tool to get further insight into the geological site investigation of potential aquifers.

LIST OF REFERENCES

- ANDERSON, M. & WOESSNER, W., 1992. *'Applied Groundwater Modeling; Simulation of Flow and Advective Transport'*, Academic Press Ltd., USA.
- BHAGIRUTTY, L., 1995. *'Groundwater modelling of Curepipe Aquifer'*, University of Mauritius.
- FOOD & AGRICULTURAL ORGANISATION (FAO), 1971. 'Land and water resources survey Mauritius: Final report: Volume III, *Climatology and Hydrology*' Italy, pp. 93-109.
- FOOD & AGRICULTURAL ORGANISATION (FAO), 1971. 'Land and water resources survey Mauritius: Final report: Volume IV, *Geology and Hydrogeology*', Italy, pp. 1-123.
- FRENCH COOPERATION, 1991. 'Master Plan Study on the Water Resources of Mauritius: Conclusions & Recommendations', *Ministry of Energy, Water Resources & Postal Services, Mauritius*.

- GIORGI, L., BORCHIELLINI, S. & DELUCCHI, L., 1999. 'Carte géologique de L'Ile Maurice au 1/50 000' Schéma hydrogéologique, *Water Resources Unit*, Mauritius.
- PADYA, B. M., 1984. 'The climate of Mauritius', 2nd Edn., Government Printer, Port-Louis, Mauritius.
- PECK, A., GORELICK, S., DE MARSILY, G., FOSTER, S. & KOVALEVSKY, V., 1988. 'Consequences of spatial variability in aquifer properties and data limitations for groundwater modelling practice', *IAHS Publication no. 175*, UK.
- PROAG, V., 1995. 'The geology and water resources of Mauritius', *Mahatma Gandhi Institute Press*, Moka, Mauritius.
- RAMROOP, K., 1987. 'Modeling of Curepipe Aquifer', *University of Mauritius*, Mauritius.
- SAMPER, J., CARRERA, J., GALARZA, G. & MEDINA, A., 1990, 'Application of an automatic calibration techniques to modelling an alluvial aquifer', *MODELCARE 90; Calibration and reliability in Groundwater Modelling*, *IAHS Publication no. 195* pp, 87-95.
- SENTENAC, R. 1962. 'Recherches D'Eau Souterraine à L'Ile Maurice; 1. Généralités', Occasional Paper no. 12, *MSIRI*, Mauritius, pp. 1-25.
- SENTENAC, R. 1963. 'Recherches D'Eau Souterraine à L'Ile Maurice II; Secteurs de Plaines Wilhems, Rivière Noire, Chamarel; Conclusion générale, Occasional Paper no. 17, *MSIRI*, Mauritius, pp. 1-23.
- SIGMA & SOGREAH, 1981. 'Study of a master plan for the development of water resources in Mauritius, Master Plan Report'.