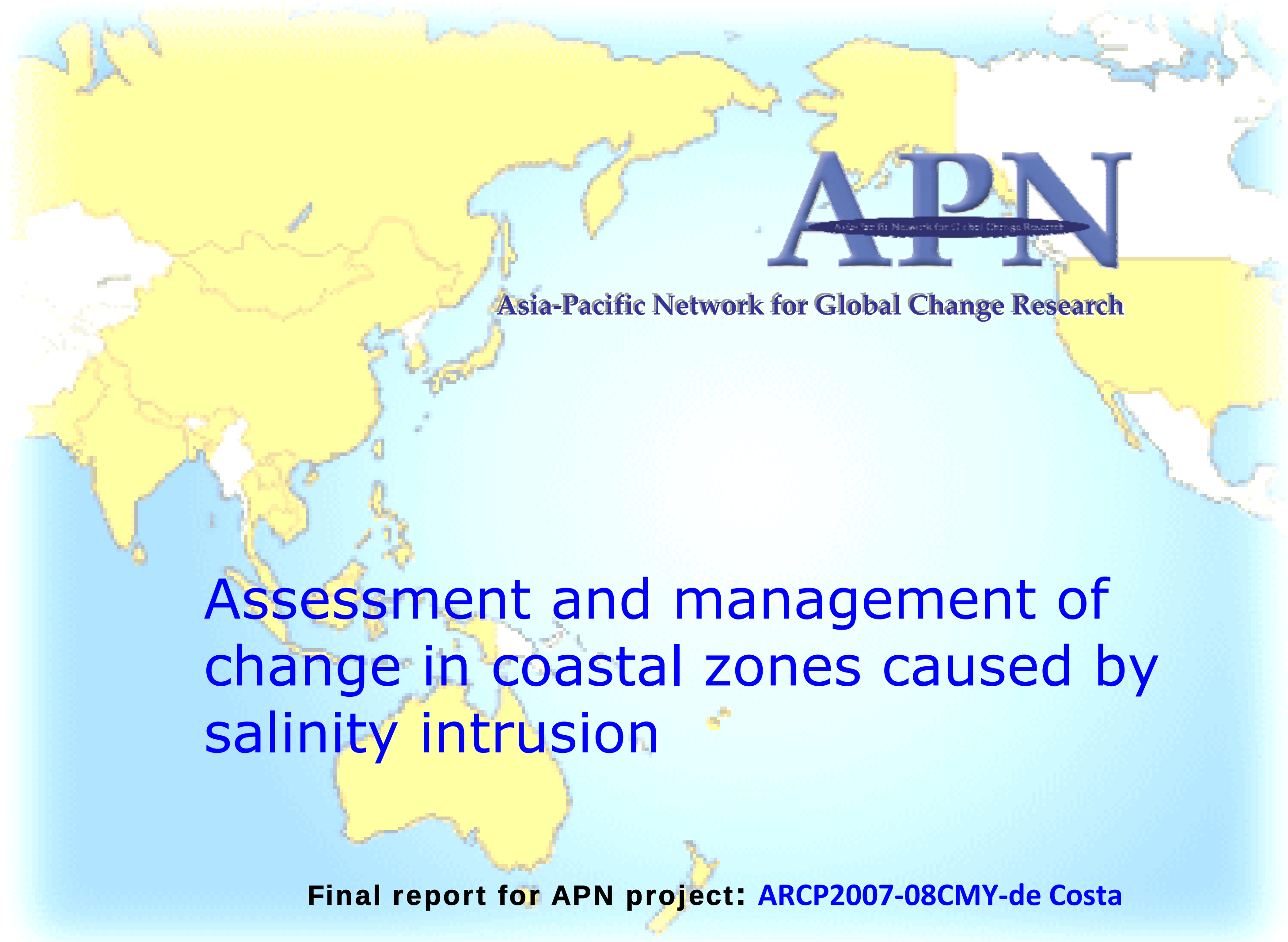

Asia-Pacific Network for Global Change Research

Assessment and management of change in coastal zones caused by salinity intrusion

Final report for APN project: ARCP2007-08CMY-de Costa

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Assessment and management of change in coastal zones caused by salinity intrusion

Project Reference Number: **ARCP2007-08CMY-de Costa**

Final Report submitted to APN

Overview of project work and outcomes

Non-technical summary

The first phase (first year) of this multi year project was delayed by 3 months due to unforeseen personal circumstances; hence completion of the first phase was extended to end March 2008. The second phase (second year) proceeded smoothly and project completed as per the revised target date, March 09. The project met all the envisaged milestones. Monetarily the project progressed as envisaged and over all project expenses are within budget.

Envisaged project objectives were all met & are as detailed below.

A research papers developed through this research were published in the proceedings of the 16th IAHR- APD Congress in 2008 and the proceedings of the 32nd Congress of the International Association of Hydraulic Research 2007. They were orally presented, at the Congress as well. Another two papers that have been sent to the 33rd Congress of the International Association of Hydraulic Research have been accepted for presentation at Congress and publication in proceedings.

Objectives

The main objectives of the project were:

1. Forecast salinity intrusion in key Asia Pacific sites (Year 01)
2. Development of technical (year01) & social management strategy (yr. 02)
3. Development of a methodology for multiple objective optimal management.
4. Increasing the profile & awareness of change in coastal zones and inland waters.
5. Establishing links and networks with policy makers in relevant countries.
6. Disseminating information to policy makers.
7. Conference paper as well research paper in recognized international journal.

Amount received and number years supported

Contract - 2006/07: USD 43,930

Received 80% of it equivalent to USD 35,200 and utilized same.

Contract 2007/08: USD 25,985

Received 80% of it equivalent to USD 20,800 and utilized same.

Activity undertaken

1. Detail data collection in study locations
2. Simulation of aquifer performance where possible and forecast future salinity situations
3. Meeting with collaborators
4. Establishing linkages between catchment change, usage pattern and salinity intrusion
5. Establish optimization model and management strategies.
6. Conducting workshops / presentations in study locations
7. Presentation of research at International Forums

Results

After detail data collection the Waiwhetu aquifer in Wellington was rigorously analyzed and simulated. Thereby a model has been developed to forecast the salinity situation in this aquifer. Aquifer behavior for numerous future scenarios was also analyzed and thereby a technical management strategy to manage salinity intrusion has been developed.

In addition a model for multiple objective optimal management has been proposed herein. Catchment change characteristics of the Waiwhetu catchment have been looked into and linkages between catchment change and water regimes have been established.

Further numerous other management strategies have been investigated with a view to adapt the best suited to the conditions given. Namely construction of underground dams to control salinity intrusion, was looked into by analyzing the ground water behavior near the Miyako island underground dam, in Japan. Controlling abstraction volume via a licensing system was investigated by analyzing the numerous management strategies implemented in the Bundaberg area of Australia. Construction of recharge and abstraction wells on the saline boundary as a measure of controlling salinity was investigated by looking at the Andra Pradesh area in India, and various dredging scenarios were looked into as a measure of controlling and maintaining a balance of sea water intrusion to surface water systems.

Relevance to APN's Science Agenda and objectives

Unmanaged extraction of ground water together with other effects has resulted in continuous change within fresh water bodies in coastal zones. Changes in catchments characteristics also interact with socio economic changes. This project commenced investigating these changes and explored ways of managing the resource / human interactions. Numerous scenarios have been analyzed and models have been developed, to equip policy makers with the means to facilitate optimization of multiple objective strategies for the management of change occurring in coastal zones.

This project falls in to theme 4 of the APN Science agenda - Use of resources / water, and pathways for sustainable development. The project also lies across several other themes as it has elements of, Theme 2 Ecosystems (Extent, causes and impacts of land use change, assessment and enhancement of land use sustainability) and, Theme 5 Cross cutting and science policy linkage (as it relates to Global change and water, science policy interfacing relating to global change and, sustainable management of coastal zones).

The project enlisted not only scientist from 6 countries working together but also collaborating with institutions and networks within their countries and resulting in scientific input to policy and decision making strengthening ties between scientist and policy makers.

Self evaluation

It was an extremely satisfactory project, which was much fulfilling both scientifically as well as personally. The project not only yielded good and tangible results to the scientific community and policy makers, it also up skilled me personally, and helped develop a wider understanding and collaboration with many scientific partners. It was, one that was physically, mentally and psychologically challenging and fulfilling. All project objectives have been more than achieved.

I would like to be involved in another such project.

Further Research questions, problems have arisen out of this research.

Potential for further work

It has been found that there is a need to establish precise linkages between overall catchment change characteristics, and both surface flow and ground water flow regimes as well as volumes. Catchment change characteristics bought about due to demographic changes as well as global change.

Further there is a need to investigate more in detail the effect of global change on temperature variation, seawater level rise and its effect on salinity intrusion.

Publications

1. Groundwater behavior in subsurface area of underground dams, Proceedings of the 16th Congress of the IAHR – APD 2008.
2. Strategic management of coastal aquifers subject to salinity intrusion, Proceedings of the 32nd Congress of the International Association for Hydraulic Research, Vol. 1, pp.520, Full paper on CD, 2007.
3. Management of coastal surface waters subject to sea water intrusion. 33rd Congress of IAHR, in publication 2009.

4. Salinity Intrusion, its Management and Control - Future Scenarios, Case of the Waiwhetu Aquifer, 33rd Congress of IAHR, in Publication 2009.

References

1. Comparative study on Salinity intrusion – case of the Waiwhetu aquifer, Wellington and the Bunderberg aquifer, Australia. Proceedings of the 30th Congress of the International Association for Hydraulic Research, Theme B, pp.565-572, 2003.
2. Salinity Intrusion, its characteristics and impacts. – Cases in the Asia Pacific Region, Proceedings of the 14th Congress of the International Association for Hydraulic Research – Asia Pacific Division, Vol. 2 pp. 2027 – 2032, 2004.
3. A study on salinity intrusion phenomena and its impact on the environment - Proceedings of the 31st Congress of the International Association for Hydraulic Research, Vol. 1, pp.313-318, 2005.
4. Towards developing a strategy for managing saltwater intrusion in coastal aquifers, Proceedings of the 15th Congress of the International Association for Hydraulic Research – Asia Pacific Division, Vol. 3 pp. 1547 – 1552, 2006.

Acknowledgments

The Project leader and collaborators express their appreciation to the staff of APN for all the support and assistance granted.

In addition they thank the Open Polytechnic of New Zealand, Auckland University, Wellington Regional Council, IIT Kanpur, Kyoto University, Moratuwa University, and University of Southern Queensland for all the facilities and assistance provided.

Technical Report

Preface

Due to the increasing need for fresh water, surface and ground water are being extensively used worldwide. As a result, gradual changes in human dimension and adjacent waters of coastal zones, caused by salinity intrusion has been a problem for a long time in some countries and is an emerging problem in many others.

This research investigated changes in coastal zones caused by salinity intrusion, i.e. first investigated changes and trends in water bodies, and next looked at catchment change. Here the long term salinity intrusion situation was assessed and predicted, and then, a link simulation multiple objective optimization model has been developed.

Numerous management strategies have been investigated and discussed, thereby it is envisaged that policy makers would be equipped to take optimal decisions with multiple objectives and to develop the best suited solution to manage their unique situations.

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1.0 Introduction

This section should include background information, scientific significance, objectives, and other relevant information leading to the development and justification of the current project.

Due to the increasing need for fresh water, surface and ground water are being extensively used worldwide. As a result, gradual changes in human dimension and adjacent waters of coastal zones, caused by salinity intrusion has been a problem for a long time in some countries and is an emerging problem in many others.

This project envisaged to develop solutions to this problem by means of,

1. Forecasting salinity intrusion in key Asia Pacific sites
2. Developing a methodology for multiple objective optimal management
3. Developing technical & social management strategies
4. Increasing the profile & awareness of change in coastal zones and inland waters.
5. Establishing links and networks with policy makers in relevant countries.
6. Disseminating information to policy makers.

In order to provide decision makers with tools to manage coastal zones subject to salinity intrusion, first a detailed assessment of coastal zones subject to salinity intrusion in key Asia Pacific sites have been made. As data is scarce and even when available sparse, an optimization approach was adopted in the distribution of research scope and work.

As it was required to, identify parameters, simulate aquifers and develop a model that could forecast the salinity intrusion situation, an aquifers where data was sufficiently available was investigated. The Waiwhetu aquifer, in Wellington New Zealand where data was not adequate but sufficient enough to do so was extensively investigated in this research. The Bundaberg aquifer in Australia too was researched.

For the Waiwhetu aquifer in Wellington New Zealand, after detail study the PMWIN model was decided upon and the aquifer was simulated. Thereafter numerous Engineering solutions have been analysed for possible future catchment changes. For greater accuracy and analysis of variability the same aquifer was simulated using FEMWATER another variation of MODFLOW. Here again possible future scenarios have been investigated.

Thereafter a link simulation optimization methodology has been proposed and this has been used to investigate multiple objective management of salt water intrusion in coastal aquifers.

Investigating a study done by Queensland Government Natural Resources and Water (NRW) and analysing the Bundaberg aquifer resulted in identifying the advantages and disadvantages of implementing numerous catchment management strategies. Investigating demographic changes and its effect of the catchment relating to the Waiwhetu aquifer ground water recharge made clear the effects of catchment change on water bodies.

In addition to the analysis of Engineering and management solutions investigated for the Waiwhetu aquifer and the Bunderberg aquifer, in order to obtain a wider view of other Asia Pacifc sites, salinity Intrusion and the groundwater situation in Andrapradesh, India were also investigated in detail and thereby further management strategies were developed.

An assessment of change and future potential of groundwater quality, quantity and salinity in Pakistan with reference to Indus Basin, is also presented.

As, our ultimate objective was to provide policy makers with a tool to manage coastal zones subject to salinity intrusion, even surface water bodies in coastal subject to salinity variation was also investigated. A details study of surface water body in Negombo, Sri Lanka, hydraulically connected to the Ocean was looked into. This water body with the passage of time, has undergone change due to natural as well as human intervention, and Engineering solutions to restore it to its original status have been investigated. A case study of the Southern Province of Sri Lanka was conducted resulting in development of management strategies to solve this issue.

While economically feasible Engineering solutions, such as recharge wells, improved in flow and seepage, to control salinity intrusion and resulting water quality issues were investigated, a possible high technology solution, namely the construction of underground dams to comprehensively solve the issue of salinity intrusion in aquifers that in any case need to be exploited due to the unavailability of water was also looked in to. Here preliminarily the ground water flow movement of aquifers subject to underground dams have been investigated with special reference to the Sunagawa underground dam in the Miyako Island of Japan.

In summary numerous management strategies to manage change occurring in coastal zones have been investigated and discussed, thereby it is envisaged that policy makers would be equipped to take optimal decisions with multiple objectives and to develop the best suited solution to manage their unique situations.

2.0 Methodology

The basic study methodology followed the following steps,

1. Detail data collection in study locations
2. Simulation of aquifer performance where possible and forecast future salinity situations
3. Meeting with collaborators
4. Establishing linkages between catchment change, usage pattern and salinity intrusion
5. Establish optimization model and management strategies.
6. Conducting workshops / presentations in study locations
7. Presentation of research at International Forums

The methodology as proposed had two inter related but distinct components to forecast future salinity scenarios. The research partners adopted a range of modelling approaches. These range from regression / statistical analysis of available catchment databases to detail numerical modelling of aquifer behaviours.

A three-dimensional numerical model will be adopted in the project for all required detail simulations. The results from all analysis will be combined to provide management strategies on coastal aquifers in the Asia pacific region.

Each collaborator acquired currently available and published data for his location. A model to simulate and forecast salinity situation was implemented for many required simulations of salinity scenarios. Each collaborator selected appropriate parameters and developed approaches to suite the particular region. A model was then developed to link the changes in waters of adjacent coastal zones to catchments socio economic trends and usage pattern

The most important component of this study is the development of optimal management strategies to manage changes occurring in coastal zones and adjacent waters. The resulting methodology is intended to be globally applicable although application at any given area may require fresh calibration and validation with local data.

These findings were then disseminated to policy makers at workshops, seminars and presentations.

3.0 Results & Discussion

Explain your actual findings, including figures, illustrations and tables. Make comments on the results as they are presented, but save broader generalizations and conclusions for later. Discuss the importance of your findings, in light of the overall study aims. Synthesize what has (and has not) been learned about the problem and identify existing gaps. Recommend areas for further work.

As this study was a sequential development of a management strategy to assess and manage change occurring in coastal zones subject salinity intrusion, initially, the Waiwhetu aquifer in Wellington New Zealand was investigated, and numerically simulated using PMWIN. Thereby the effect of numerous Engineering solutions for different scenarios have been analyzed. They are presented in section 3.1. For greater accuracy and analysis of variability the same aquifer was simulated using FEMWATER another variation of MODFLOW. Here again possible future scenarios have been investigated. This is presented in section 3.2. Salinity Intrusion and the groundwater situation in Andrapradesh, India were also investigated in detail. Here too engineering solutions have been developed to manage and control salinity intrusion. The results of this study are presented in Section 3.3.

Once aquifers were simulated and related Engineering solutions developed for numerous scenarios, next catchment change and various other catchment management control methods were investigated. Initially, Impact of changes in catchment characteristics on artesian water supply of the Waiwhetu aquifer in Lower Hutt Wellington was investigated and this is presented in section 3.4. The Bundaberg aquifer and numerous catchment management strategies were also investigated and this is presented in section 3.5. Section 3.6 details some issues with respect to ground water in the Indus basin of Pakistan.

As the research consist of coastal management, even surface water bodies subject to salinity intrusion in coastal zones were investigated and a case study of the Negombo lagoon, in which a strategy to restore it to original salinity levels is proposed in section 3.7.

As the above deals with both Engineering solutions as well as catchment management strategies next a link simulation optimization model that will facilitate multiple objective management of saltwater intrusion in coastal aquifers was developed and this is presented in section 3.8.

A comprehensive case study done on the Southern province of Sri Lanka to manage saltwater intrusion in low lying coastal zones is presented in section 3.9. While a separate high tech high cost comprehensive solution to solve saltwater intrusion by way of under ground dams is presented in section 3.10.

3.1 Waiwhetu aquifer, numerical simulation scenario analysis and engineering solutions

ABSTRACT

Waiwhetu aquifer which is a significant source of water for the Wellington region is susceptible to salinity intrusion. This research endeavored to model the aquifer using PMWIN model, and then investigate non conventional methods to monitor salinity intrusion. In addition to the conventional Abstraction control technique the effect of recharge on salinity intrusion was analyzed, by investigating controlled river floods, use of river banks and water traps, use of infiltration basins and injection wells. It has been shown that with a combination of low impact development techniques i.e. infiltration basins, water traps, injection wells, abstraction could be doubled without a risk of salinity intrusion.

Key words – salinity intrusion

1. Introduction

Waiwhetu Groundwater Aquifer is an important source for freshwater supply in the Wellington region. The Lower Hutt Groundwater Zone supplies about one third of Wellington's water demand. As ground-water use has increased in the coastal area, so has the recognition that ground-water supplies are vulnerable to overuse and contamination. This paper illustrates traditional approaches to monitoring and managing saltwater intrusion, and investigates new methods of salt water intrusion control into aquifer leading to sustainability of coastal ground-water resource.

The primary objective of this research is to develop a ground-water flow model to complement the Waihetu Aquifer research. This model will serve as a baseline for conducting a ground water evaluation analyze, for saltwater intrusion in the area of interest. Here, PMWIN has been adopted to develop a three dimensional model in the study area. The model is used to understand the ground water movement and the risk of saltwater intrusion. Through which critical aquifer stress conditions whereby saltwater intrusion is likely to occur has been identified. Based on resulted conditions, the paper highlights some of the possible approaches to use for enhancing the sustainability of ground-water resources.

2. Research Background

There is a long history of groundwater use and investigation in Lower Hutt; the first artesian bore recorded in the valley was drilled in 1883 (Hughes and Morgan, 2001). Consequently, this highly productive aquifer system has been used and well understood. More investigative work was done by the Hutt Valley Underground Water Authority in the 1960s. "Groundwaters of the Hutt Valley" (Donaldson, I.G. and Campbell, D.G. 1977) is a detailed study of the hydrology of the Hutt Valley basin. The study evaluates the potential and risk of saline water intrusion in the Waiwhetu Artesian Aquifer. Critical to the assessment of saline water intrusion is the characterization of the aquifer discharge processes. Three mechanisms of groundwater discharge into the harbour have been perceived:

a. discharge from the uncapped aquifer area,
b. discharge through discrete 'holes' in the aquitard taking the form of submarine springs,
c. general widespread leakage through the aquitard layer (Petone Marine Beds)

Submarine discharges from the Waiwhetu Artesian Aquifer were regarded to have been considerably reduced as a result of increased abstraction which may have caused many of the spring leakage sites to cease flowing. The large sea floor depression to the south of Somes Island is assumed to represent an important potential access site for saltwater intrusion into the Waiwhetu Aquifer. Donaldson and Campbell (1977) argue that the critical condition whereby saline water backflow into the aquifer would be when the aquifer pressure equalizes with the sea bed pressure following the prolonged reversal of the hydraulic gradient between the depression and the foreshore. Using Darcy flow equation, they concluded that higher outflows will occur in shallower waters and, conversely, salt water inflow will occur preferentially at the deeper leak sites.
Based on Donaldson and Campbell conceptual saltwater intrusion model, Cussins' (WRC, 1995) study re-calculated the minimum foreshore piezometric level at which offshore hydraulic gradients would reverse in the Waiwhetu Aquifer. The study found 2.8m above the sea level as being the minimum piezometric level.

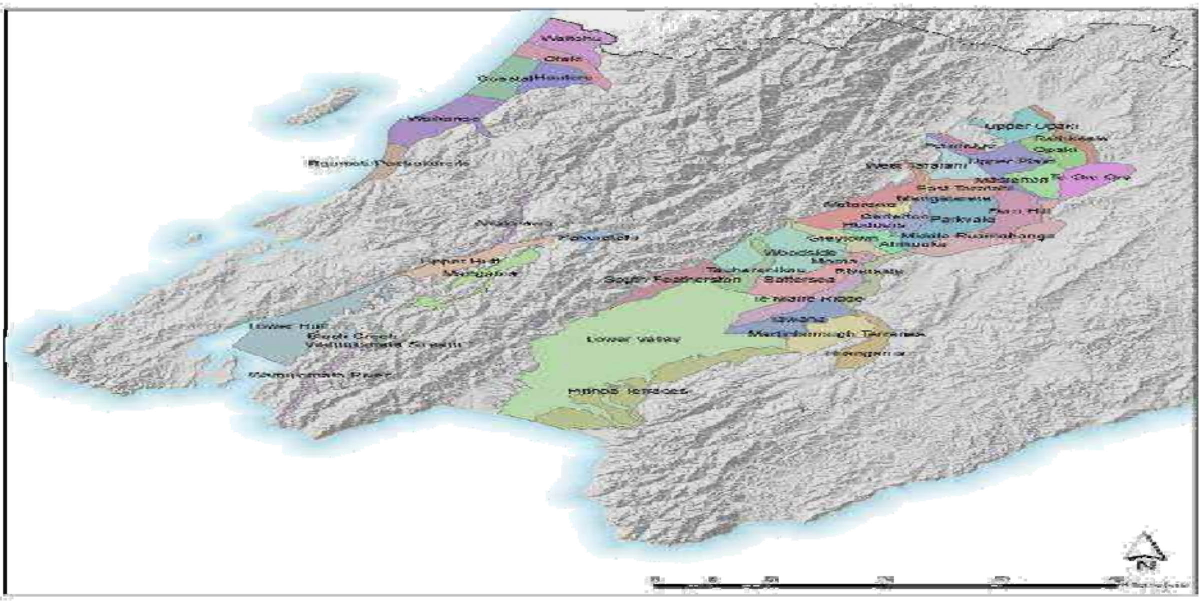
Phreatos (2003) constructs a new model (HAM2) based on Reynolds (1993) model, but using the recent advances in the geological and hydro-geological understanding of the groundwater system. The new model has a more detailed layer structure and re-designed boundaries. The information and analysis on the aquifer system has been used to review the critical level for hydraulic heads on the aquifer. Based on the results, a control of abstraction to manage the levels has been recommended.

3. Lower Hutt Zone Characteristics

3.1 Description of Study Area

There are three principal groundwater areas in the Wellington region: Lower Hutt Valley, Kapiti Coast and the Wairarapa Valley. Secondary groundwater areas include:Upper Hutt, Mangaroa Valley, Wainuiomata Valley and Sections of the Eastern Wairarapa Coastline. Aquifers in all of these areas are found in unconsolidated alluvial, aeolian, and beach sediments of varying grain size. Minor aquifers are also found in limestone and fractured greywacke in some areas of the region.

Figure 1. Groundwater Areas in the Wellington Region
Source: Wellington Regional Council Reports



The Waiwhetu Artesian Aquifer (Figure 2) extends offshore and underlies much of Port Nicholson where it discharges into the harbour at discrete submarine springs. The water enters Whaiwhetu aquifer from the Hutt River in the Taita gorge, following then the hydraulic gradient toward Melling area. Saline water is thought to inhabit parts of the offshore aquifer and has the potential, under stressed aquifer conditions, to encroach on the shoreline and affect water supply bores.

Figure 2. Waiwhetu Aquifer.
Source Google map,2007

3.2 Hydrological and geological description of the aquifer

The Lower Hutt basin is bounded by the Wellington fault to the West and basement rock to the East. The basin was formed as a result of movement on the fault, and folding to the East of the fault, over the last million years. Entrusted basement rock forms Somes/Matiu and Ward Islands in the harbour. As the basin has evolved, it has been in-filled with sediment. The thickness of sediment varies from a few meters at Taita Gorge, to over 600m at Kaiwharawhara (Wood and Davy, 1992). The sediments that have in-filled the basin are predominantly gravel, sand and silt sourced from the southern Tararua Range and deposited by the Hutt River. This alluvial material is separated by fine-grained marine and marginal marine sediments. The local glacial and interglacial divisions are based on Grant-Taylor study(1959).

Aquifers have been formed by the thick accumulations of gravel deposited by the Hutt River. These aquifers are separated by aquitards formed by beds of fine- grained marine sediments, which extend across much of the basin but deter out north of the Kennedy Good Bridge. North of the bridge the aquifers become unconfined. The unconfined aquifer is recharged predominantly by losses through the bed of the Hutt River. River losses at low flow are estimated to be aproximately 85,000 m3/day and 100,000 – 160,000 m3/day at average flow (Phreatos, 2003). The two main confined aquifers are the Waiwhetu Artesian Gravels and the Moera Basal Gravels. See Figure 3. The Waiwhetu Gravels forms the primary aquifer in the valley. A recent investigation bore confirmed that these gravels contain a laterally continuous, intermediate fine-grained layer that separates an upper and lower aquifer (Brown and Jones, 2000).

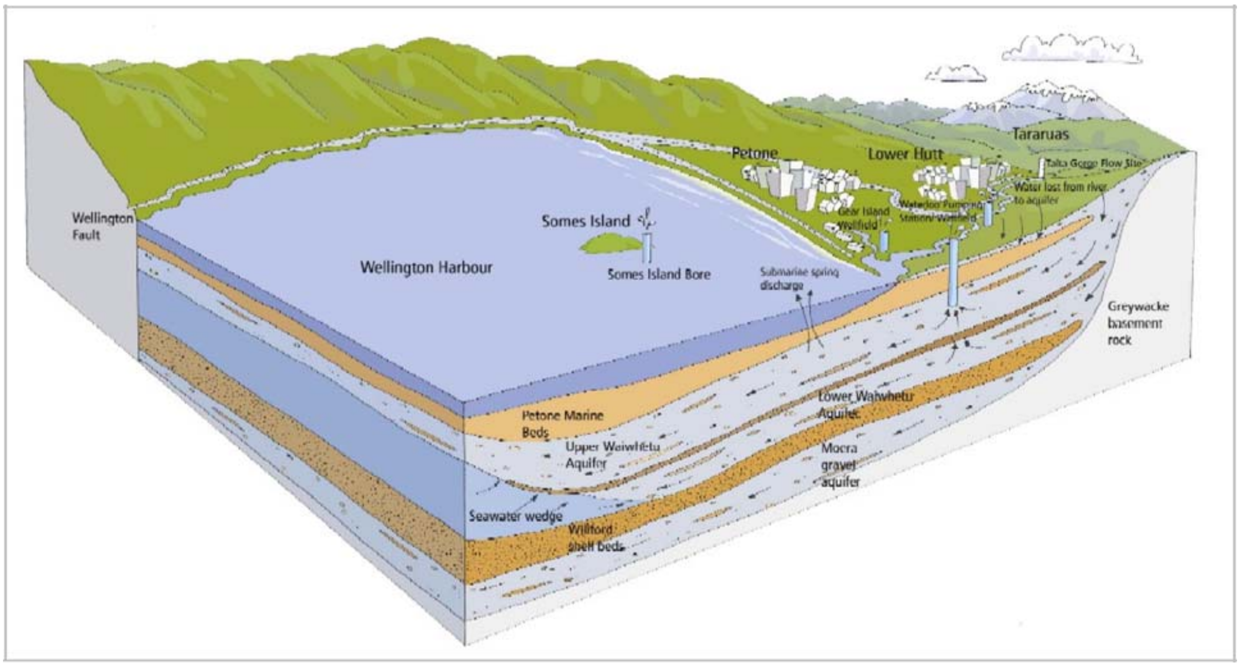


Figure 3. Lower Hutt Groundwater System-conceptual model
Source: Wellington Regional Council Report.

Table 1 Lower Hutt Aquifers Hydraulic Characteristics

Statigraphic Unit	Conductivity, Transmissivity, Storage capacity
Taita Alluvium most gravel, but sequence of sand, silt,clay thickness from 0 to 16m,thickening to Taita	2,700 to 52,000 m^2/day, average 4,500m^2 /day
Melling Peat and Petone Marine Beds fine-grained silt, sand and coarse sand ,shells 10-20m thick	10 to $1x10^{-4}$ m/day (WRC,1995)
Waiwhetu Artesian Gravels-Upper and Lower silt and sand 30-50m thick, maximum 55m on western side.	28,000m^2/day storage $3x10^{-4}$ to $1x10^{-3}$
Wilford Shell Bed silt, clay and sand deposits 25m thick,	0.1 to 0.01 m/day (based on lithology)
Moera Gravels brown gravels 25m thick	2,100 to 2600 m2/day storage 4 to $8x10^{-5}$
Deeper glacial/interglacial deposits alluvial and marine sediments	70m^2/day

Isotopic analyses of the Upper Waiwhetu Aquifer have been undertaken to determine the mean residence time of the water in the aquifer system. Residence times vary from 1.5 years at the Waterloo wellfield to ~25 years at Somes/Matiu Island. The variation in residence times indicates there is preferential pathway for water down the eastern side of the basin. The Upper Waiwhetu Aquifer is in hydraulic connection with the sea through numerous springs on the harbour floor (Harding, 2000). The deeper aquifers are thought to only have an indirect connection with the sea.

3.3 Hydrological Stresses

3.3.1 Recharge

At low to normal flow the Hutt River loses 900-1800 L/S to groundwater.(Jones, Baker 2005). The variation in groundwater level in the unconfined recharge area correlates well with variations in river flow as shown in following Figure. This correlation applies throughout the whole aquifer system although the effect of pumping and tidal variation introduces additional variation downstream of the recharge area. An extended period of low flow in the Hutt River from January to April 2003 is reflected in declines in groundwater level throughout the aquifer system. Modest increases in river flow from April 2003 resulted in rapid recovery of groundwater levels. Likewise, peaks in river flow are simultaneously represented by sharp increases in groundwater level.

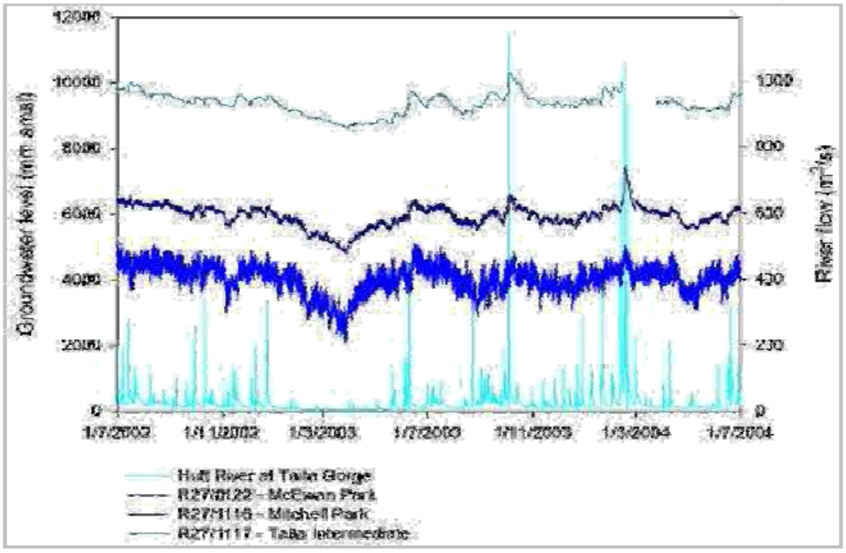


Figure 4.River flow-Groundwater level correlation
Source (Jones, Baker 2005)

3.3.2 Abstraction

The Waiwhetu Aquifer is exploited primarily for municipal water supply with a small number of industrial users. Since the mid-1980’s municipal abstraction was shifted from Gear Island near the foreshore, some 3km inland, to the Waterloo Wellfield.

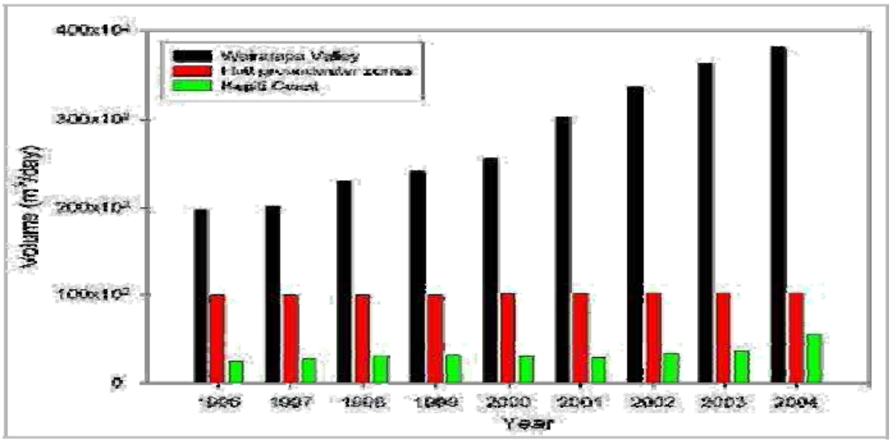


Figure 5 Water Abstraction Volume from Wellington Groundwater Region
Source Wellington Regional Council Reports

4. Model description

4.1 Model code

Processing Modflow simulation system package was used to model the Lower Hutt Groundwater zone. MODFLOW 2000 is used for water flow simulation and MT3D has been used for the solute transport modeling. PMPATH 99 has been used for visualization of the water flow.

4.2 Grid Design

MODFLOW employs a finite difference solution method which requires the use of a rectilinear, block-centered spatial grind and a number of layers. For this study 58 rows by 25 columns model has been developed. The grid (Figures 6, 7) has been aligned with the principal groundwater flow vector (Figure 7), parallel to the valley walls (NE_SW).

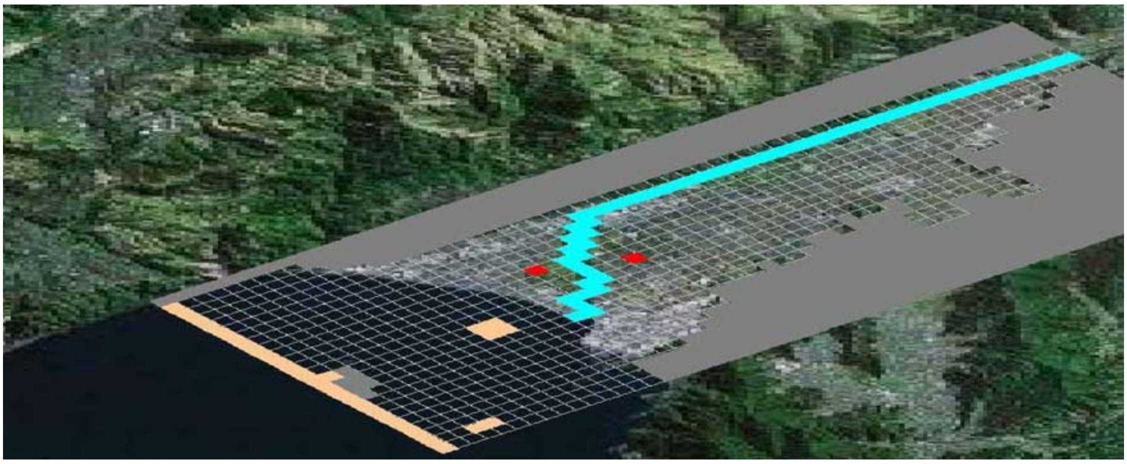


Figure 6. Model Grind, real world presentation

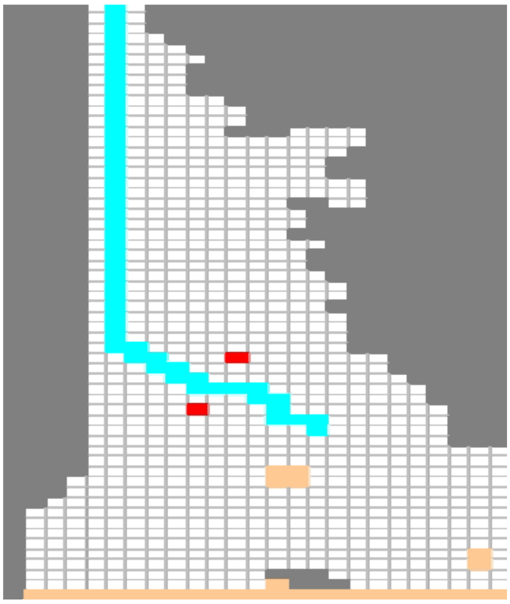


Figure 7. Grind Model

4.3 Layers Structure

The model has a seven layers structure. A summary of the characteristics of the layers are summarized in the following table. (Table 2)

Table 2. Layers Characteristics

Model Layers		MODFLOW Layer Type
Layer v1	Taita Alluvium	Type 1-Uncofined
Layer 2	Petone Marine Beds	Type3-Confined
Layer 3	Upper Waiwetu Gravels	Type 0-Confined
Layer 4	Intermedial -Upper Waiwhetu Gravels	Type 0-Confined
Layer 5	Lower Waiwhetu Gravels	Type 0-Confined
Layer 6	Wilford Shell Beds-Moera Gravels	Type 0-Confined
Layer 7	Moera Gravels	

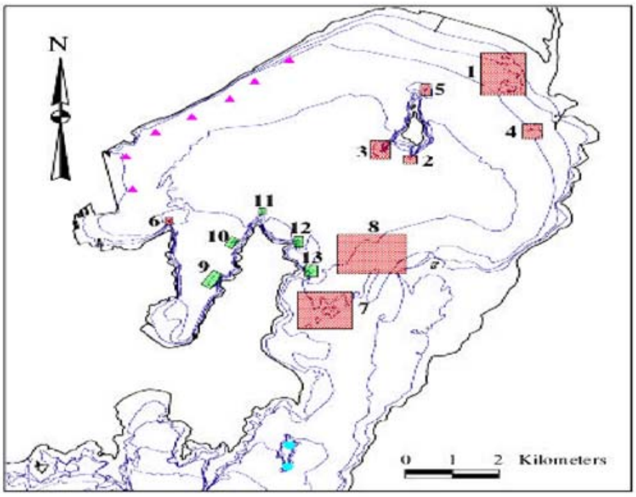
4.4 Model Boundaries

The following model boundaries have been assigned:

Eastern boundary: Junction between the unconsolidated alluvium and marine sediments and the basement greywacke which plunges towards the Wellington Fault.
Western Boundary: Coincident to Wellington fault
Northern Boundary: Taita Gorge where the thin sediments and are constricted within the gorge.
Southern Boundary: 2 kilometers south of Somes Island

4.5 Aquifer Discharge

Discharge from the confined aquifer take place through vertical upwards leakage into harbour over a broad area, although discharges are locally manifest as discrete submarine springs. The model handles aquifer discharge as diffuse leakage principally in area where the confining beds are thin and where a number of submarine springs have been identified. (Harding, 2000)



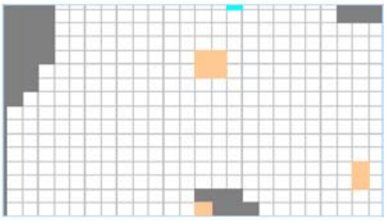
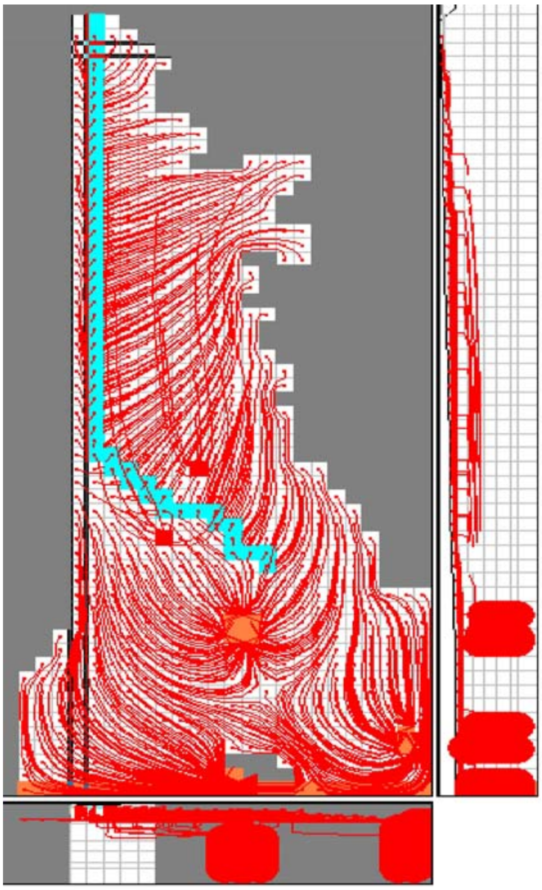


Figure 8: Location map of the areas of suspected, or known, submarine discharge.
Source - Wellington Regional Council Reports

Using PMPATH, Figure 9 and Figure 10 show the path of water flowing to discharge zone.



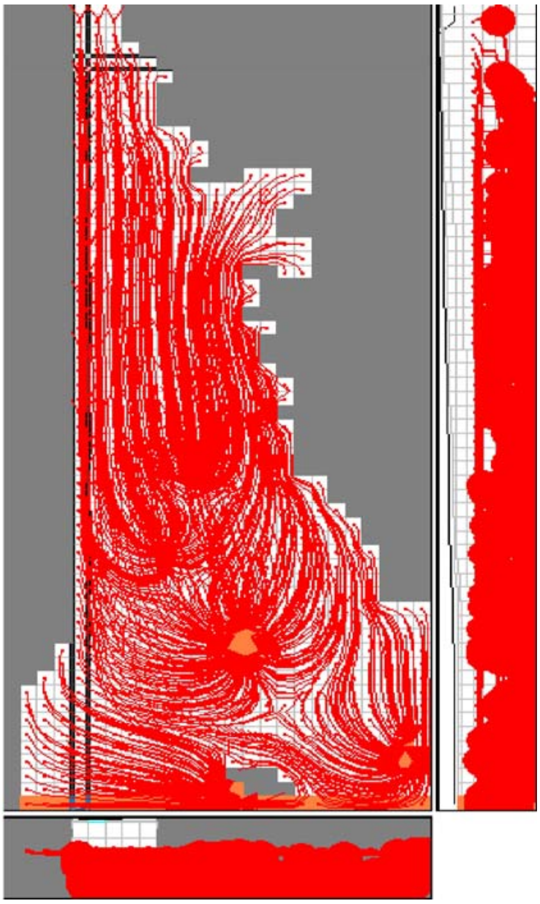


Figure 9. Flow path layer – 1 **Figure 10, Flow path layer 3**

The principal active spring discharge zones identified by Harding (2000) are those shown in Figure 8 and are as follows:

1. Hutt River mouth (zone 1)
2. Seaview (zone 4)
3. Northern tip of Somes island (zone 5)
4. Falcon Shoals and harbour entrance (zones 7 and 8)

5. Seawater intrusion mechanisms

The general pattern of fresh ground-water flow in coastal aquifers is from inland recharge areas where ground-water levels (hydraulic heads) are highest to coastal discharge areas where ground-water levels are lowest. This pattern of flow is illustrated by the ground-water flow paths in figures 9 and 10. Hydraulic head is a measure of the total energy available to move ground water through an aquifer, and ground water flows from locations of higher head (that is, higher energy) to locations of lower head (lower energy).

Later study conducted by Phreatos (Phreatos, 2002), have identified two mechanisms of saline water intrusion,
* Backflow of saline water currently residing in the offshore aquifer through the reduction in aquifer through flow and reversal of flow gradients caused by abstraction at the Waterloo Wellfield.
* Intrusion of sea water at submarine spring/depression sites and in areas where the capping layer is absent as a result of the lowering of groundwater levels and the equalization of aquifer and harbor pressures.

The first mechanism relies on the premise that saline water is currently occupying parts of the offshore aquifer. In the absence of information to the contrary, it must be assumed that this is the case. Reduction in groundwater through flow with associated lowered groundwater heads and ultimately, reversed flow gradients, will cause the wedge of saline water to move landwards and encroach on foreshore bores. This mechanism does not require that the piezometric level in the aquifer attains an equilibrium with the harbor floor pressures at potential saltwater intrusion (spring) sites.

The second mechanism entails the lowering of groundwater heads in the vicinity of potential intrusion sites to such an extent that saline water is able to diffuse and flow back into the aquifer. This scenario could occur at a submarine spring site or sea floor depressions where the capping layer is absent or very thin.

Study of the water flow model shows that seeping of seawater through the river bed and abstraction stress represents another possible seawater intrusion. The general movement of water within the Lower Hutt aquifer is from inland region to coastal discharge areas. Water in the upper aquifer is under unconfined conditions, and the water table responds quickly to recharge, evapo-transpiration, and pumping from supply wells. Often, in most places the aquifer and the river are in direct hydraulic connection, which facilitates rapid interchange of water between the river and ground-water system. During the dry seasons and because the river tidal movements, the sea water is moving inland along Hutt river allowing water to seep from the river into the aquifer and retarding saltwater intrusion. There is no exact information about how far the seawater is moving upstream of the river, but as you can see in figure 11, part of the water abstracted from Gear Island well field is coming from the estuary of the Hutt River and that may be a source of saltwater into the aquifer.

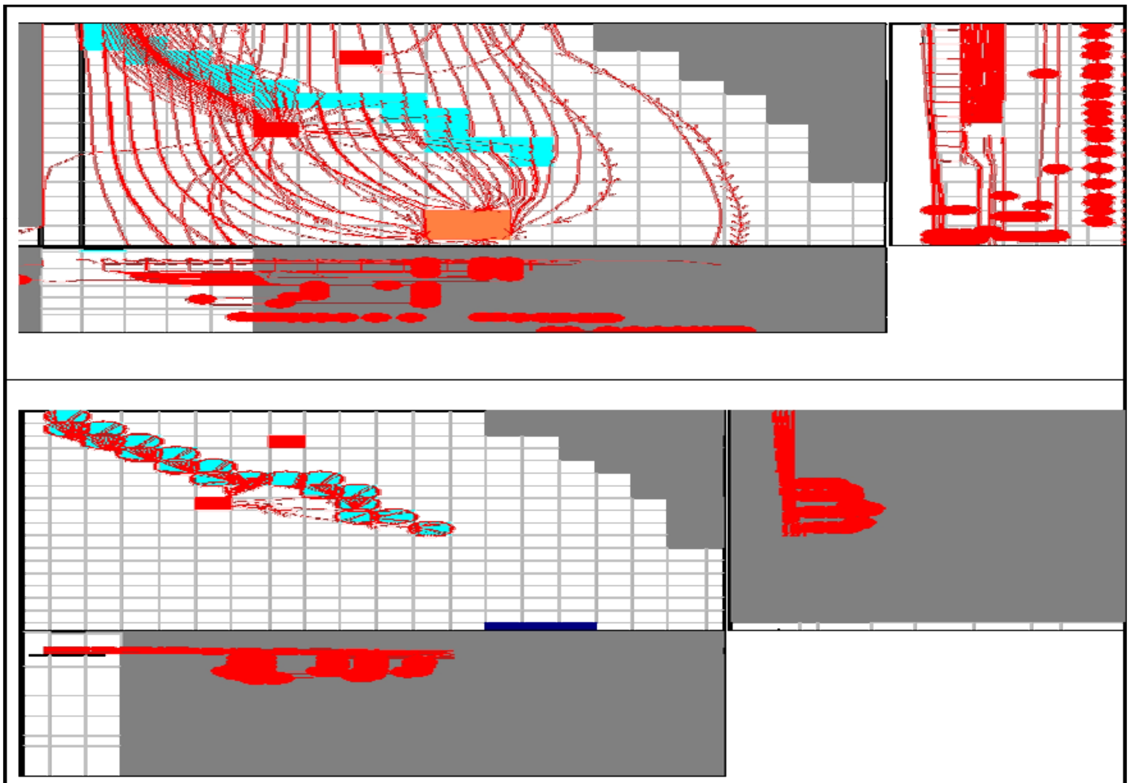


Figure 11. PMPATH representation of water flow from river bed to abstraction well in dry period

During the periods of high recharge rates, the danger of seawater intrusion from river estuary is minimal.

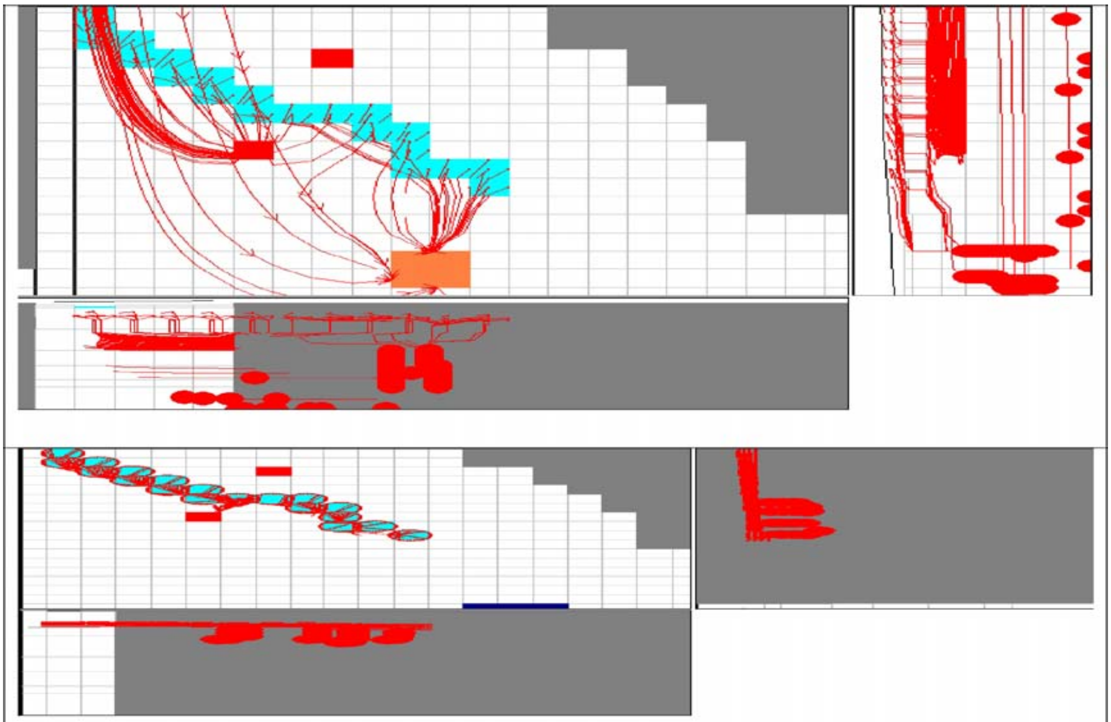


Figure 12. PMPATH representation of water flow from river bed to abstraction Well in high recharged period.

6. Monitoring and Management of Seawater Intrusion

PMWIN model package is used to test different assumptions on how the system may develop in the future. Since the future is uncertain, some assumptions about the evolution of the main source/sink terms need to be made resulting in different future scenarios. The complete set of scenarios provides a wide insight into the long term sustainability of existing pumping rates under different conditions. Furthermore, they provide information about where and which additional corrective measures are needed. Many corrective measures can be considered. Basically, they can be grouped into: reduction of groundwater pumping; increase of recharge; relocation of pumping wells; and in the case of coastal aquifers, additional engineering solutions to restore groundwater quality (e.g. hydraulic barriers).

6.1 Control of the water abstraction

Control of abstraction to manage the levels recommended by different studies is the traditional method to control seawater intrusion in Waiwhetu Aquifer. The new model has a more detailed layer structure and re-designed boundaries. The information and analysis on the aquifer system has been used to review the critical level for hydraulic heads on the aquifer. Donaldson, I.G. and Campbell, Cussins and Phreatos studying the aquifer's flow under different stresses calculated a critical level for hydraulic heads on the aquifer. Based on the results, control of abstraction to manage the levels was recommended.

The model simulations showed a noticeable effect of seawater intrusion for the dry period. Assuming that the recharge is zero (aquifer recharge only from river bed seepage, no recharge from raining or other sources), after five years period with constant abstractions of 15000, 25000 and 50000 mc/day for each of the wells, the results are show a considerable advance of the seawater intrusion.

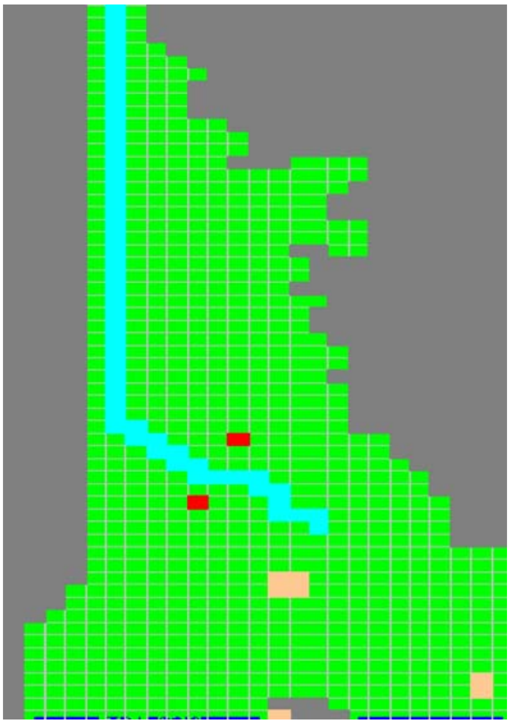


Figure 13. Seawater intrusion. No abstraction, no recharge. Blue line is the seawater location. green zone is freshwater zone

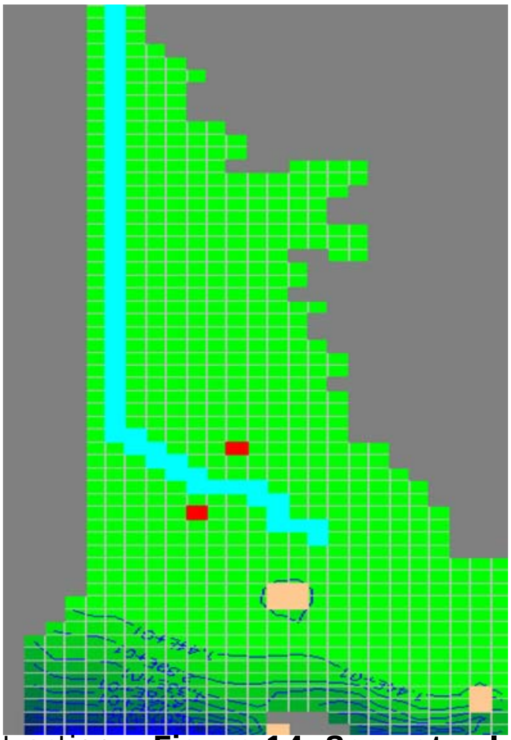


Figure 14. Seawater Intrusion. 15000mc/day each well. No recharge. Blue sea water location, green is fresh water

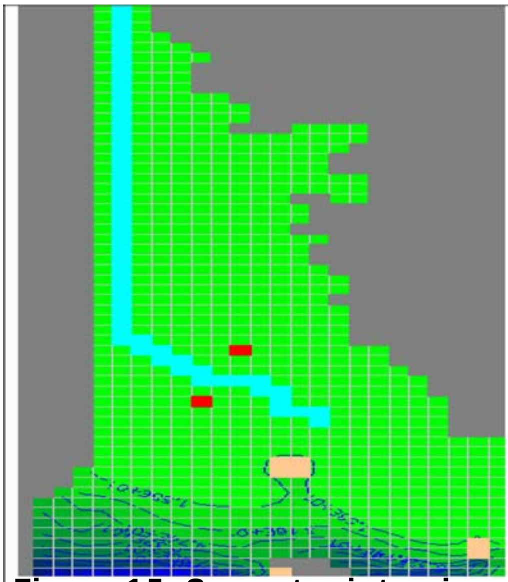
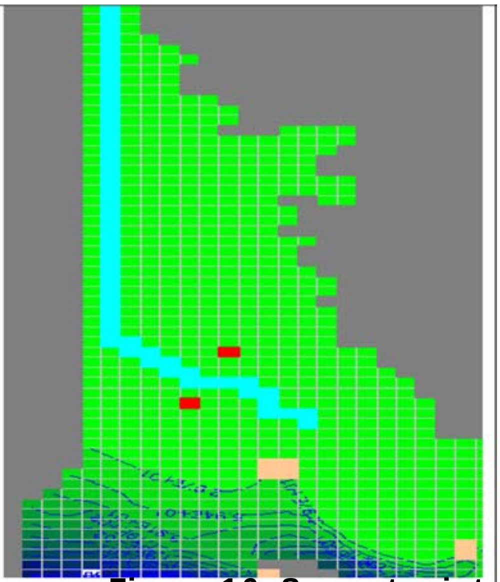
	

Figure 15. Seawater intrusion. 25000mc/day each well. No recharge. Blue line is the seawater location. green zone is freshwater zone	**Figure 16. Seawater intrusion.** 50000mc/day each well. No recharge Blue line is the seawater location. green zone is freshwater zone

If the recharge is increased to 400mm/years, the seawater intrusion is less significant for the abstraction of 15000, 25000mc/day but considerable for 50000 mc/day.

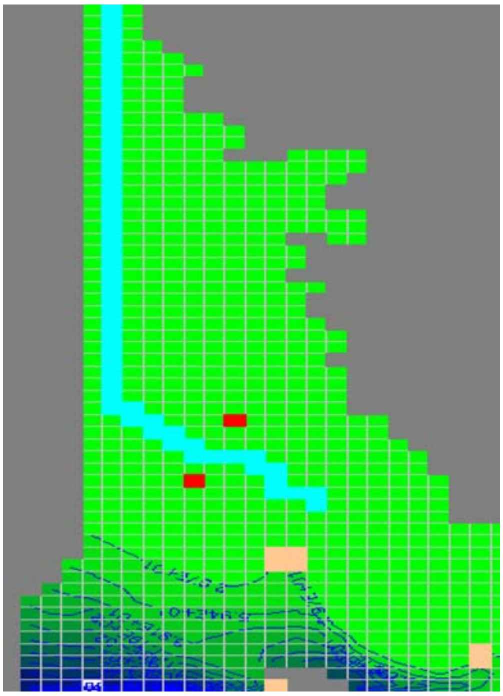


Figure 17. Seawater intrusion. 50000mc/day each well, 400mm, recharge Blue line is the seawater location. Green zone is fresh water zone.

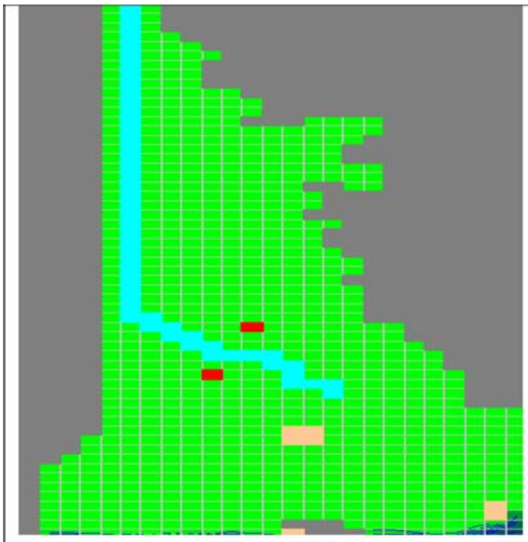


Figure 18. Seawater intrusion.

15000mc/day each well.
Blue line is the seawater location.
Green zone is freshwater zone.

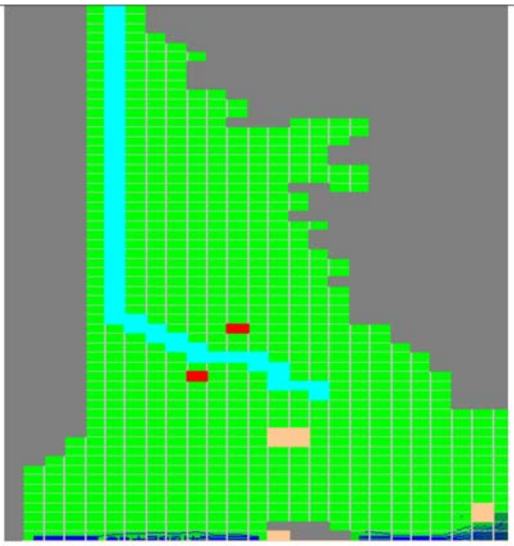


Figure 19. Seawater intrusion.

25000mc/day each well.
Blue line is seawater location
Green zone is fresh water zone.

6.2 Recharging the Aquifers

This investigation deals with artificial recharging of the unconfined part of the aquifer. Natural replenishment of aquifers occurs very slowly. Therefore, withdrawal of groundwater at a rate greater than the natural replenishment rate causes declining of groundwater level, which may lead to decreased water supply, contamination of fresh water by intrusion of pollutant water from nearby sources, seawater intrusion into the aquifer of coastal areas, etc. To increase the natural replenishment, artificial recharging of the aquifer is becoming increasingly important in groundwater management. The artificial recharge may be defined as an augmentation of surface water into aquifers by some artificially planned operation. The source of water for recharge may be direct precipitation, imported water, or reclaimed wastewater. The purpose of artificial recharging of groundwater systems has been introduced to reduce, stop, or even reverse the declining trend of groundwater level; to protect fresh groundwater in coastal aquifers against saline water intrusion from the ocean; and store surface water, including flood or other surplus water, imported water, and reclaimed wastewater for future use.

Possible adverse effects of the excess recharging may lead to the growth of water table near the ground surface and causes several types of environmental problems, such as water logging, soil salinity, and may effect natural aquifer storage and recovery systems.

6.2.1 Methods to increase recharge rate:

A. Increase aquifer recharge using controlled river floods.

During high volume rainfall events, some adjacent river areas can be flooded and water can slowly infiltrate after the storm. After using this method within one year a back movement of seawater could be seen. The movement is not significant, but in conjunction with other methods it is a possible to develop solution to eradicate salt water intrusion. Figure 20 shows the seawater location after 5 years of high level of abstractions (double than actual abstraction) and Figure 21 shows the back movement of seawater after one year of using flood river control.

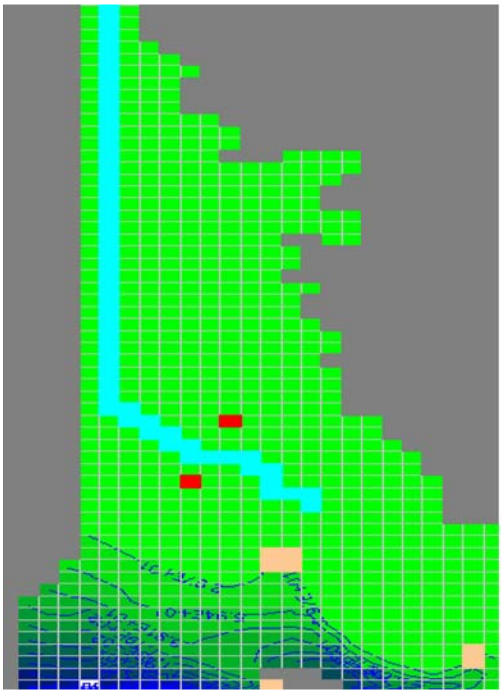


Fig. 20 Seawater location after very high level of Abstraction.

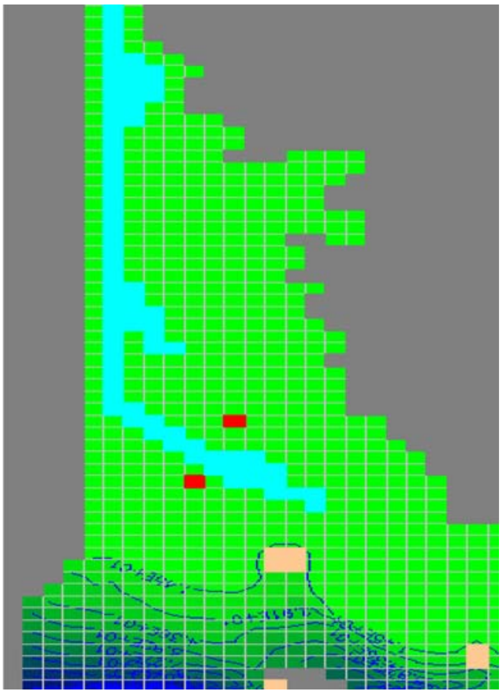


Fig. 21 Seawater location. One year after using Controlled river flood

B. River Banks, Water Traps

Water traps or river banks are used to increase infiltration in riverbed. The traps are earthen dams of variable height, usually 1m to 2m constructed of locally available materials. They are perpendicular to river banks. Water traps are designed to operate during rainfalls of up to an l-in-50-year frequency. The simulation was performed in assumption of traps along a 1 km stretch of river, at intervals of 70 m to 100 m. Their storage capacities for one trap fluctuate between 200 and 400 m3. Figure 22, 23 depict increasing infiltration in riverbed using water traps reduces the seawater intrusion.

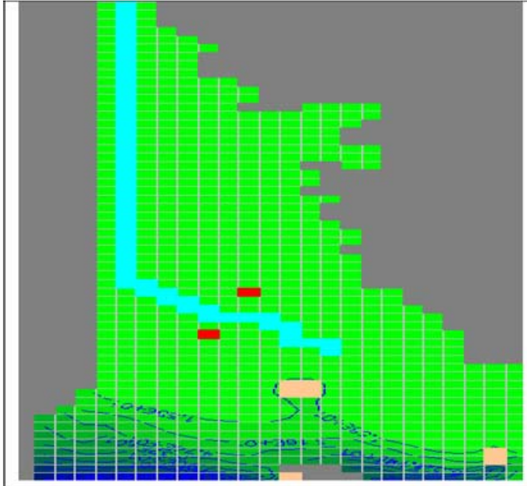


Figure 22. Blue area seawater intrusion zone

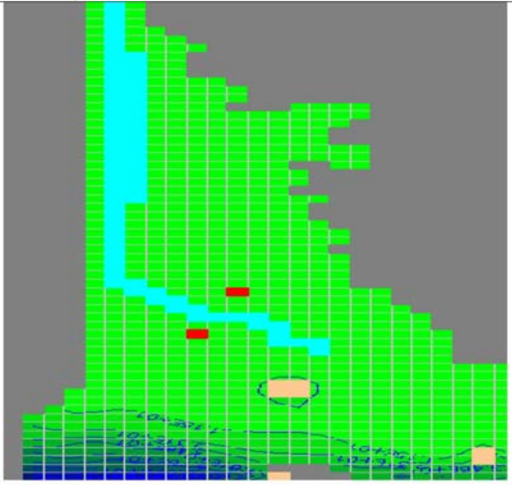


Figure 23. After one year of using water traps.

C. Injection Wells and water traps

The simulation uses the following scenario:
-One injection well with 10000mc/day for one year. The result of the simulation can be seen in figure 24 and 25. They shows a considerable recession of seawater from the aquifer.

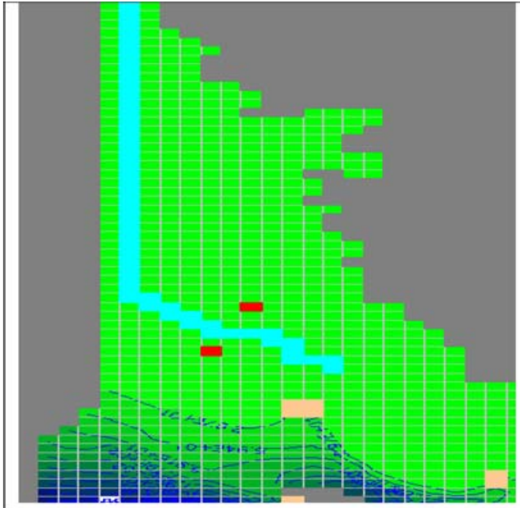


Figure 24. Level of seawater before using water traps and well injection

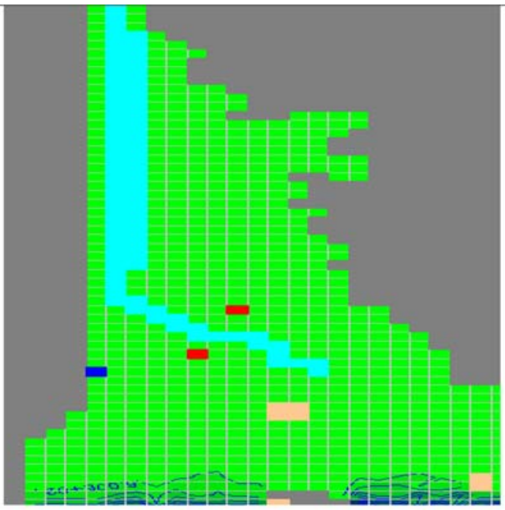


Figure 25 Seawater intrusion decline after one year of using water traps & injection wells.

D. Infiltration Basins and Injection Wells

The first simulation consisted of five infiltration basins, combined with five injection wells. The source of water for basins and the injection wells may be from direct precipitation, or reclaimed wastewater. The simulation shows that the basins and wells drastically reduce seawater advance, and even for an abstraction of 100000mc/day, double than actual abstraction, advance of seawater is minimal. The next figure compares position of seawater in

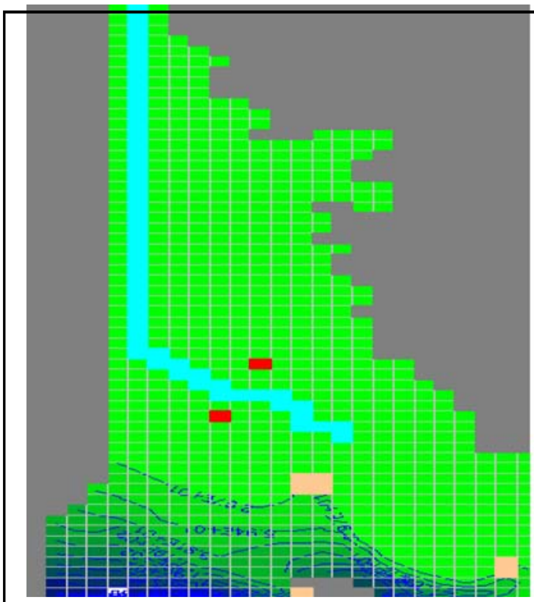


Figure 26. Blue is the zone of seawater intrusion

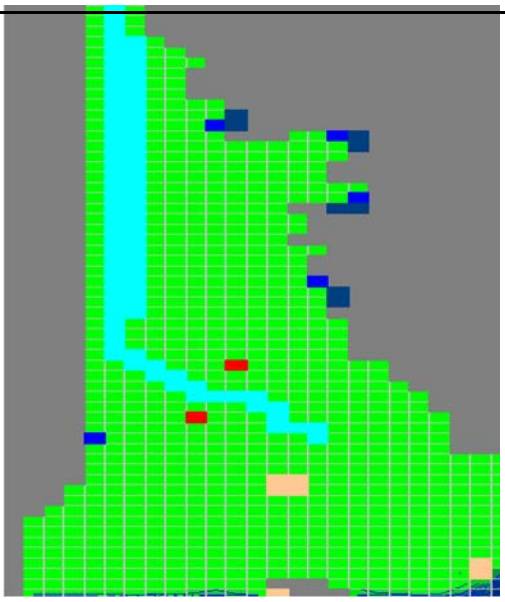


Figure 27. Seawater intrusion after one year of using infiltration basins and injection wells.

case of 100000mc/day abstraction with no basins, same abstraction with basin.
The water from two of the basins is seeping to river bed and removing these basins will not affect the recharge of the aquifer. See figure 26, 27, 28.

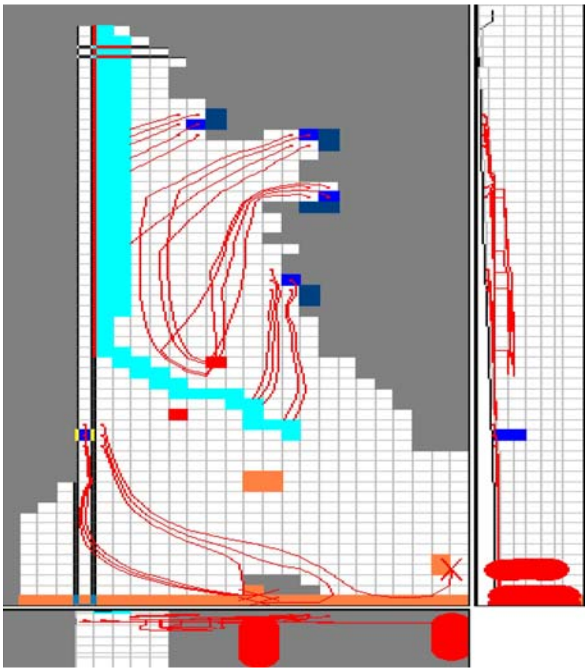


Figure 28. The water from two of the basins seeping to river bed

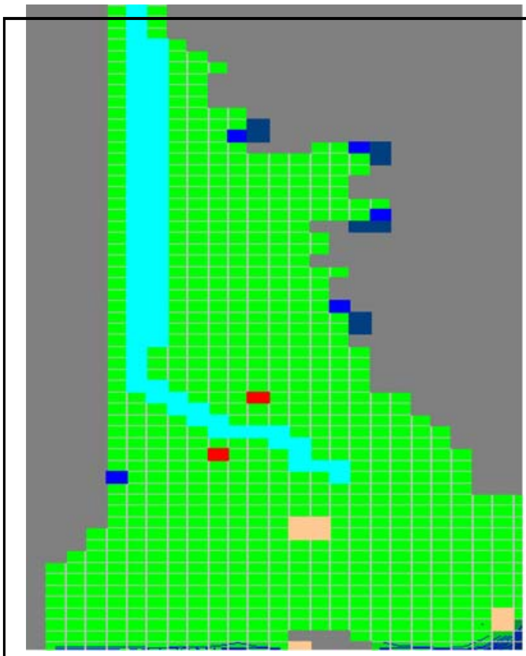


Figure 29. Increasing infiltrations using five basins

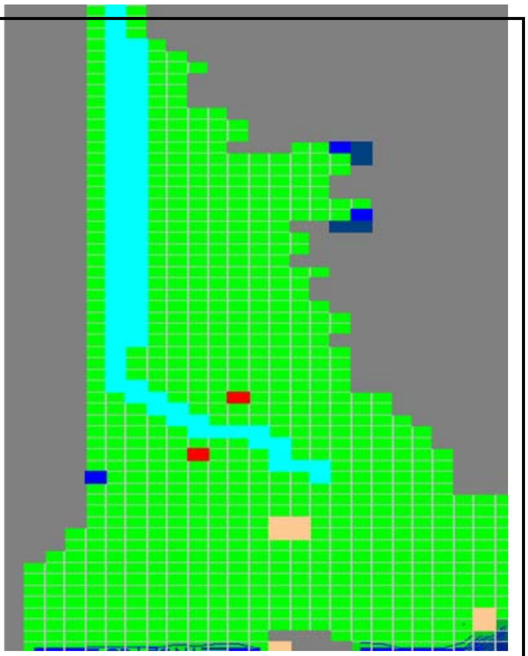


Figure 30. Similar level of aquifer infiltration using only 3 basins. Water from two of the basins is seeping to the river.

7. Conclusion

This paper presents modeling of the Waiwhetu aquifer, and expresses the stresses under which the aquifer is subject to. PMWIN model has been used to simulate the aquifer, and some innovative scenarios have been investigated to identify possible solutions to reduce the risk of seawater intrusion. The result of the simulations shows that the risk of sea water intrusion can not be reduced only by controlling the level of abstraction particularly if demand continues to increase and recharge decrease, but augmentation of recharge is a superior and viable alternative which facilitates abstraction as well. River banks, infiltration basins and injection wells have been simulated and the result show that the using a combination of different techniques abstraction could be maximized. The simulation studies show that abstraction can be double the actual current abstraction with no risk of seawater intrusion. Model Simulations indicate that implementation of aquifer management practices and varying methods to augment the recharge are alternatives that could be considered for the aquifer if it is subject to higher abstraction levels, lower recharge & salinity intrusion.

Acknowledgements

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3.2 Modelling, scenario analysis and engineering solutions

Abstract

The Waiwhetu artesian aquifer is major source of water for the Wellington Region. Here in this study, the aquifer has been simulated in order to identify the responses to various possible scenarios of discharge and recharge. Therefore, few critical future withdrawal and freshwater recharge scenarios have been incorporated as different scenarios for simulating the response of the aquifer. The thrust of the study being approximately quantifying the response of the aquifer over the future decades and determine if the threat if any of saltwater intrusion to the aquifer is significant. The simulations indicate that it is not impossible that in few locations close to the sea front, a situation may develop where the piezometric head may reach mean sea level, possibly resulting in localized sea water intrusion.

1. Introduction

The groundwater flow and possible saltwater transport in the confined multilayered Waiwhetu aquifer aquifer system which is adjacent and below the Wellington Bay is simulated and investigated in this study. Here, the aquifer response to various critical withdrawal and freshwater recharge scenario to examine if significant amount of saltwater intrusion may occur in future, with growth in demands and depletion of fresh water recharge has been investigated.

The fresh water recharge to the aquifer is mainly from the Hutt River around Taita Gorge. The confined system of aquifers is currently maintaining piezometric heads well above the sea level. Therefore springs in the Wellington Harbor around Somes Island (http://www.gw.govt.nz/section667.cfm) are delivering fresh water, and saltwater does not appear to enter the aquifer. Also, the saltwater boundary formed by the Wellington Harbor is not resulting at present, in saltwater intrusion to the aquifer system. Although localized saltwater wedges may develop due to local drop in piezometric heads around pumped wells.

This study is aimed at using a numerical 3-D flow and transport simulation model (FEMWATER embedded in GMS) to test the response of the aquifer to various critical stress scenarios. These simulation results for various hypothetical future withdrawal and recharge scenarios are utilized to predict the possible aquifer state and possibility if any of saltwater intrusion in this aquifer system, which could endanger the fresh water supply from this aquifer may occur.

These simulation results are used to predict the response of the aquifer system to various stress scenarios. A 3-D , transient , density dependent , finite element based flow and transport simulation model is used. When flow and transport processes are transient in nature, the saltwater intrusion process becomes highly non linear and the flow and transport parts become density dependent.

2. Numerical simulation

The phenomenon of saltwater intrusion in a coastal aquifer can be mathematically represented by two partial differential equations namely the flow and the transport equations. Since the density (F) of the liquid depends on hydraulic conductivity (K) and the hydraulic conductivity in turn depends on the concentration , the flow and the transport equations need to be coupled by density (F) and Darcy velocity terms which makes the saltwater intrusion problem highly non - linear . These non linear equations need to be solved simultaneously to solve the saltwater intrusion problem .

FEMWATER , a 3 dimensional finite element based , transient , density driven flow and transport Groundwater model is incorporated to simulate the Coastal aquifer under study mathematically . The FEMWATER numerical model with input and output pre - processors and post processors are utilized in this project. This simulates flow and transport in both the saturated and the unsaturated media .Furthermore , the density dependent problems
such as salinity intrusion can be simulated by the coupled flow and transport motion.

Advantages of FEMWATER is that the model boundaries and stratigraphic units can be modeled precisely as well as anisotropy and heterogeneity of aquifer are easily taken care of in FEMWATER. Disadvantage being 2 FEMWATER simulations cannot preferably be run at a time on a computer, FEMWATER is memory intensive and Solutions are time consuming.

The 3 dimensional flow equation is given by equation 2.1

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla\left[K\left(\nabla h + \frac{\rho}{\rho_0}\nabla z\right)\right] + \frac{\rho^*}{\rho_0} q \qquad \text{(Lin et al.,1997)}$$

Equation 2.1

F = Storage Coefficient
h = Reference hydraulic head
t = Time
K= Hydraulic Conductivity tensor
z = Potential head
q = Volumetric flow rate of Source and / or sink

p_0 = Water density at zero chemical concentration
p = Water density at chemical concentration
p^* = Density of either the injection fluid or the withdrawn water

The Storage coefficient F is defined by equation 2.2

$$F = \alpha' \frac{\theta}{n} + \beta'\theta + n\frac{dS}{dh} \qquad \text{(Lin et al.,1997)}$$

Equation 2.2

Theta = Moisture Content
n = Porosity of the medium
S = Saturation
K‘ = Modified compressibility of the medium
Beta‘ = Modified compressibility of the water
Alpha‘ = Alphap_0g and Beta‘ = Betap_0g
Where,
Alpha = Compressibility of the medium
Beta = Compressibility of the water

The Hydraulic conductivity K is a function of density (p) and viscosity (μ) as shown in Eq. 2.3

$$K = \frac{\rho g}{\mu} k = \frac{\left(\rho / \rho_0 \right)}{\left(\mu / \mu_0 \right)} \frac{\rho_0 G}{\mu_0} k_s k_r = \frac{\left(\rho / \rho_0 \right)}{\left(\mu / \mu_0 \right)} k_{so} k_r$$ (Lin et al.,1997)

Equation 2.3

Where,

μ = Dynamic Viscosity of water at chemical concentration
μ_0 = Dynamic Viscosity of water at zero chemical concentration
k = Permeability tensor
k_s = Saturated Permeability tensor
k_r = Relative permeability or relative hydraulic conductivity
k_{so} = Referenced saturated hydraulic conductivity tensor

The referenced value is usually taken at zero chemical concentration . The density and dynamic viscosity are functions of chemical concentration as shown in Equations 2.4 and 2.5 respectively, hence Hydraulic Conductivity K is a function of chemical concentration.

$$\frac{\rho}{\rho_0} = a_1 + a_2 C + a_3 C^2 + a_4 C^3$$ (Lin et al.,1997)

Equation 2.4

$$\frac{\mu}{\mu_o} = a_5 + a_6 C + a_7 C^2 + a_8 C^3$$ (Lin et al.,1997)

Equation 2.5

Where, a1,are the parameters used to define concentration dependence of water
a2...........a8
Density and viscosity, and C is the chemical concentration .

In case of saltwater intrusion , the relation between fluid density and concentration is as per Equation 2.6 .

$$\frac{\rho}{\rho_o} = \left(1 + \varepsilon c \right)$$ (Lin et al.,1997)

Equation 2.6

Where,

c = Dimensionless chemical concentration (actual divided by the maximum one)
e = Dimensionless density reference ratio defined by Equation 2.7.

$$\varepsilon = \frac{\rho_{\max}}{\rho_o} - 1$$ (Lin et al.,1997)

Equation 2.7

Where P_{max} ---- is the maximum density of the fluid.

The Darcy velocity is calculated by Equation 2.8

$$V = -K \left(\frac{\rho_o}{\rho} \nabla h + \nabla z \right)$$ (Lin et al.,1997)

Equation 2.8

The governing equations for transport describe the material transport through the groundwater systems. These equations are obtained on the basis of law of continuity of mass and flux. The major processes involved in this are advection, dispersion / diffusion, adsorption, decay, biodegradation and injection / withdrawal.
The Transport equation is

$$\theta \frac{\partial C}{\partial t} + \rho_b \frac{\partial C}{\partial t} + V.\nabla C - \nabla.(\theta D.\nabla C) =$$

$$-\left(\alpha' \frac{\partial h}{\partial t} + \lambda \right)(\theta C + \rho_b S) - (\theta K_W C + \rho_b K_S S) + m - \frac{\rho^*}{\rho} qC + \left(F \frac{\partial h}{\partial t} + \frac{\rho_o}{\rho} V.\nabla \frac{\rho}{\rho_o} - \frac{\partial \theta}{\partial t} \right) C$$

(Lin et al.,1997) Equation 2.9

Where,
Theta = Moisture content Pb = Bulk density of the medium
C = Material Concentration in aqueous phase S = Material Concentration in adsorbed phase
t = time ∞ = Del operator
D = Dispersion tensor Alpha �similar = Compessibility of the medium
h = Pressure head Lambda = Decay constant
K_w = First order biodegradation rate constant through dissolved phase
K_s = First order biodegradation rate through adsoebed phase F = Storage coefficient

The flow and the transport equations are coupled by the density coupling coefficient and by the Darcy velocity terms which renders the saltwater intrusion non linear.

3. Study area

Petone and Lower Hutt consists of many residential areas and at these places, together the groundwater withdrawal has increased from 40ML/day (million liters/day) prior to 1999 to about 70 to 90 ML/day over one year period in 1999 (Phreatos limited, 2001 and http://www.gw.govt.nz). The current rate is estimated at a total about 110 ML/day for the entire well field in this area.

3.1 Data Collection

The major data required for the simulation of the saltwater intrusion is sought from the report of the Waiwhetu Artesian Aquifer Saltwater Intrusion Risk Management Review ‟ prepared by Phreatos Limited, April 2001; Publication No.RINV - T - 01 / 26. The maps and some the recent updates are obtained from various departments of the web address of the Ground Water Dept. of the government of New Zealand, http://www,gw.govt.nz .

3.2 Head

Head distribution of the whole Aquifer area of the Upper Waiwhetu Aquifer as of 2001 is given in the review in the form of contours and are shown in Fig. 1 (as modeled heads) and as in different sections of the report . All these values are gathered, the effect of the present pumping and recharge into the Aquifer being assessed and the average is taken as initial head for 2007 at various locations of the study area. The contours shown in Figure 1 depicts the modeled heads of Upper Waiwhetu Aquifer as of April 2001.

As such, the total head distribution of the Lower Waiwhetu Aquifer region is not provided by the report but it is stated that there exists a 0.4 to 0.5 meter head difference between the Upper and the Lower Aquifers and hence using the head values of the Upper Waiwhetu Aquifer, the total head values of the Lower Waiwhetu Aquifer are accounted for.

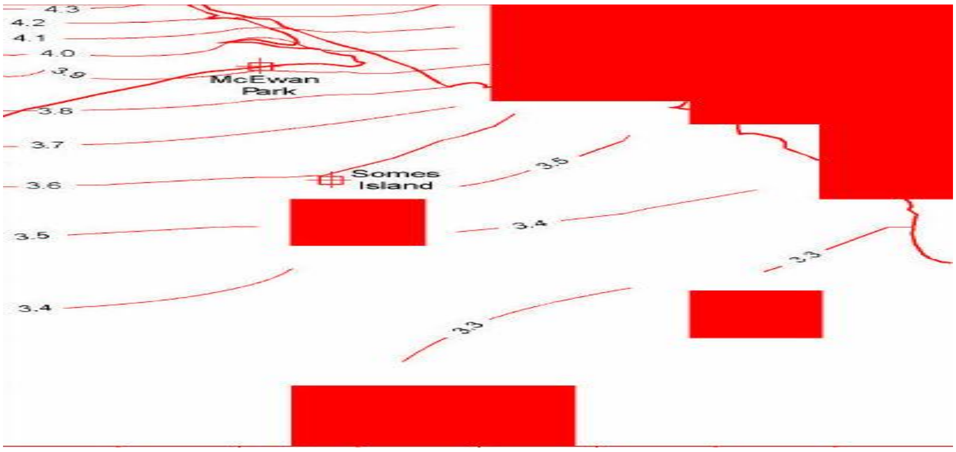


Fig 1 : Piezometric Head Contours of 2001 (Source Phreatos Limited, 2001) In meters above mean sea level

3.3 Wells and Pumping Rates

Discharge from the Gear Island wells is about 25 Million Litres per day and from that of the Waterloo is 85 Million Litres per day (total of 110 ML/day) (Phreatos Limited, 2001). The depth of these wells varies from 20 meters to 40 meters.

3.4 Stratigraphical Data

Lower Hutt Groundwater Zone is a multi layered Aquifer system .The study area generally consists of sand, gravel, silt and clay. The stratigraphical data of the Upper Confined Aquifer is well shown in Fig.2, in the form of contours. The depth of the Upper Waiwhetu Aquifer varies between 20 metres (at the Eastern edge) and 70 metres (at the Western edge) . The Lower Waiwhetu Aquifer dimensions are almost parallel to that of the Upper Waiwhetu Aquifer with an average thickness of 20 meters . The upper Aquitard sequence is on an average 10 meters thick and the bottom Aquitard is too thin relative to the dimensions of the Aquifer and is approximately

1 meter to 2 meters thick. The values shown in Fig 2 are the elevations in meters below mean sea level of the bottom of the upper confined Waiwhetu Aquifer (Phreatos Limited, 2001). The Area under consideration is around 70 KM^2.

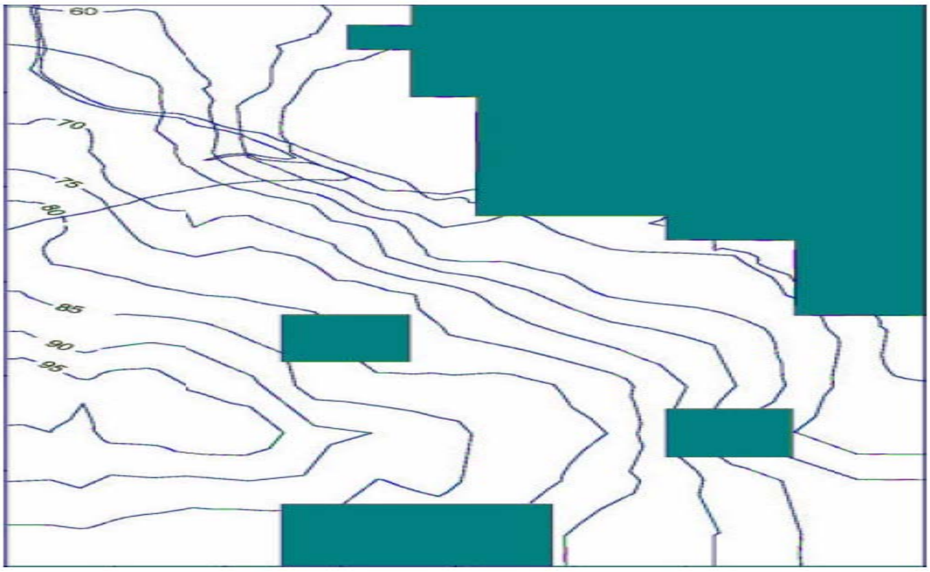


Fig 2. Depths of the bottom of Upper Waiwhetu Aquifer

The Aquifer, as of 2001, has not witnessed any salt water intrusion. But for modeling the transport model, as a future precaution, the salt concentration at the boundary is assumed to be 2400 mg / litre .

Using these data a three dimensional finite element model (FEMWATER) is implemented to simulate the flow or the flow and transport processes in the Aquifer study area. As all data necessary for accurate simulation of the aquifer responses are not available, some assumptions are made to predict future scenarios of the aquifer responses which are acceptable, although uncertain to some extent. These assumptions are described in the following chapter.

4. Scenario evaluation using numerical simulation model

The collected data from the Phreatos Report and other sources including internet sources are utilized for developing and implementing the 3 D Finite element simulation model (FEMWATER). The input output processing module of the Groundwater Modelling System, GMS was utilized to prepare the input data for FEMWATER , also for finite element mesh generation and spatial interpolation of aquifer data. Initially only the flow process was modeled, as there is no existing evidence of saltwater intrusion in the study are. However , to predict the response of the aquifer system to plausible future withdrawal and recharge scenarios, subsequently both the flow and transport processes were modeled using FEMWATER.

FEMWATER models the density dependent coupled flow and transport processes in the aquifer. Calibration of the simulation model was not performed as the data available was not sufficient for satisfactory calibration and validation of the model. The given parameter values, boundary conditions etc. were utilized as representative information for the study area. Also, the basic aim was to test the sensitivity of the aquifer responses to different scenarios of future stresses available does not suffice the requirement.

The simulation model is used to simulate aquifer conditions for the present discharge and recharge scenarios, and also for plausible scenarios of increasing discharge through new assumed wells at Petone and Lower Hutt in the coming years as the industrialization of Petone and Lower Hutt gains pace. These plausible future scenarios were also studied for assumed future decrease in recharge to the aquifer system. These simulations / predictions are also aimed at predicting possible critical situations if at all, such as near zero piezometric head at the locations in the vicinity of the shore. It was aimed at investigating the response to possible critical scenario and to help prevent the situation which endangers the freshwater Aquifer.

4.1 Assumptions

Some of the necessary data are available in the Phreatos Limited, 2001. Some data were obtained from internet and other sources. In addition, best judgment was used to assume some necessary data while implementing the 3 Dimensional Finite element based simulation model. Some of these assumed data are :

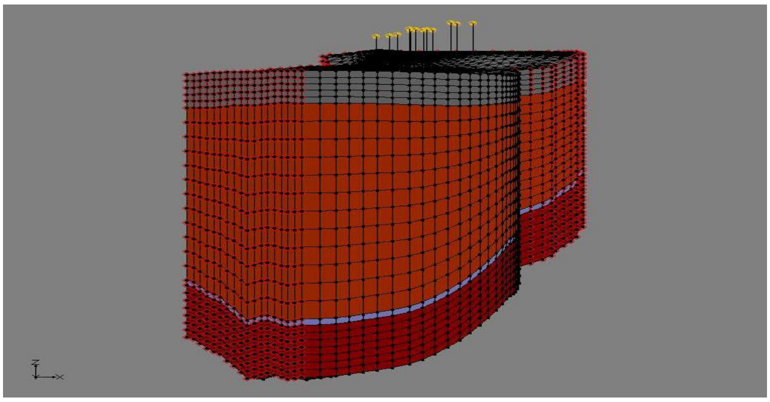
The area bounded by the Eastern direction is assumed to be a no œ flow boundary. In the case of additional wells assumed for some future scenarios, discharge at these additional wells at Petone and at Lower Hutt are assumed to be same as that for the Gear Island and that of Waterloo as follows.

Discharge from Petone (additional wells) = Discharge from Gear Island = 25 ML/day
Discharge from Lower Hutt (additional wells) = Discharge from Waterloo = 85 ML/day

Seasonal fluctuations as well as Tidal effects are not considered.

4.2 Implementation of the Flow Simulation model

Fig 3. The 3-D view of the study area of the aquifer system as generated by GMS



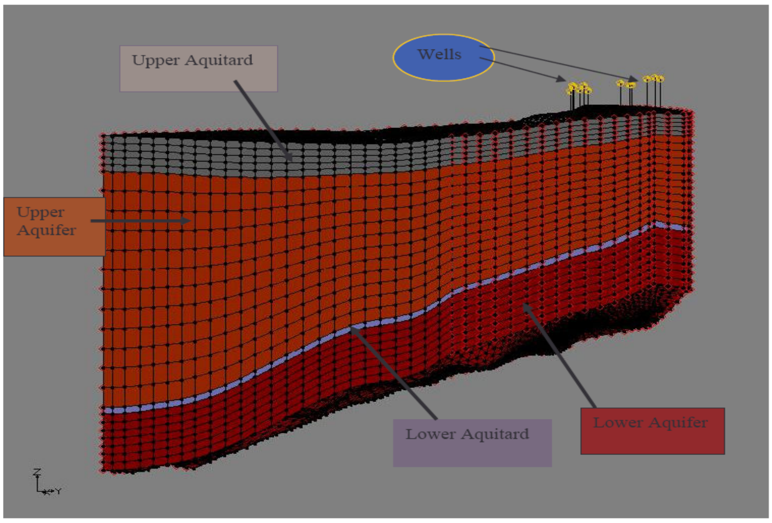


Fig 4 Front view of the study area

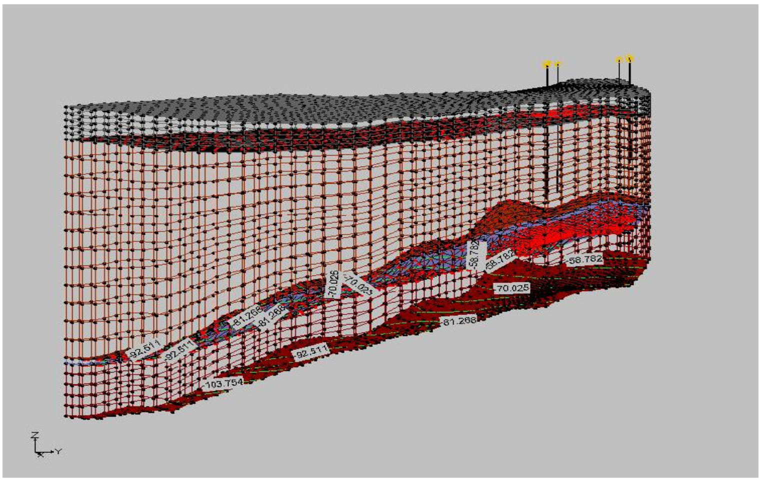


Fig 5. Three dimensional view showing wells

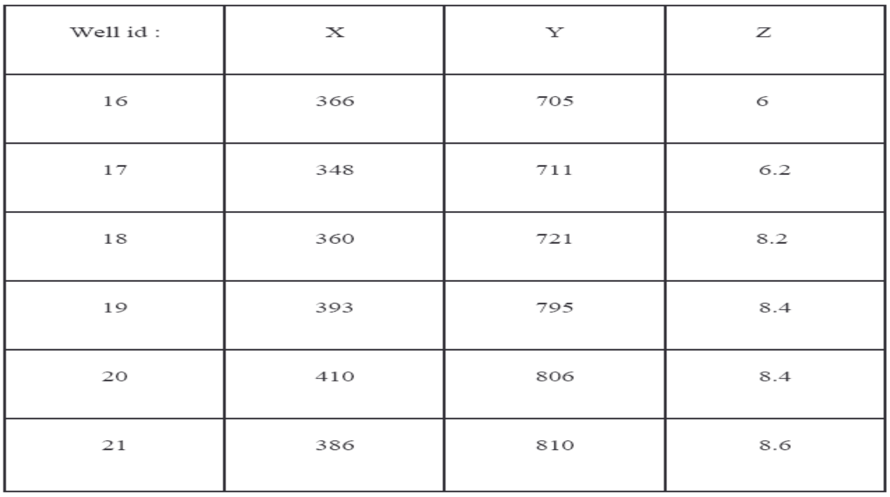
Figure 5 shows the 3 dimensional view which is very much same as the view of Figure 3, except that the Figure 8 shows the depth of the wells up to the bottom of the wells in the Upper Aquifer. The square blocks between the various layers of the study area (Figure 5) represent the 3 dimensional mesh data generated using the GMS(Groundwater Modeling System).

4.2.1 Scenario – 1

With original recharge and discharge, without any new wells.
Simulation of the flow model with initial recharge and discharge for the whole duration of 10 years, i.e, simulation the flow in the Aquifer with the assumption that there is no future increase / decrease in recharge / discharge .
In this Flow Simulation , no additional wells (due to industrialization of Petone and Lower Hutt) is considered.

Flow simulation results for the aquifer are obtained at various location namely Petone , Lower Hutt, Gear Island, Waterloo and the Bay area at the South . The initial piezometric head values at each of these locations are specified and simulation results corresponding to various points of time at these locations are gathered , to help predict if the critical situations may develop which can endanger the aquifer due to saltwater intrusion into the Aquifer.

The total / Piezometric heads shown in Tables 1 to 24 are the average of the piezometric heads for a number (4 to 5) of wells in the vicinity of the mentioned location. Hence it does not correspond to the head at a single point only or to a single depth.

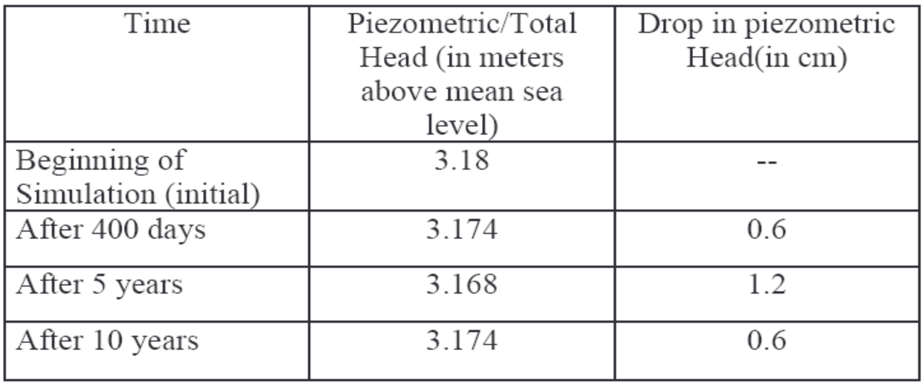


Well id :	X	Y	Z
16	366	705	6
17	348	711	6.2
18	360	721	8.2
19	393	795	8.4
20	410	806	8.4
21	386	810	8.6

Table 1. Coordinates of well locations

The Well id's 16, 17, 18 correspond to the Gear Island region and the Well id's 19, 20 , 21 correspond to the Waterloo region. Table 2 to 12 describe the simulation results in detail.

Lower Hutt

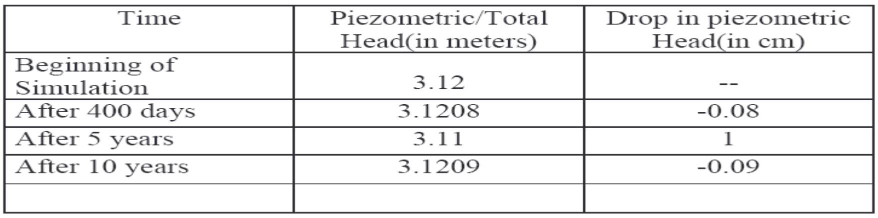


Time	Piezometric/Total Head (in meters above mean sea level)	Drop in piezometric Head(in cm)
Beginning of Simulation (initial)	3.18	--
After 400 days	3.174	0.6
After 5 years	3.168	1.2
After 10 years	3.174	0.6

Table - 2 Piezometric head with time for scenario 1

As seen, the drop or the rise in head over a 10 year period is too low compared to the the initial piezmotric head at various points and at various depths of the Lower Hutt region.

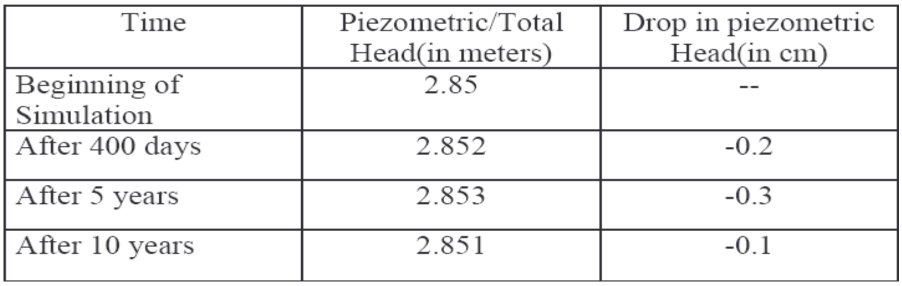
Petone



Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	3.12	--
After 400 days	3.1208	-0.08
After 5 years	3.11	1
After 10 years	3.1209	-0.09

Table - 3 Petone does not experience much change. Piezometric head with time for scenario 1

Gear Island

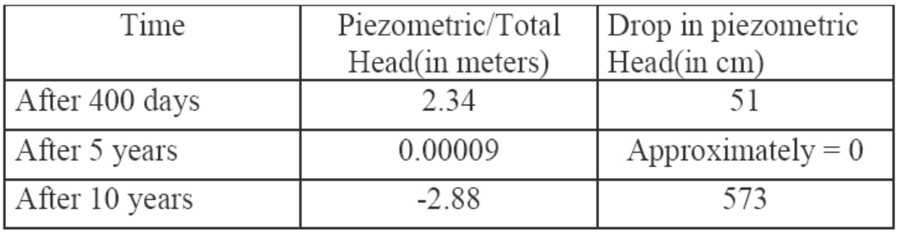


Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	2.85	--
After 400 days	2.852	-0.2
After 5 years	2.853	-0.3
After 10 years	2.851	-0.1

Table 4. Piezometric head with time for scenario 1

Gear Island, one of the locations, may not experience much change as well in head in the forthcoming decade. Though, if instead of local averaging, the head at the exact discharge well location is considered, considerable change in the piezometric head may be possible, probably due to local drawdown at the pumping location. These changes are shown in Tables 4. 5 and 6. The pizometric heads at exact well locations shown by well ids are given in Tables 4,5 and 6.

Table - 5. Well Id 16 Piezometric head with time for scenario 1

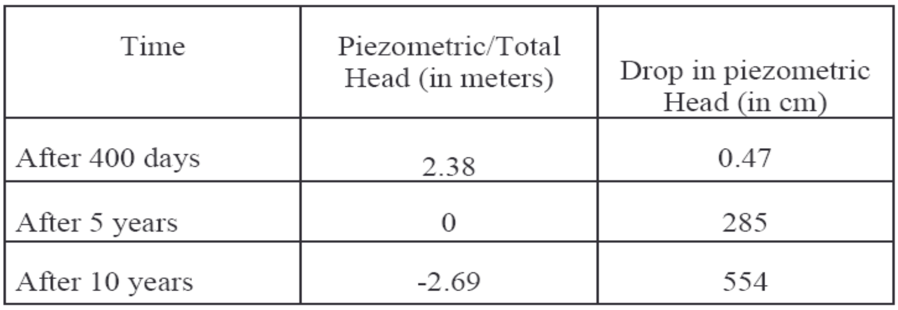


Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
After 400 days	2.34	51
After 5 years	0.00009	Approximately = 0
After 10 years	-2.88	573

Table - 6 Well id 17 Piezometric head with time for scenario 1

Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
After 400 days	2.41	2.44
After 5 years	0	285
After 10 years	-2.66	551

Table – 7 Well id 18 Piezometric head with time for scenario 1



Time	Piezometric/Total Head (in meters)	Drop in piezometric Head (in cm)
After 400 days	2.38	0.47
After 5 years	0	285
After 10 years	-2.69	554

Table - 8 Waterloo Piezometric head with time for scenario 1

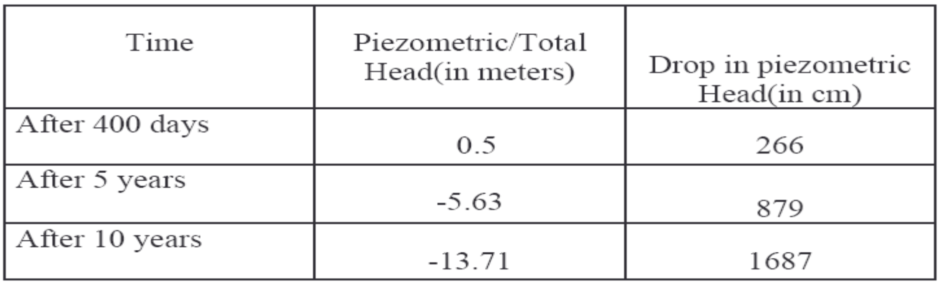
Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	3.16	--
After 400 days	3.156	0.4
After 5 years	3.168	-0.8
After 10 years	3.1612	-0.12

Waterloo, the other Wellfield , has a similar situation as that of Gear Island. However, the at the exact well locations considerable change in the piezometric head is possible over the years. The changes are shown in Tables 9, 10, 11.

Table 9. Well id 19 Piezometric head with time for scenario 1

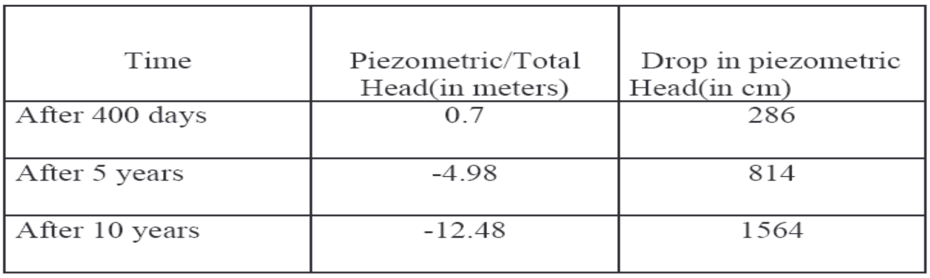
Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
After 400 days	0.67	249
After 5 years	-5.14	830
After 10 years	-12.81	1597

Table 10. Well id 20 Piezometric head with time for scenario 1



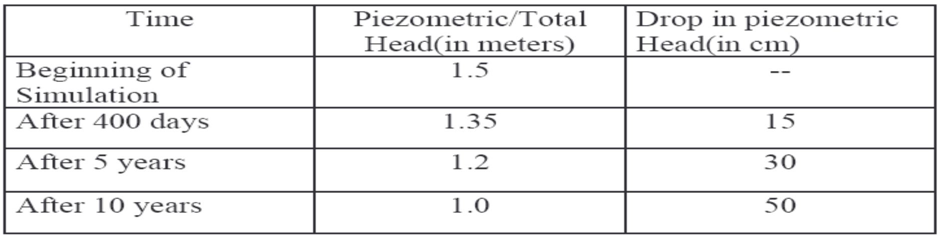
Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
After 400 days	0.5	266
After 5 years	-5.63	879
After 10 years	-13.71	1687

Table 11. Well id 21 Piezometric head with time for scenario 1



Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
After 400 days	0.7	286
After 5 years	-4.98	814
After 10 years	-12.48	1564

Table 12. Bay area Piezometric head with time for scenario 1



Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	1.5	--
After 400 days	1.35	15
After 5 years	1.2	30
After 10 years	1.0	50

This area has shown some decrease in the total head values over the years, but the critical situation (piezometric head nearly 0.0) at which the piezometric head , at Gear Island located adjacent to the sea, may occur after 2 decades or so.

Important Note :
At Somes Island, the location of active Spring discharges, has quite surprisingly, not responded much in terms of change in potentiometric head over time. The expected changes were very small and of the order of .0001 m. The simulation results are displayed in the form of head contours at 400 days, 5 years and 10 years. These contours are shown in Figures 7, 8 , and 9.

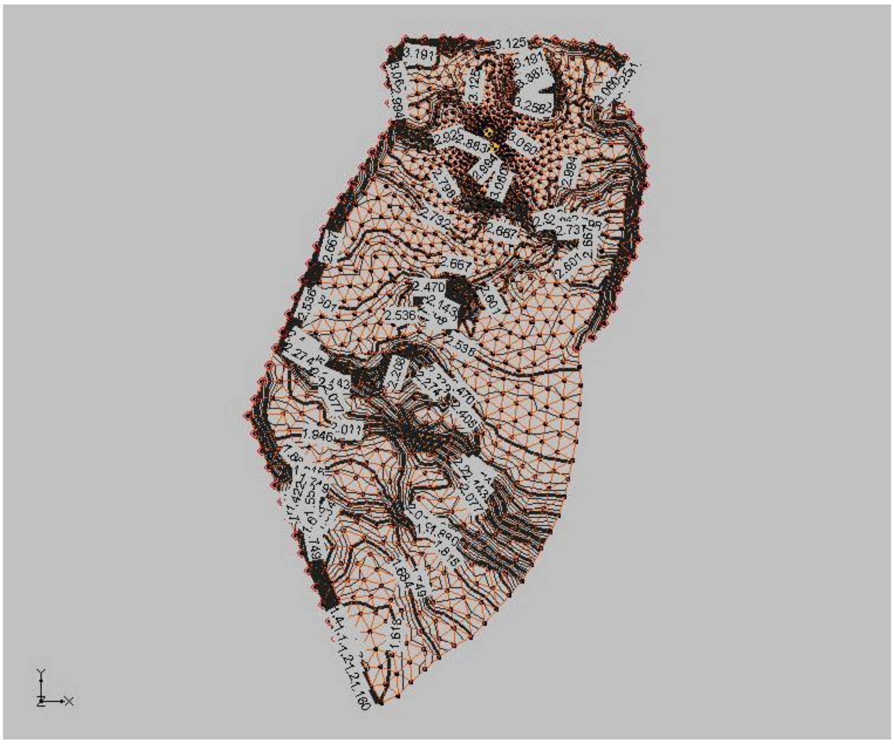


Fig 6. Piezometric Head after 400 days

Fig 6 shows the piezometric head contours over the whole study area after 400 days from the beginning of the simulation for scenario 1.

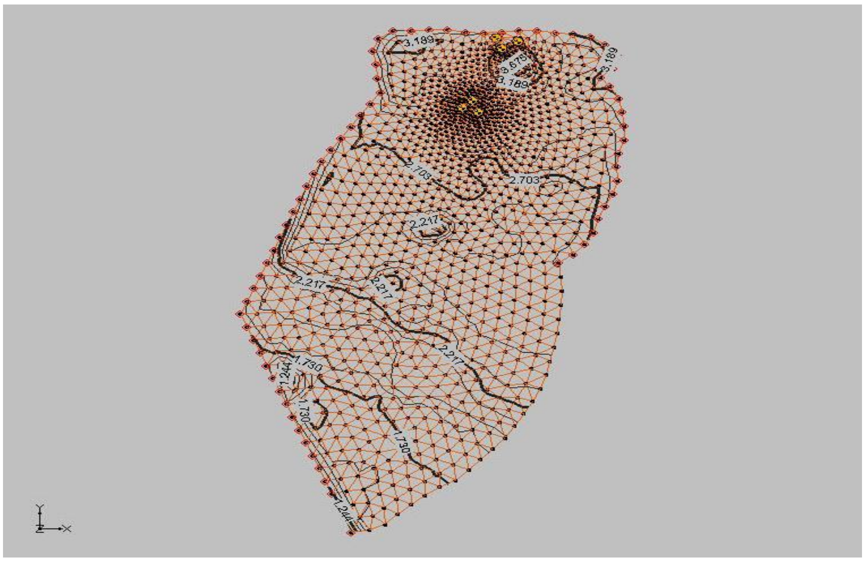


Fig 7. Head contours after 5 years - Scenario 1

Fig 7 shows how the Piezometric heads change in course of time after 5 years from the beginning of the simulation.

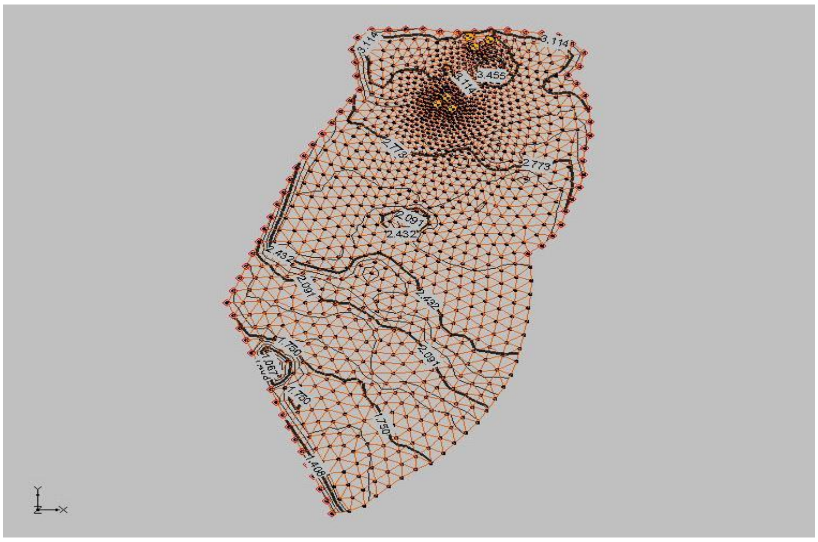


Figure 8. Head contours after 10 years

Figure 8 shows how the head at the bay south of the study area, under the harbour has changed considerably.

4.2.2 Scenario 2

In this scenario, the following assumptions were made: from the two locations Gear Island and Waterloo,

Recharge = (Current, 2001 estimated total Recharge) / 10
Discharge= 10 x (Current, 2001 estimated total Discharge)

With extra wells at Petone , Waterloo:

The additional discharge from the additional wells of Petone is chosen same as that of the new specified Gear Island discharge (250 ML/day) and the discharge from the additional wells of Lower Hutt is chosen same as that for Waterloo (850 ML/day).
Additional Discharge from Petone = 250 ML / day (Assumption)
Additional Discharge from Water Loo = 850 ML / day (Assumption)

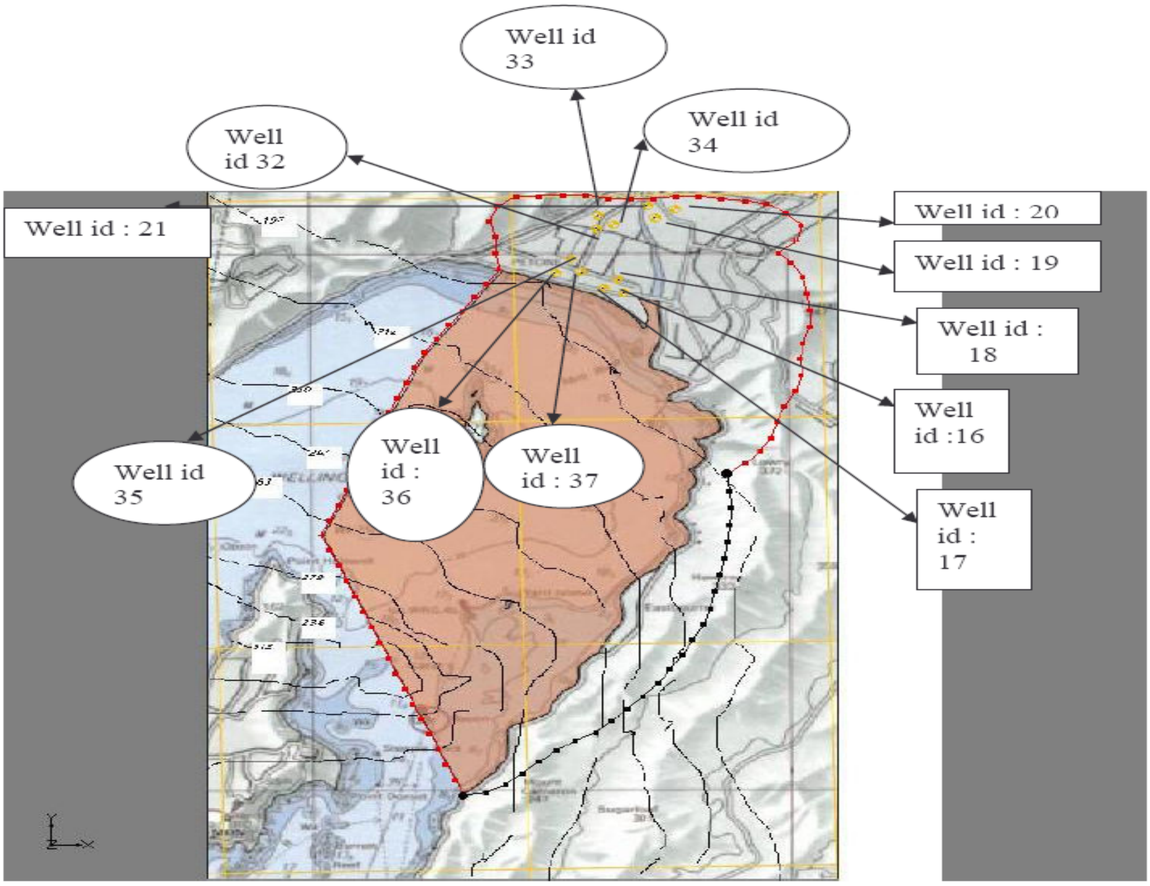
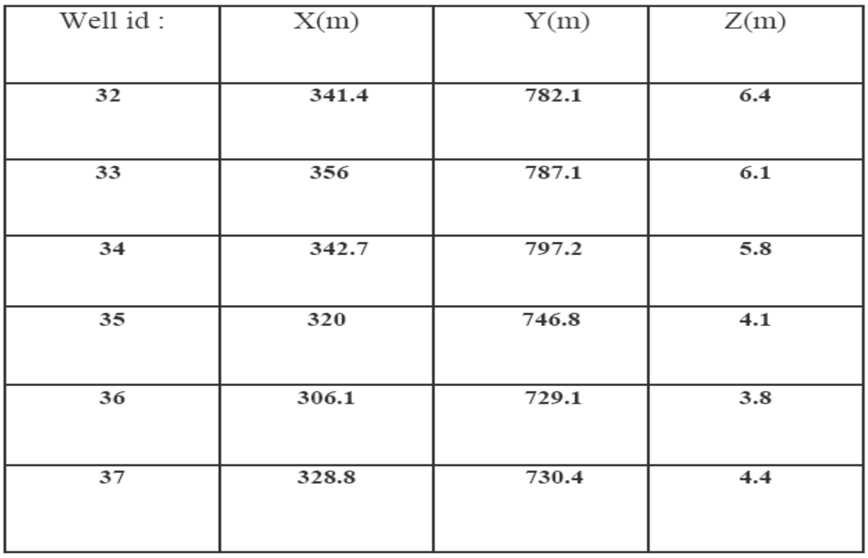


Fig 9 Well locations for scenario 2

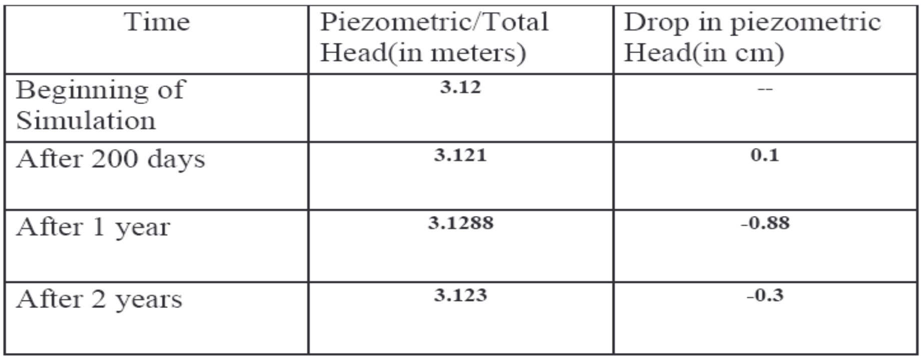
With the above mentioned assumptions, the simulation model was run for predicting heads after 200 days, 1 year and 2 years and the results obtained at various regions are shown in Tables 14 to 18.

Table 13. Coordinates of additional wells for Scenario 2



Well id :	X(m)	Y(m)	Z(m)
32	341.4	782.1	6.4
33	356	787.1	6.1
34	342.7	797.2	5.8
35	320	746.8	4.1
36	306.1	729.1	3.8
37	328.8	730.4	4.4

Table 14. Lower Hutt Piezometric head with time for scenario 2



Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	3.12	--
After 200 days	3.121	0.1
After 1 year	3.1288	-0.88
After 2 years	3.123	-0.3

Table 15. Petone Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	3.12	--
After 200 days	3.1107	-0.93
After 1 year	3.119	0.1
After 2 years	3.117	0.3

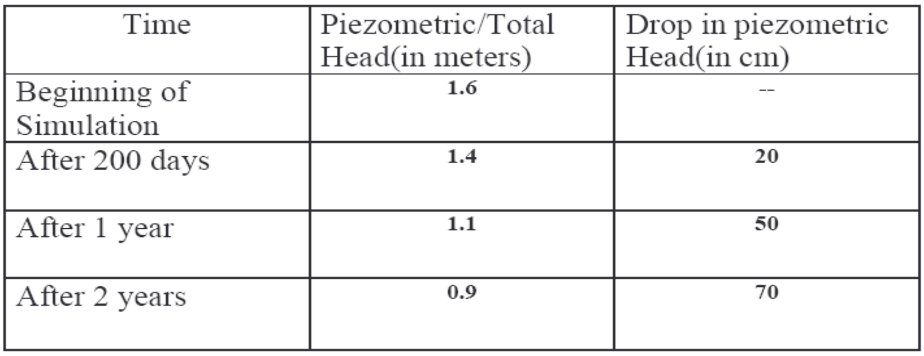
Table 16. Waterloo Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	3.18	--
After 200 days	3.199	-1.9
After 1 year	3.187	0.7
After 2 years	3.182	-0.2

Table 17. Gear Island Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	2.85	--
After 200 days	2.854	-0.4
After 1 year	2.853	-0.3
After 2 years	2.851	-0.1

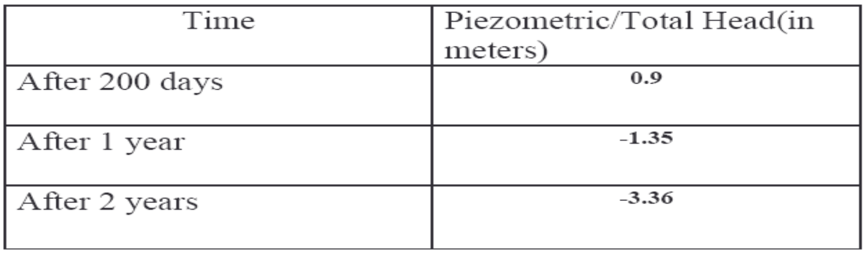
Table 18. Bay area Piezometric head with time for scenario 2



Time	Piezometric/Total Head(in meters)	Drop in piezometric Head(in cm)
Beginning of Simulation	1.6	--
After 200 days	1.4	20
After 1 year	1.1	50
After 2 years	0.9	70

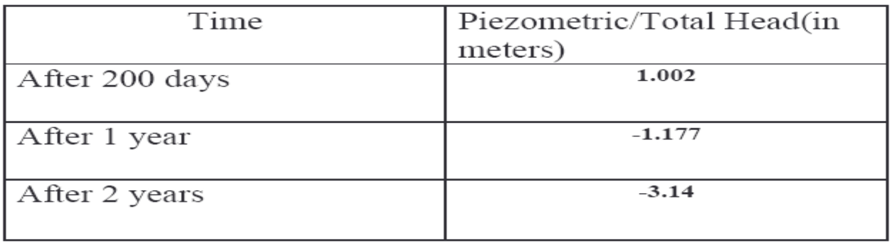
Critical Situations :
Some Critical situations have been observed from simulation results at the exact well locations, as in Scenario 1.

Table 19. Well id 16 Gear Island Piezometric head with time for scenario 2



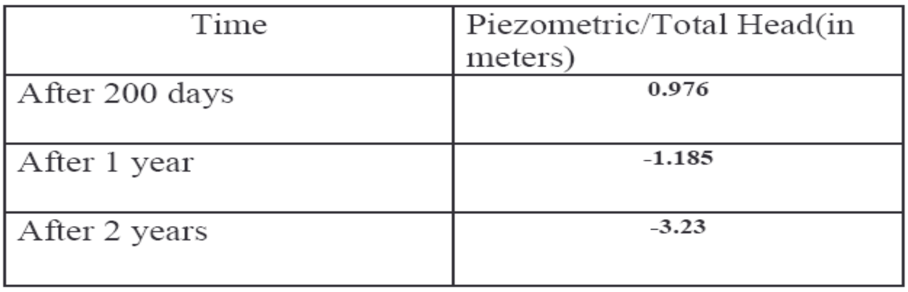
Time	Piezometric/Total Head(in meters)
After 200 days	0.9
After 1 year	-1.35
After 2 years	-3.36

Table 20. Well id 17 Gear Island Piezometric head with time for scenario 2



Time	Piezometric/Total Head(in meters)
After 200 days	1.002
After 1 year	-1.177
After 2 years	-3.14

Table 21. Well id 18 Gear Island Piezometric head with time for scenario 2



Time	Piezometric/Total Head(in meters)
After 200 days	0.976
After 1 year	-1.185
After 2 years	-3.23

Table 22. Well id 19 Waterloo Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)
After 200 days	-1.32
After 1 year	-10.39
After 2 years	-12.2

Table 23. Well id 20 Waterloo Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)
After 200 days	-1.6
After 1 year	-12.32
After 2 years	-13.47

Table 24. Well id 21 Waterloo Piezometric head with time for scenario 2

Time	Piezometric/Total Head(in meters)
After 200 days	-1.245
After 1 year	-9.98
After 2 years	-11.24

It has been observed that at some well locations at Petone, head may drop 0 meters after 500 days. Some locations at Lower Hutt have also shown a zero head value at a time of 150 days. The contour map fro this scenario after time interval of 200 days, 1 year, 2 year are shown in Fig 10 to 12.

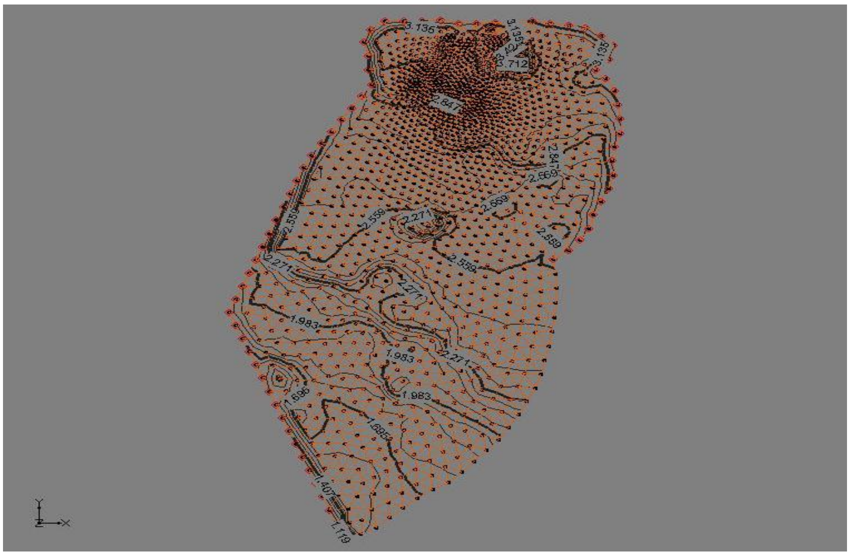


Fig. 10 Piezometric Head contours after 200 days – Scenario 2

It could be seen that the head‘s drop after 200 days. In particular, at the south of the bay heads drop considerably.

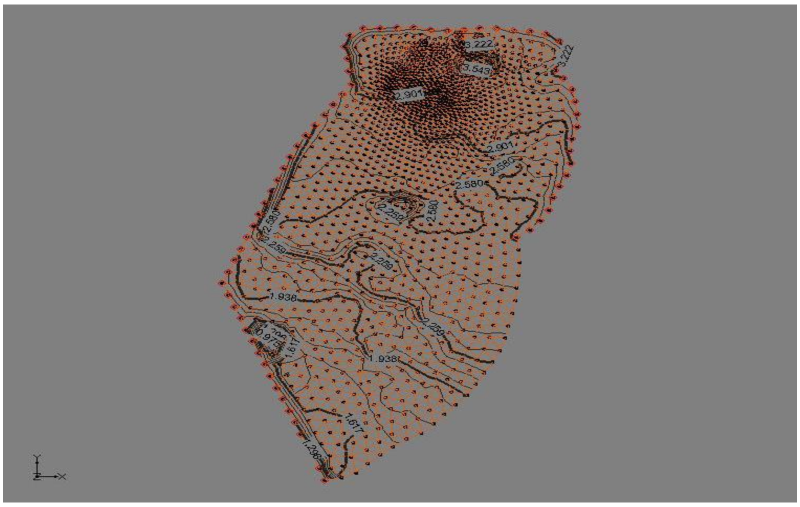


Fig.. 11   Piezometric Head contours after 1 year – Scenario 2

Fig. 11 shows how the heads drop after 1 year . Although the period between 200 days and 1 year has not shown much change at other places, at the bay the head drops by almost 20 cm after 200 days.

Fig 12 shows the piezometric head variation after 2 years over the study area for scenario 2

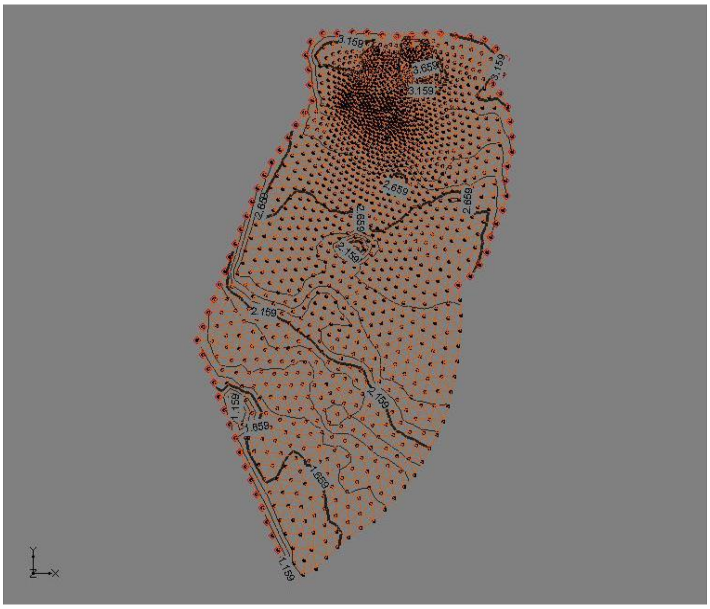


Fig 12 Piezometric head variation after 2 years – scenario 2

4.2.3 Scenario 3

Varying discharge, recharge for head after 600 days, and without any additional wells.

In this case the situation when the time is fixed is analyzed, then the only parameter which changes is Discharge and Recharge. Various recharge / Discharge ratios have been incorporated to predict critical situation if any.

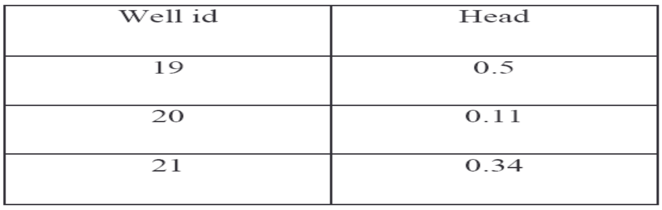
When, Recharge = (Initial Recharge) / 5
Discharge= 5 x (Initial Discharge)

Table 25. Piezometric head with time for scenario 3

Well id	Head
19	0.3
20	-0.84
21	-0.53

When, Recharge = (Initial Recharge) / 4
Discharge= 4 * (Initial Discharge)

Table 26. Piezometric head with time for scenario 3



Well id	Head
19	0.5
20	0.11
21	0.34

Tables 25 and 26 show that critical head conditions may develop even after nearly 2 years (600 days) time at well locations at Waterloo, if the discharge increases by 4 to 5 times at well located in Waterloo only.

4.3 Simulation of Transport Model

Existing data and preliminary simulation results show that immediate possibility of salt water intrusion in the confined aquifers are not appreciable. However, as a note of caution, it can be mentioned that very localized salt water intrusion in the form of localized wedges may be possible, especially in the vicinity of discharging wells close to the sea front. With drastically the dropping heads at Gear Island and at the South of the Bay, there may be a chance of localized saltwater intrusion in near future. To assess this risk, a saltwater concentration of 2400 mg / liter is assumed at the sea front boundary. Also, with this boundary condition, and defined initial conditions and parameter valus, the coupled flow and transport models of FEMWATER were run for this study area. The parameter values used in the transport model are given below.

Bulk Density = 1025 kg /m^3
Tortuosity = 1
Longitudinal Dispersivity = 5
Lateral Dispersivity = 0.5
Molecular Diffusion Coefficient = 0.66
Effective porosity ratio = 0.3

The simulation results using both the density dependent saltwater flow and transport model the simulated head distributions almost matched those obtained using the flow model only. No salt water intrusion was simulated even for the critical scenarios. Therefore the conclusions remain same, as stated earlier for the simulation results for different scenarios, using the flow model. However, again, the possibility of localized wedge shaped saltwater intrusion cannot be totally ruled out for plausible future scenarios of highly stressed aquifer conditions.

5. Analysis

The Simulation Model is used to evaluate the effectiveness of few pumping and withdrawal scenarios on the Saltwater intrusion process in the study area. As explained earlier, some extra wells are specified for the purpose of testing the response of the Aquifer System.

Scenario 1

With the Current years (assumed to be 2001) discharge and Recharge and without any consideration of extra wells.

The wells of Gear island (id : 16 , 17 , 18) are prone to zero piezometric head. The following graphs show these results. It is clear from Figure 10, that the head at well id 16 may fall to 0 after 5 years, resulting in some localized seawater intrusion at least. However, the accuracy of the simulation results, very close to discharging wells would remain an issue, which should be also considered.

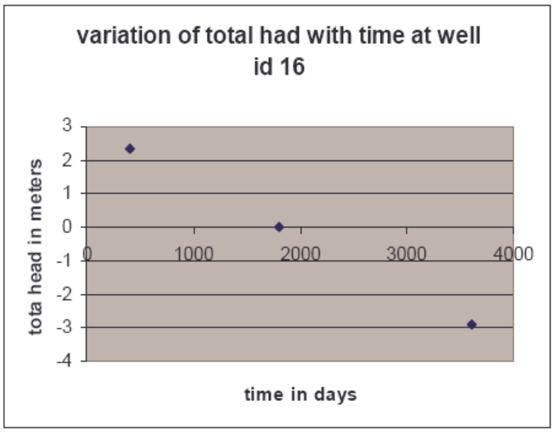


Fig 13 Head variation at well with time for Scenario 1

As Figure 11 shows, head at well id 17 drops to 0 after about 1750 days with the current (2001) discharge and recharge rates.

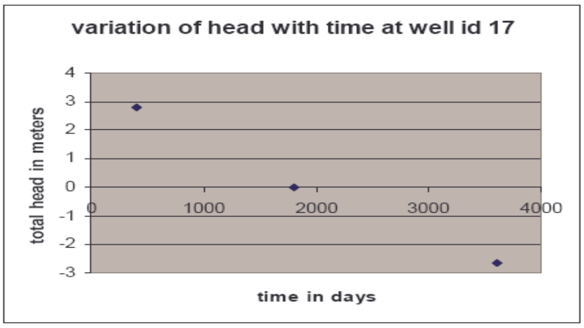


Fig 14. Head variation at well with time – scenario 1

Very similarly head at well id 18 drops to zero as well after 5 years with the current discharge and recharge rates as shown in Figure 12

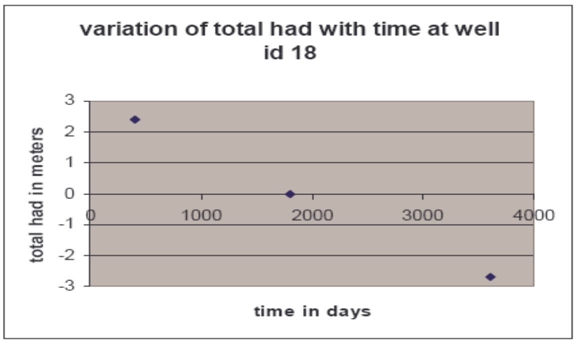


Fig 15. Head variation at well with time – Scenario 1

But in case of wells at Waterloo (well id's : 19 , 20 , 21), the situation is different At these wells, heads drop to zero quite early in time. i.e much earlier than 5 years. Figures 13, 14 and 15 show the variations in head with time.

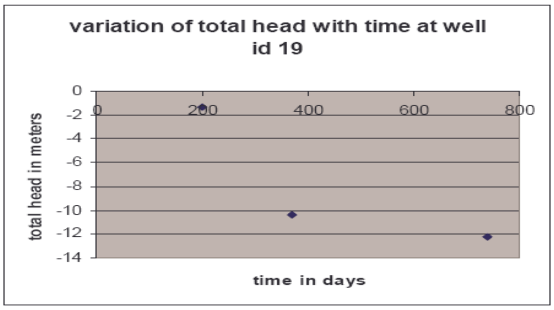


Fig 16. Head variation at well with time – Scenario 1

As seen in Figure 13, head at well id : 19 drops to 0 after about 180 days with the current Discharge and Recharge.

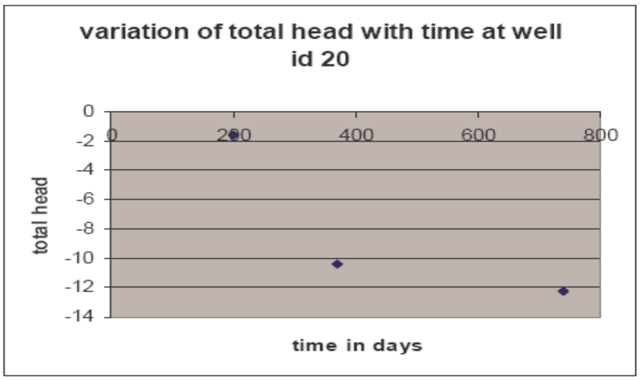


Fig 17. Head variation at well with time – Scenario 1

As Figure 14 shows, head at well id : 20 drops to zero after about 165 days with the current Discharge and Recharge rates

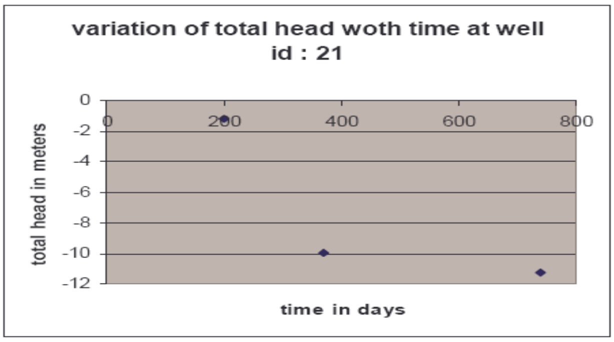


Fig 18. Head variation at well with time

Figure 15 shows that head at well id: 21 drops to zero after about 190 days with the current Discharge and Recharge rates.

These limited and to some extent approximate simulations do show that it is not impossible that in few locations close to the sea front, a situation may develop where the piezometric head may come close to the mean sea level, resulting possibly to localized sea water intrusion. The results reported here are based on very limited information and the associated uncertainties cannot be discounted. No definite conclusions are possible based on this study. However, the simulation results shows that very critical and drastic increase in withdrawal from this aquifer along with drastic reduction in recharges entering the aquifer may prove to be critical at some stage in the future. If the current trend in withdrawal and fresh water recharges continue, possibility of appreciable sea water intrusion in the aquifer do not appear strong. Care must be taken to endure also, that the potentiometric heads at the springs e.g., at Somes Island should remain much above the mean sea level. Otherwise the sea water can directly enter the underlying confined aquifers. really critical.

These limited simulation results may lead to the conclusion that the situation may become critical for the Gear Island wells as they are close to the sea coast and hence there is some risk of seawater intrusion into the land through these wells if the head drops close to the mean sea level, even locally, close to the discharging wells. It is possible that if and if at all, sea water intrudes into the Gear Island , there is a possibility that the salt water may wedge into Waterloo wells as and ultimately the Lower Hutt areas . Precautionary Measures like planned control of rate of yearly rise in discharge, controlling the usage of water from Water Loo and Gear Island wells andsteps to ensure recharge to the aquifer, on a long term basis are worthwhile to consider.

Scenario 2

In this case, the Aquifer response with increase in discharge is studied and it is attempted to propose an optimum Discharge / Recharge proportion.

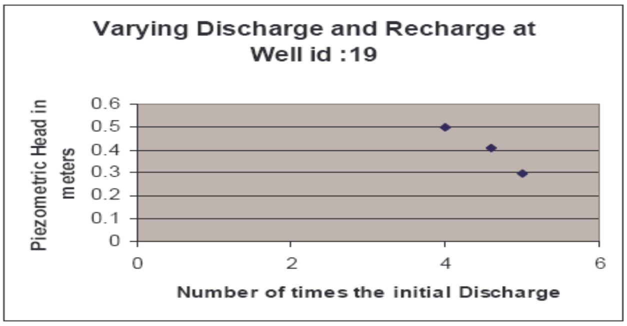


Fig 19. Head variation at well with time – Scenario 2

As Figure. 19 shows , at a discharge = 5.4 * (initial discharge) and recharge = (initial recharge) / 5.4 , the piezometric head drops to zero at well id : 19 .

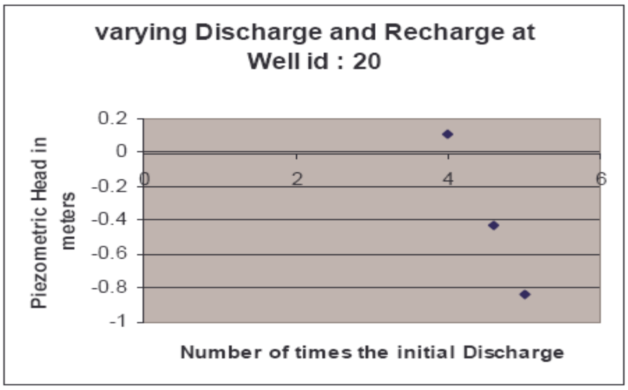


Fig 20. Head variation at well with time – Scenario 2

Figure 20 shows that well id 20 drops to zero at about
Discharge = 4.1 * (initial discharge) &
Recharge = (initial recharge) / 4.1

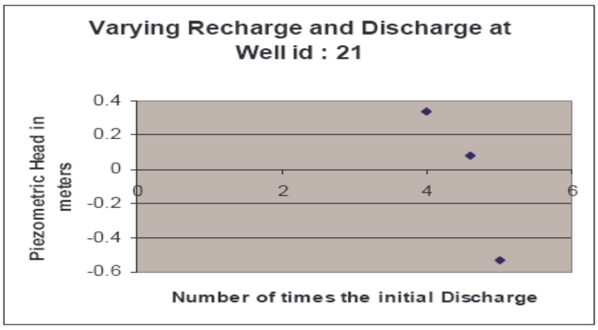


Fig 21. Head variation at well with time - scenario 2

Figure 21 shows how well ID : 21 drops to zero at about
Discharge = 4.7 * (initial discharge) &
Recharge = (initial recharge) / 4.7

So , the conclusion is that,

On an average discharge = 4.73 * (initial discharge) & recharge = (initial recharge) / 4.73

As shown, the heads at the Water Loo Wells may drop to Zero . Since the rate of discharge is increasing at a rate of 40 ML / day (Phreatos Limited, 2001), it wouldn't take a long time for the Discharge to reach 4.7 times the initial one . As calculated ,it will take about 7 years for the Discharge (/ Recharge) to multiply (/ divide) by 4.7 . So the concerns are not immediate in nature.

6. Conclusions

These simulations show that it is not impossible that in few locations close to the sea front, a situation may develop where the piezometric head may come close to the mean sea level, possibly resulting in localized sea water intrusion into the two layer confined aquifer system. The results reported here are based on limited information and the associated uncertainties cannot be discounted. The obtained simulation results also show that very critical and drastic increase in withdrawal from this aquifer along with drastic reduction in recharges entering the aquifer may prove to be critical at some stage in the future. If the current trend in withdrawal and fresh water recharges continues, possibility of appreciable sea water intrusion in the aquifer system does not appear strong.

These very limited and approximate simulation results may lead to the conclusion that the situation may become critical for the Gear Island wells as they are close to the sea coast, and hence there is some risk of seawater intrusion into the land through these wells if the head drops close to the mean sea level, even locally, in the vicinity of the discharging wells. If sea water intrudes into the Gear Island, there is a possibility that the salt water may wedge into Waterloo wells as well, and ultimately to the Lower Hutt areas.

Acknowledgements

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3.3 Saltwater intrusion in Andra Pradesh and its management

ABSTRACT

An international research effort is being contemplated for the Asia pacific region, focussing on the global phenomenon of saltwater intrusion in coastal areas due to natural causes and human intervention. The focus of this joint effort is to link the study areas in different countries and develop a comprehensive methodology with emphasis on practical solution approach. The envisaged total research endeavours to investigate changes in coastal zones caused by salinity intrusion, i.e. both of the catchments socio economic trends as well as the water bodies, and first would, assess and predict the long term salinity intrusion situation, and then, develop a linked simulation model that will actively link the changes in the catchments socio – economic trends to the changes in waters of adjacent coastal zones.

The methodology has two interrelated however, distinct components. The numerical model for simulating density dependent flow and transport in coastal aquifers, and the next component of the proposed study being the development of the regional optimal management strategies to control changes occurring in coastal zones and adjacent waters. Presented here is a brief overview of cases in selected aquifers in the Asia Pacific region, namely in India, New Zealand, Australia, Japan and Sri Lanka, and the first component, the implementation of a numerical model, with an emphasis on Andhra Pradesh, India. The calibrated and partially validated simulation model is used to evaluate the effectiveness of few pumping or withdrawal scenarios on the saltwater intrusion process in the study area. To observe the response of the system, some extra wells are specified in a hypothetical scenario and the simulated results are compared with those for the existing.

1. INTRODUCTION

Coastal aquifers are important sources of water in coastal regions. As population density in many coastal areas increased, need for fresh water also increased. Along with the population, industrial and agricultural growths in these areas accelerate the exploitation of groundwater. Over exploitation of groundwater from coastal aquifers may result in intrusion of saltwater in the aquifer. This is mainly due to excess withdrawal of groundwater compared to the recharge rate, and unplanned pumping locations and pumping patterns. Saltwater intrusion often results in loss of fresh potable water, loss of water for irrigation, increase in soil salinity etc. This results in even possible relocation of habitants from villages due to non-availability of productive soils and drinking water effectively changing the catchments characteristics including its socio economic characteristics. Natural causes may also lead to salinity changes especially in coastal water bodies. Natural disasters such as the recent tsunami have severely affected the groundwater and surface water bodies in South Asia.

On the whole, contamination of coastal aquifers may lead to serious consequences on environment, ecology and economy of that region. The envisaged research endeavours to investigate changes in coastal zones caused by salinity intrusion, i.e. both of the catchments socio economic trends as well as the water bodies, and first, would assess and predict the long term salinity intrusion situation, and then, develop a linked simulation model that will actively link the changes in the catchments socio – economic trends to the changes in waters of adjacent coastal zones. Thereby it is envisaged to develop a model that would facilitate the policy makers to take optimal decisions with multiple objectives to manage the changes occurring in coastal zones including the water bodies, for causes such as even global warming, Tsunami after effects and planned or unplanned groundwater withdrawal strategies. The focus of the envisaged international research effort is to identify affected areas, analyze the underlying causes of salinity changes in local water bodies, and ultimately try to evolve a strategy based on both socioeconomic and physical considerations.

Presented here are preliminary details of few selected aquifer study areas in the Asia Pacific region, namely in India, New Zealand, Australia, Japan and Sri Lanka. A simulation model is being implemented to simulate and predict the aquifer responses in a small portion of the selected study area in Andhra Pradesh India. Some of these simulation results are also presented here to establish the relevance of developing such saltwater intrusion simulation models for coastal aquifers.

2. RESEARCH METHODOLOGY

Often, the management of coastal aquifers requires, careful planning of withdrawal strategies for control and remediation of saltwater intrusion in coastal aquifers. Such strategies can be evolved only if, the physical process involved in the coastal aquifers are simulated through models. Generally these models are mathematical models, which require solution using numerical techniques. It is also possible to identify likely cause and extent of the salinity intrusion problem by using simulation tools.

A mathematical simulation model once implemented for a specific study area after calibration and validation can be used to simulate the response of the aquifer system to various pumping and recharge strategies. These simulation results are essential to predict the response of the aquifer system and to design possible remedial measures to control the saltwater intrusion process. The methodology that we plan to implement for carrying out this international research effort has two interrelated however, distinct components. The numerical model for simulating density dependent flow and transport in coastal aquifers are available as computational tools. In the first component, we would implement (calibrate, validate) the numerical model for selected study areas. This will entail data collection data preparation using iterative calibration and validations, and model modification.

The second component of this proposed study is the development of the regional optimal management strategies to control changes occurring in coastal zones and adjacent waters. This would be accomplished by computationally linking the implemented / calibrated numerical simulation model with an optimization model with specified single and/or multiple objective functions, as well as other physical and managerial constraints. This methodology would be globally applicable, although, for each localized study area fresh calibration and validation of the simulation model would be necessary.

A few selected cases in the Asia Pacific region is presented with an emphasis on the case study in the coastal region of Andra Pradesh India.

3. CASE STUDIES – India, Andhra Pradesh

In the state of Andhra Pradesh, saltwater intrusion is widespread in the Delta regions of the eastern coast. Cities/towns affected by deteriorating groundwater quality due to increase in salinity are Vijayawada, Guntur, Tenali, and south regions of the Krishna River. This study area is known for large amount of groundwater withdrawals for agriculture and aquaculture. The increasing salinity in the explored groundwater aquifers is a matter of concern.

A 3-D, transient, density dependent, finite element based flow and transport simulation model is implemented for the selected area in Nellore District, in Andhra Pradesh, India. This area is extensively utilizing pumped water from the underlying aquifers for agricultural, domestic and aqua cultural uses. The simulation model is calibrated using observed head and concentration data. The calibrated model is then utilized for evaluating the impact of adapting few pumping strategies for controlling the saltwater intrusion process.

The geographical location of study area is show in Figure 1. The study area falls under alluvium soil type. These soils comprises of admixtures of sand, silt and clay in various proportions. The quartz pebbles are invariably encountered at different depths in almost all places in alluvial areas. It is generally light brown to pale gray and sandy in nature. The thickness of coastal alluvium is very large as evident from the exploratory wells drilled by Central Ground Water Board (CGWB) in this area. Bedrock was not encountered even at drilling depths ranging from 250 to 500 m.

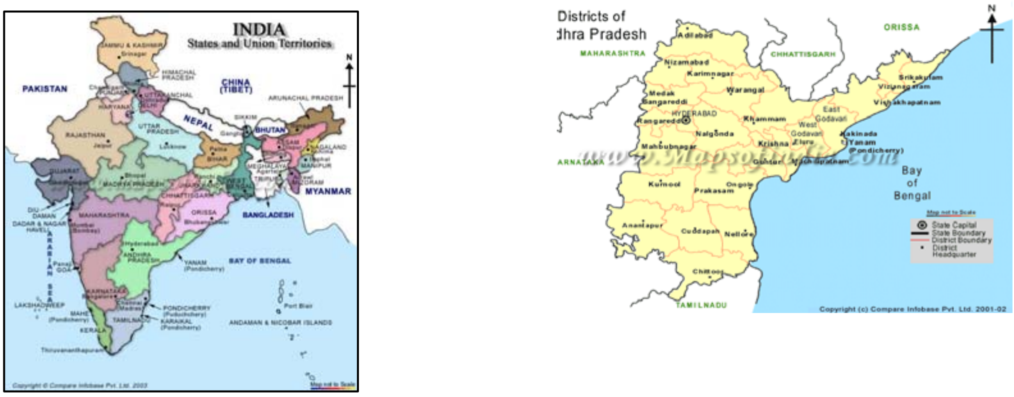


Fig – 1 Location of the aquifer

Saltwater intrusion is already occurring in this area. This is mainly due to excess withdrawal of groundwater for domestic, agriculture and aquaculture uses. For the past 5 years the growth of aquaculture industries is very high, which requires huge amount of water. The only usable water source in this area is groundwater. The observation data by State Groundwater Department, Nellore suggest that water the table is going down every year. In addition to high pumping, there is no good amount of rains for the past 4 years (2001-2004). This further accelerates the groundwater deterioration. The only source of groundwater recharge is through rainfall. The data collected for this study area are briefly described below. A 3D, transient, density dependent, finite element based flow and transport simulation model, FEMWATER is implemented for simulating the coupled flow and transport processes of saltwater intrusion in a coastal aquifer in Nellore district of Andhra Pradesh, India Available data for a selected study area of around 355 km^2 was collected from different agencies to be used as input data for implementing the numerical simulation model for the study area. Due to the scanty nature of available data and questionable reliability of all available data the best but subjective judgment was used in selecting the data for implementing the model.

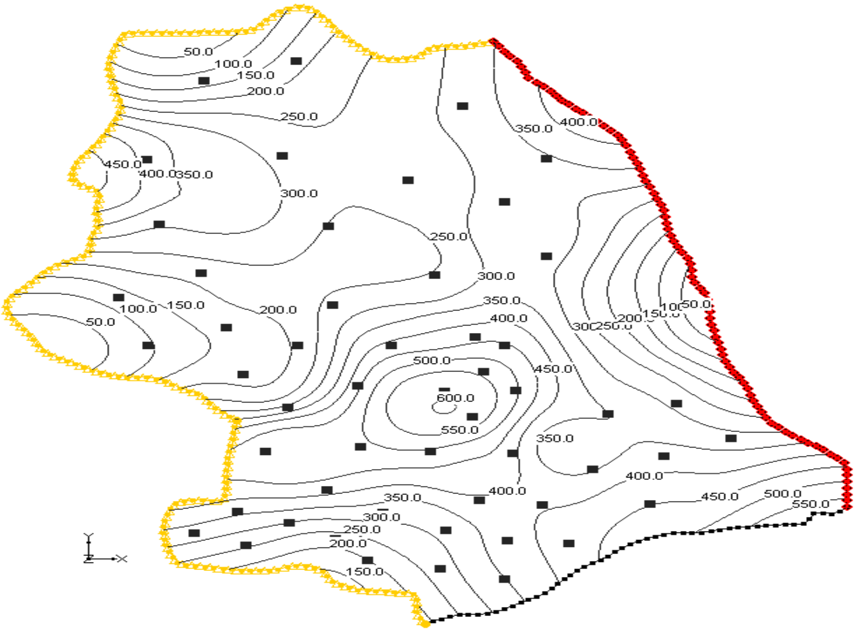


Figure 2. Observed salt concentration contours July 2001

The numerical model was calibrated for two years time period, between July 2000 and July 2002, both in terms of hydraulic heads and salt concentration. The aquifer was considered heterogeneous in terms of vertical stratification. Both flow and transport are considered transient. Withdrawal from aquifer is estimated based on available data, and assuming an increasing trend over the period of calibration and validation. The calibrated simulation model was used to predict the saltwater transport scenario in the study area at future time periods. This predicted head and concentration values show the future saltwater intrusion patterns if the present trend of pumping continues. These results also show if the withdrawal rate continues to increase over time it may have detrimental effect on the salt concentration in the study area.

These evaluation results are based on very limited data and are limited in scope. Actual implementation of planned pumping strategy for economic management of the coastal aquifer will required more rigorous calibration and validation with additional reliable data.

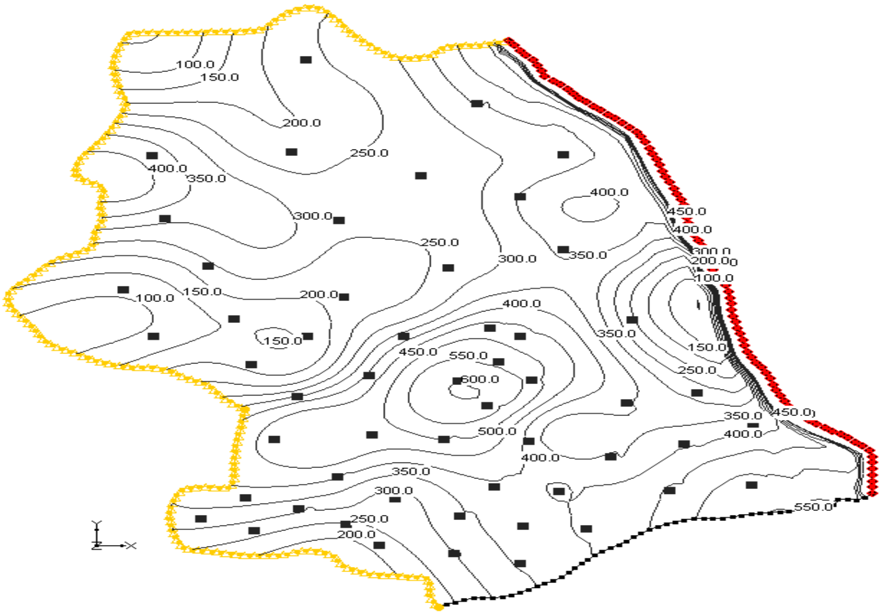


Figure 3. Simulated salt concentration contours July 2001

4. Using Planned Pumping as Strategies for Saltwater Intrusion Control

The calibrated and partially validated simulation model is used to evaluate the effectiveness of few pumping or withdrawal scenarios on the saltwater intrusion process in the study area. To observe the response of the system, some extra wells are specified in a hypothetical scenario and the simulated results are compared with those for the existing. These scenarios are explained below.

Scenario 1:

Additional pumping wells near coast in Utukuru village of Vidavalur Mandal (South of study area)

Additional pumping is assumed from five extra wells near the coast in the Utukuru village of Vidavalur Mandal. Figures 4a and 4b show the old and new pattern of the well locations respectively. The pumping rates are kept at 3,50,0000 m^3/yr for all additional wells specified in scenario 1.

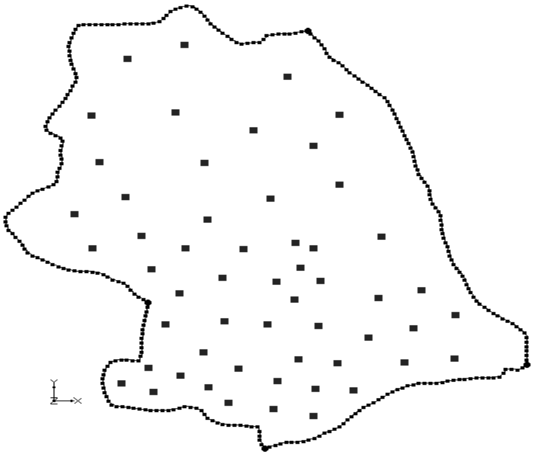


Figure 4a: Location of wells in existing old pumping pattern

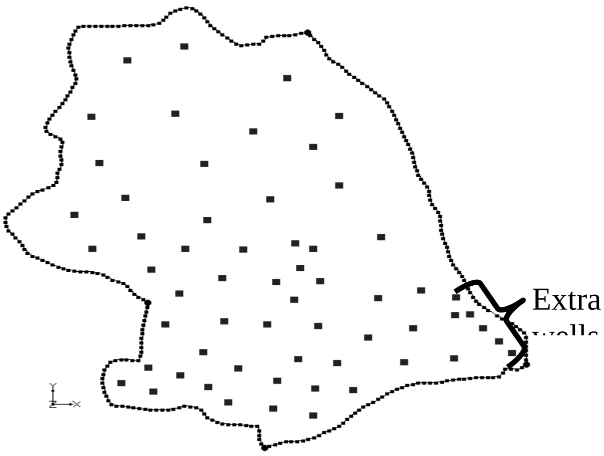


Figure 4b: Location of wells for new hypothetical pumping pattern (scenario 1)

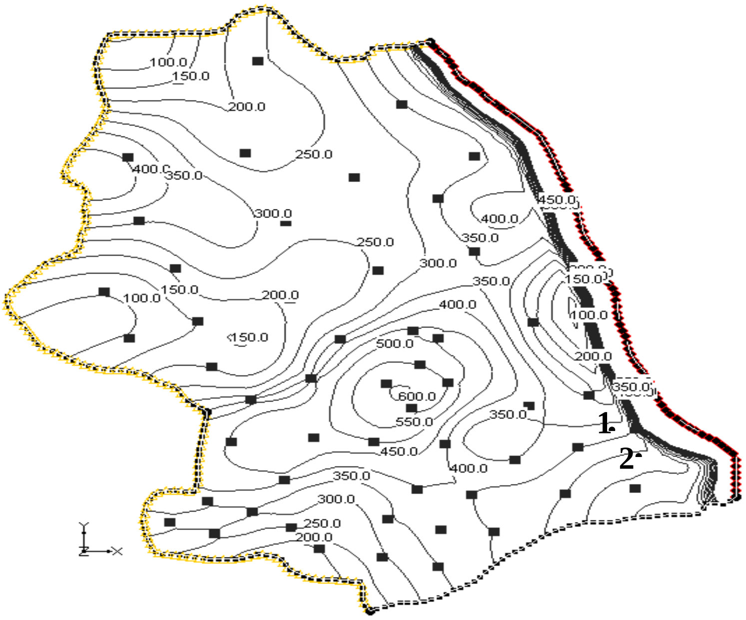


Figure 5a: Salt concentration contours in July 2009 (Existing old pumping pattern)

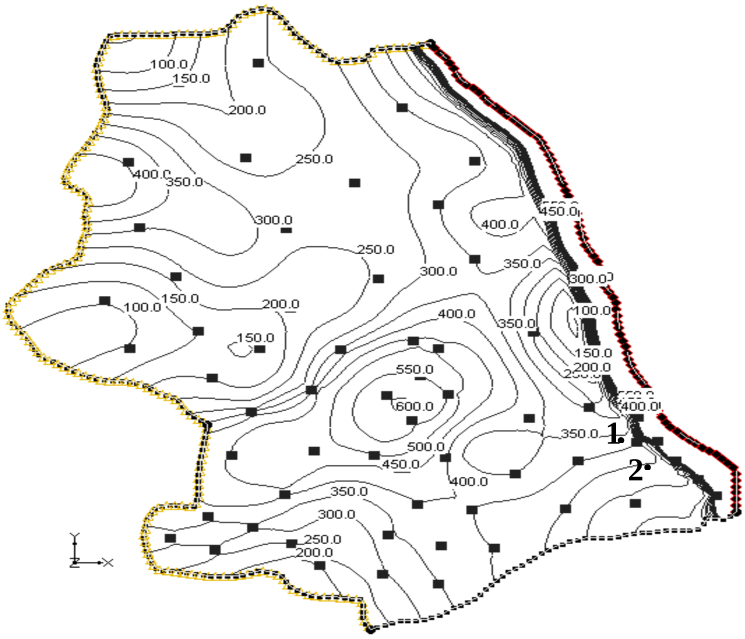


Figure 5b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 1)

It is observed from the concentration contours of July 2009, there is a decrement in salt concentration with extra wells in scenario 1.

Although only marginally, by inducing additional pumping at selected carefully chosen locations, it is possible to reduce the salt concentration levels at some other locations. Therefore it is possible to lower salt concentrations by careful planning of pumping patterns. This may improve groundwater condition in areas away from the coast line by controlling the saltwater intrusion.

Scenario 2: Additional pumping wells near coast line in Iskapalli village of Allur Mandal (East of study area)

Five extra pumping wells are hypothetically specified near the east coast line in Iskapalli village of Allur Mandal. Figure 5.5a and 5.5b shows the old and new pattern of the well locations respectively. The pumping rates in the additional wells are 3,50,0000 m^3/yr

The pumping in these new wells starts from the fifth year i.e., in July 2005. Figure 7a and 7b shows the concentration contours after five years.

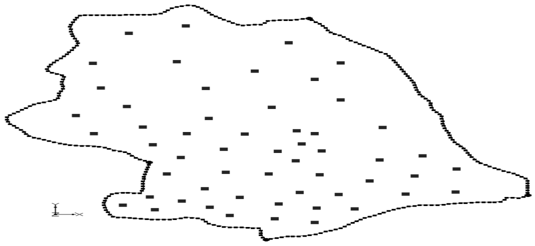


Figure 6a: Location of wells in existing old pumping pattern

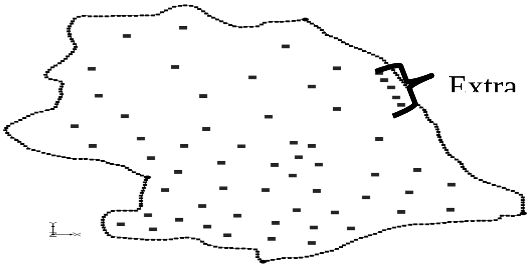


Figure 6b: Location of wells for new hypothetical pumping pattern

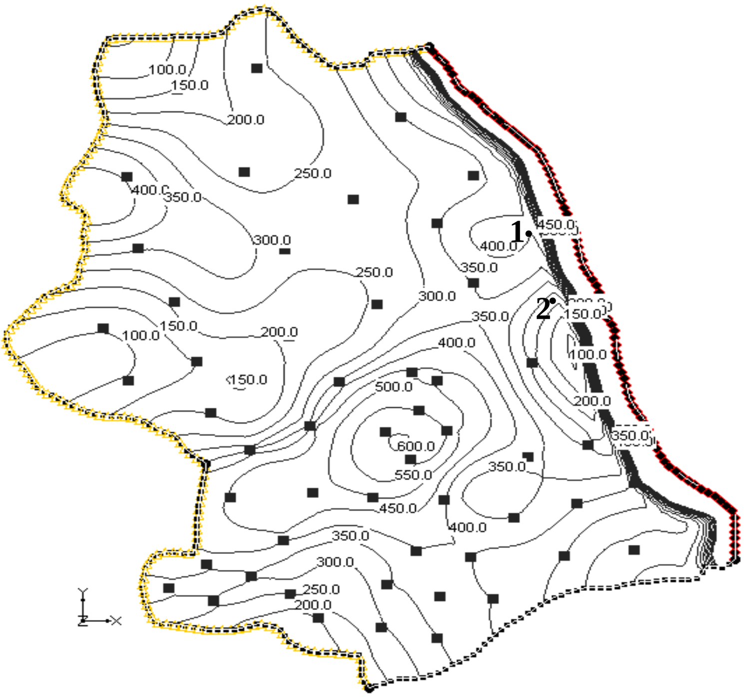


Figure 7a: Salt concentration contours in July 2009 (Existing old pumping pattern)

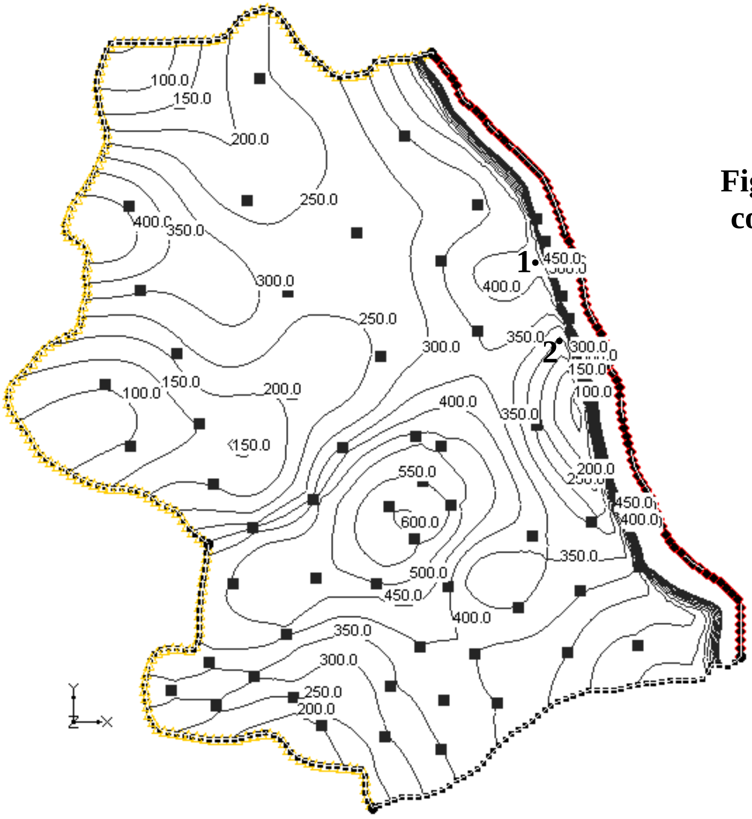


Figure 7b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 2)

It is observed from the above concentration contours of July 2009, shown in figures there is a decrement in concentration with additional pumping induced in some locations. Figure 8 and 9 shows concentration variation with time for the existing and new pumping patterns at different specified locations. Actually, the increasing trend in concentration is arrested in both locations 1 and 2 by inducing these additional pumping.

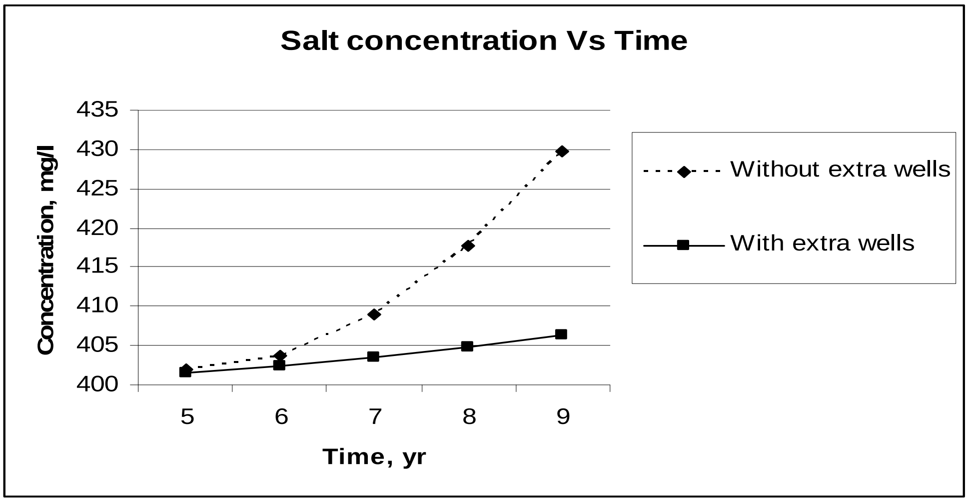


Figure 8: The concentration variation with time for both pumping patterns at location 1 (Scenario 2)

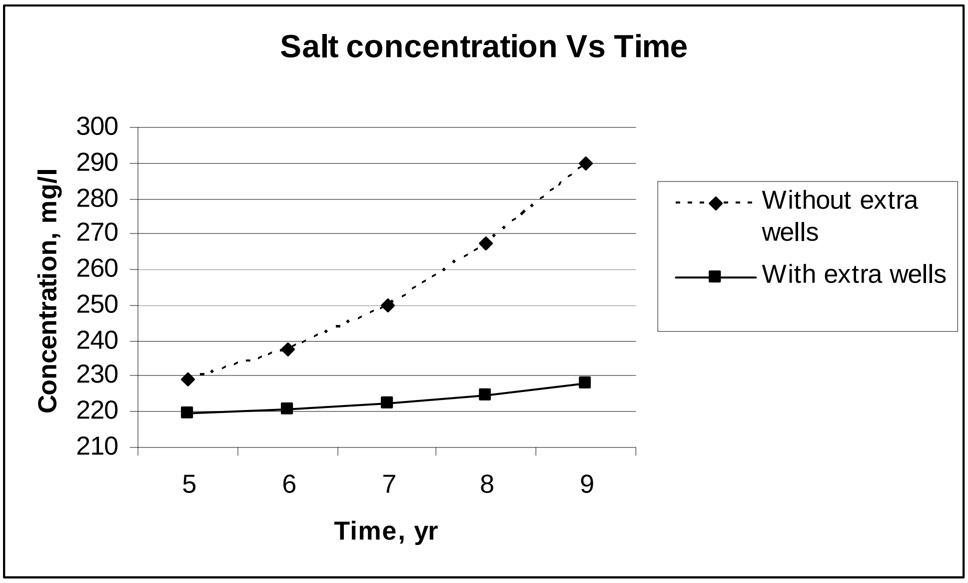


Figure 9: The concentration variation with time for both pumping patterns at location 2 (Scenario 2)

Scenario 3: Additional pumping wells at Dampuru village of Vidavalur Mandal.

In scenario 3, five additional pumping wells are induced at Dampuru village of Vidavalur mandal. Figure 10a and 10b shows the old and new pattern of the well locations respectively. The pumping rates in the additional wells are 3,50,0000 m^3/yr.

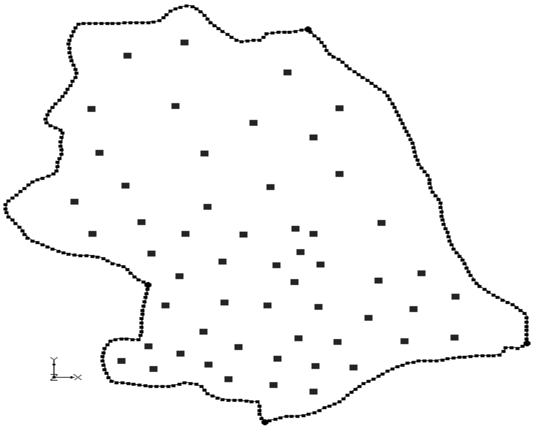


Figure 10a: Location of wells in existing old pumping pattern

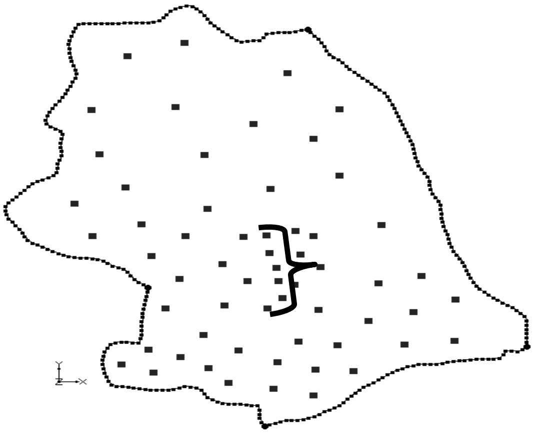
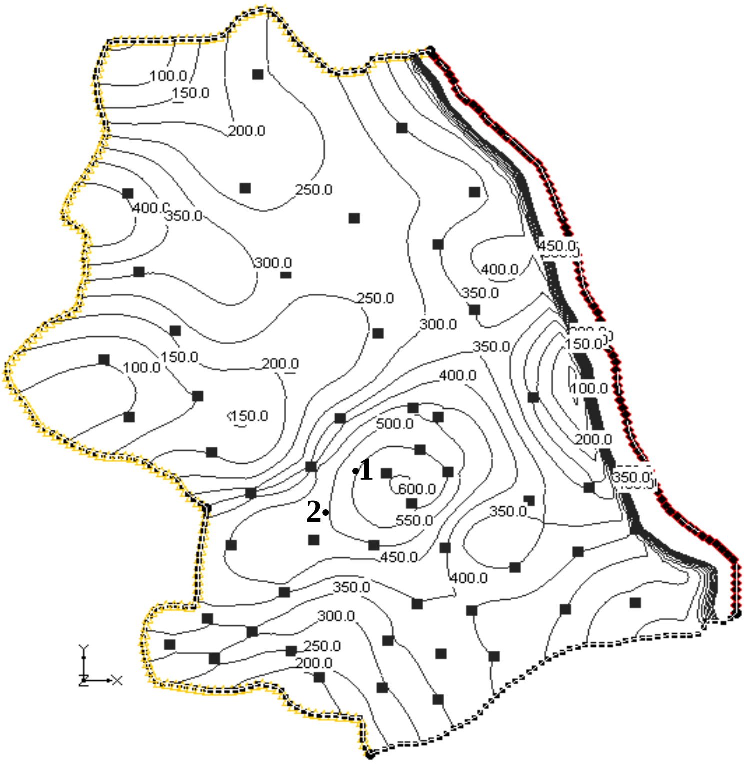


Figure 10b: Location of wells for new hypothetical pumping pattern (scenario 3)

It can be observed from the resulting concentration contours of July 2009, that there is a decrement in concentration, with additional pumping new wells in some locations, compare to the existing pattern. In both the cases concentration is decreasing with time, but the decrement is more in the new pattern compared to the old one.



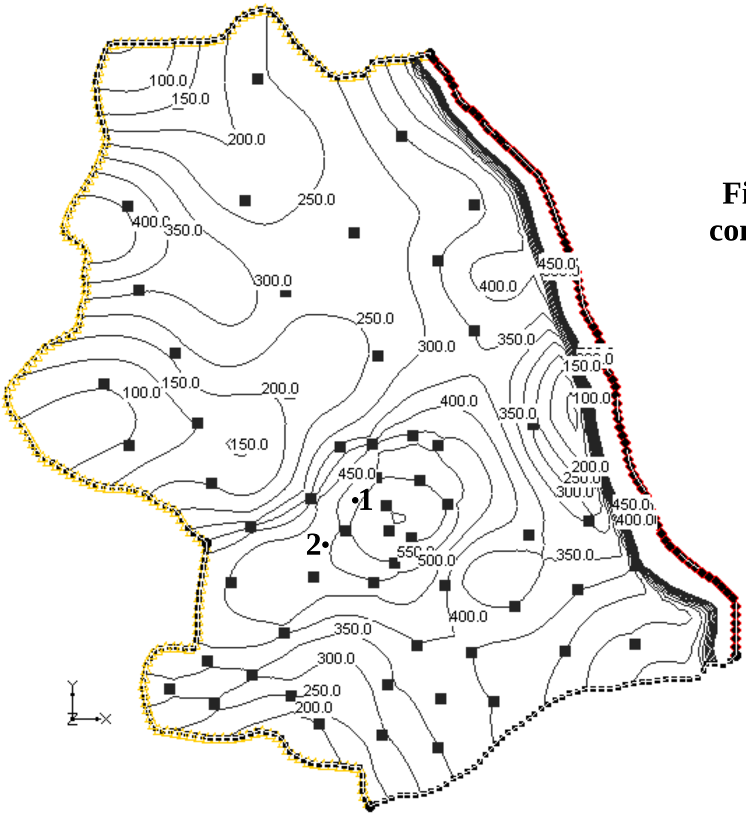


Figure 11b: Simulated salt concentration contours in of July 2009 (Hypothetical new pumping pattern, scenario 3)

It is observed from the concentration contours of July 2009, there is some marginal increment in salt concentration with increase in pumping rates.

These evaluation results obtained for hypothetical pumping scenarios selected with some consideration for possible control of saltwater intrusion, no doubt establish the fact that it is possible to alter the salt concentration in the aquifer by modifying the pumping patterns. These results, although very limited in scope, do show these pumping as a planned strategy can be applied to control salt concentration patterns and therefore, manage the saltwater intrusion process. These results are also useful in predicting the salt concentration scenario in the future, for existing pumping patterns.

5. Summary and Conclusion

One example is presented to demonstrate the applicability of simulation tools to model and predict saltwater intrusion scenarios in coastal aquifer. Such implemented simulation models would be one of the useful tools for predicting and controlling future scenarios of saltwater intrusion in coastal water bodies especially focused towards the Asia Pacific Region.

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3.4 Impact of changes of catchment characteristics on aquifers

Abstract

The long-term changes in catchment characteristics brought about by human interactions have been investigated. These are in the form of changes to land use due to urbanisation and industrialisation, and the related socio-economic factors associated with these, namely increasing population growth and changes in demography. Demographic changes and land use patterns occurring in this region impact on the demand on water resources. Hence a basic regression analysis has been carried out to identify the nature of the changes and its impact on ground water.

Even though the scale of impact by demographic and catchment changes on the aquifer has not been quantified it has been found that over a 50 year period, 25 years past and 25 years future, there has been and will be significant changes. The infiltration area changed in the past 25 years by 10% and forecast to change by a further 10% in the next 25 years. It has also been found that while population increased in the said catchment, the population density decreased both which negatively impacting on the groundwater resource.

1. Introduction

The backdrop to these investigations has been the increase in demand for freshwater and the high vulnerability of available freshwater resources at a local level in the Wellington Region. In addition demographic changes and land use patterns occurring in this region impact on the demand on water resources. This investigation aims to focus on the long-term changes in the catchment characteristics, which have been brought about by human interactions. These are in the form of changes to land use due to urbanisation and industrialisation, and the related socio-economic factors associated with these, namely increasing population growth and changes in demography.

Historically, the area was well known for its conducive environment for human habitation, earlier with the Maori, and then followed by the European settlers. These have all contributed to vibrant human activities that have continued unchanged over time, which could inevitably have had some impacts on this invaluable underground natural resource. Thus, these investigations on impacts, are expected to generate more specific data, that would be directly relevant to decision makers regarding on-going resource planning for the area, particularly regarding freshwater resources.

The information may further help to focus and highlight the fragility of this unique resource, and the vulnerability of it to over exploitation and consequent extinction, unless currently, rigid processes are in place with strict compliance of the same, in order to ensure good sustainable management. Thus these investigations in general, could contribute to a better understanding and planning for the sustainable use of the current, as well as for future sustainable use of the artesian water supply of the Waiwhetu aquifer, which infact is a small sub- system of the more extensive Hutt Valley - Port Nicholson / Wellington Habour groundwater basin system (Stevens, 1956).

Geomorphlogy and Catchment Characteristics of Study Area

The Waiwhetu catchment is a relatively small part of the larger Hutt river catchment, and opening into the floodplain of the Hutt river (Fig. 1). It is assumed that results of a detail investigation performed on this sub catchment could be extrapolated to the whole catchment.

The Waiwhetu stream rises in the eastern hills of the Hutt Valley above the suburb of Naenae. The catchment area is approximately 19 square kilometres, with a main channel length of about nine kilometres (WRC Report, 2001). The headwaters of the stream in the eastern hills of Taita Gorge are relatively steep, but as the stream emerges onto the valley floor in Naenae, it flows at a much flatter gradient. It then runs south for approximately six kilometres through the suburbs of Epuni, Waterloo, Waiwhetu and Gracefield to its confluence with the Hutt River estuary at Port Road. An estuarine zone of about three kilometres extends upstream from the Waiwhetu stream mouth. The only major tributary is the Awamutu stream which meets the main channel of the Waiwhetu stream at Hutt Park (Fig. 2).

According to Stevens (1956), the available geological data support the presence of the Hutt Valley - Port Nicholson groundwater basin system (HVPNGBS), which is a sedimentary formation comprised of a succession of gravels and silts deposited during geologic periods of fluctuating sea levels. A much simplified picture of this groundwater basin system is obtained, if the lower valley floor was visualised as a deltaic formation that was grading steadily from approximately Taita Gorge to the present Petone shoreline.

The uppermost sedimentary beds are referred to as the Taita Alluvium, and overlie numerous sedimentary beds of earlier origin, which are of diverse composition, and which dip at a steeper angle into the body of the HVPNGBS. These offer relatively open and permeable fresh water recharge areas. It is also thought that some groundwater must percolate to lower aquifers from the valley floor and eastern hill slopes. It is generally understood that most of the recharge water of the aquifers has passed through the Taita Gorge as river water or water under flowing the coarse and open alluvium of river bed. Hence any changes to these open areas would result in changes to inflow into groundwater

From an economic point of view, the sedimentary member of most significance appears to be the Waiwhetu Gravels. As an aquifer body, this lies below Hutt City at 60 feet to 160 feet, and its waters are artesian. The ultimate safe yield from this aquifer has been estimated to be 25-30 mgd, and deeper aquifers appear unlikely to produce water of such good quality or in such abundance. Currently the Hutt City takes 6-8 mgd from the Hutt Park bores in order to meet urban water demands. The aquiclude below Hutt City, Petone, and the Port Nicholson Harbour is sensitive to disturbances and is readily punctured with risk of loss of artesian waters (Stevens,1956).

Study Method

A number of methods have been applied during the investigation in order to examine the current basic structure, the spatial and temporal characteristics of land use change, as well as the factors affecting them, with a view to gauge the specific and overall impacts on the Waiwhetu artesian system.

At the onset of these investigations, a thorough literature survey was initially done, so that past trends regarding land use and other human interactions were well understood. This was with a view to relate the current situation as best as possible to the recurrent changes that have taken place in the past. In this regard, a detailed examination has been made of the demographic profiles for the area, during the past several decades. Information derived from aerial survey remote sensing techniques, as well as ground surveys of past and recent times for the area have been used as supplementary data. These were basically from the available large - scale aerial photographic coverage (1:5000 before 90's) and computer derived maps (1:500 of 1997, 2003 and 2008) for the area (see **Figs. 1& 2**).

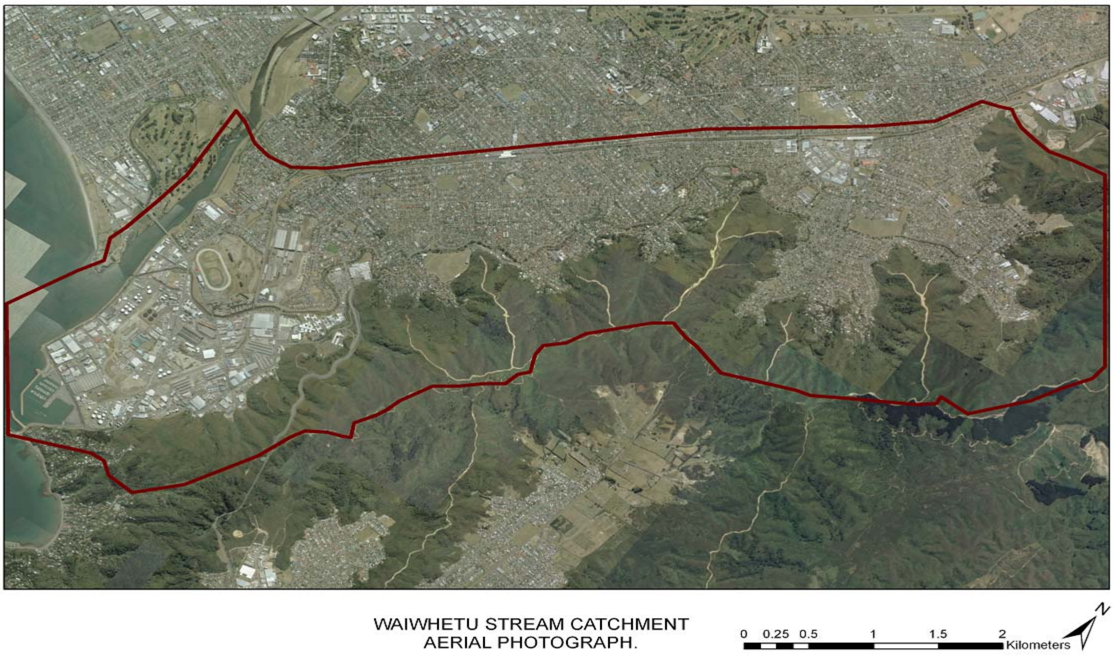
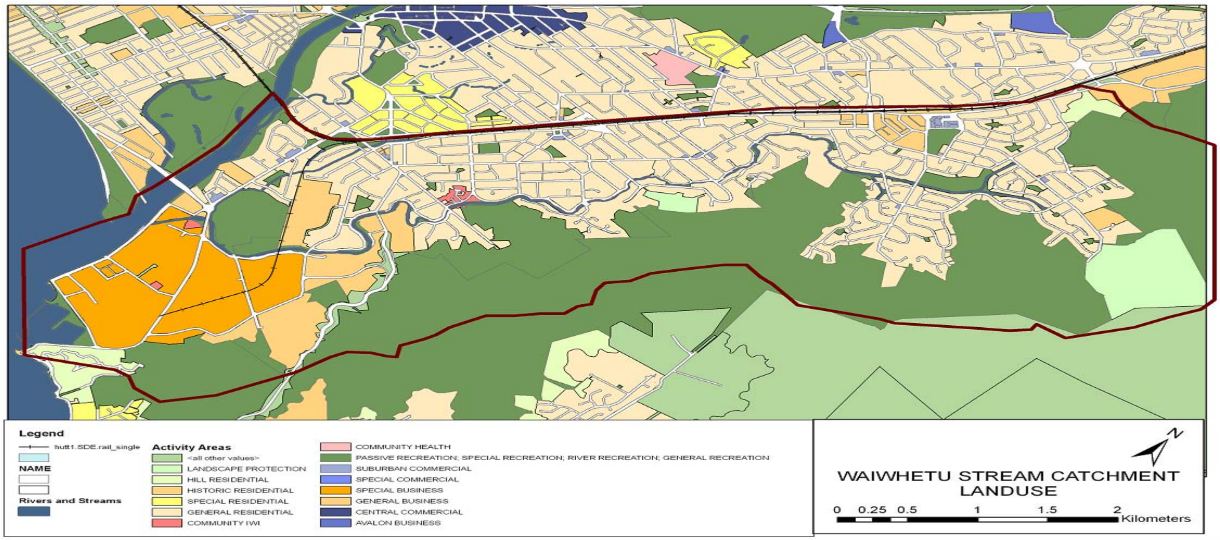


Fig 1 Waiwhetu stream catchment aerial photograph
Source Wellington regional Council and Lower Hutt City Council

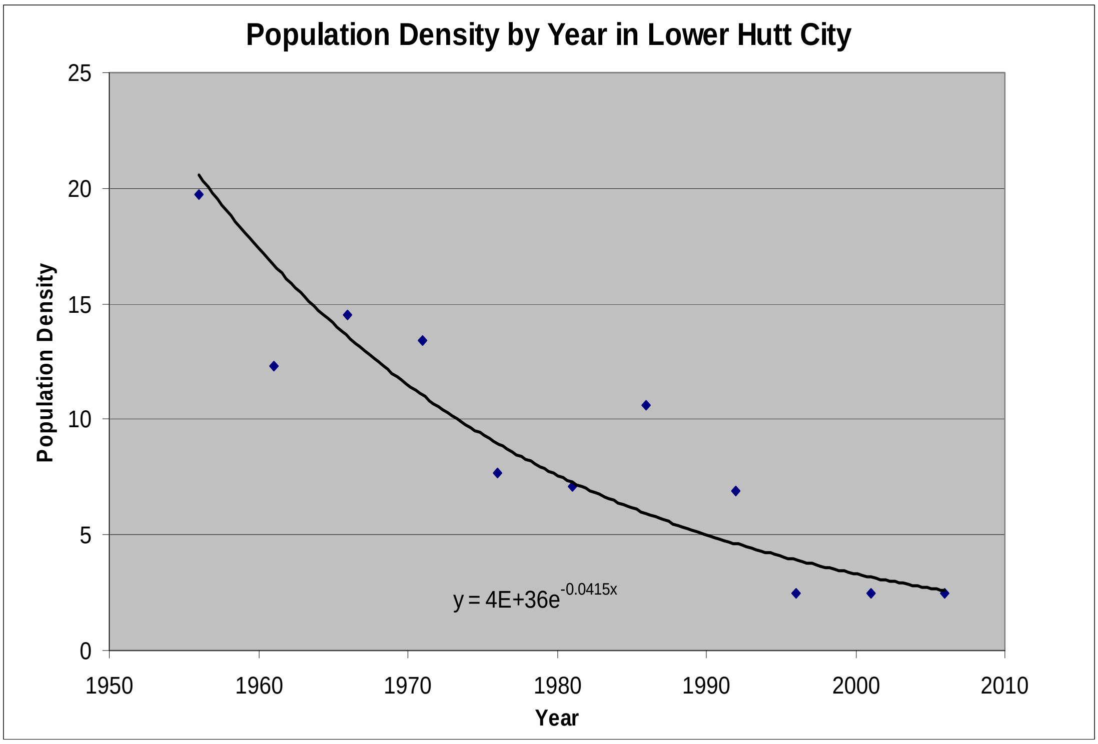
Fig 2 Waiwhetu stream catchment land use pattern
Source Wellington regional Council and Lower Hutt City Council



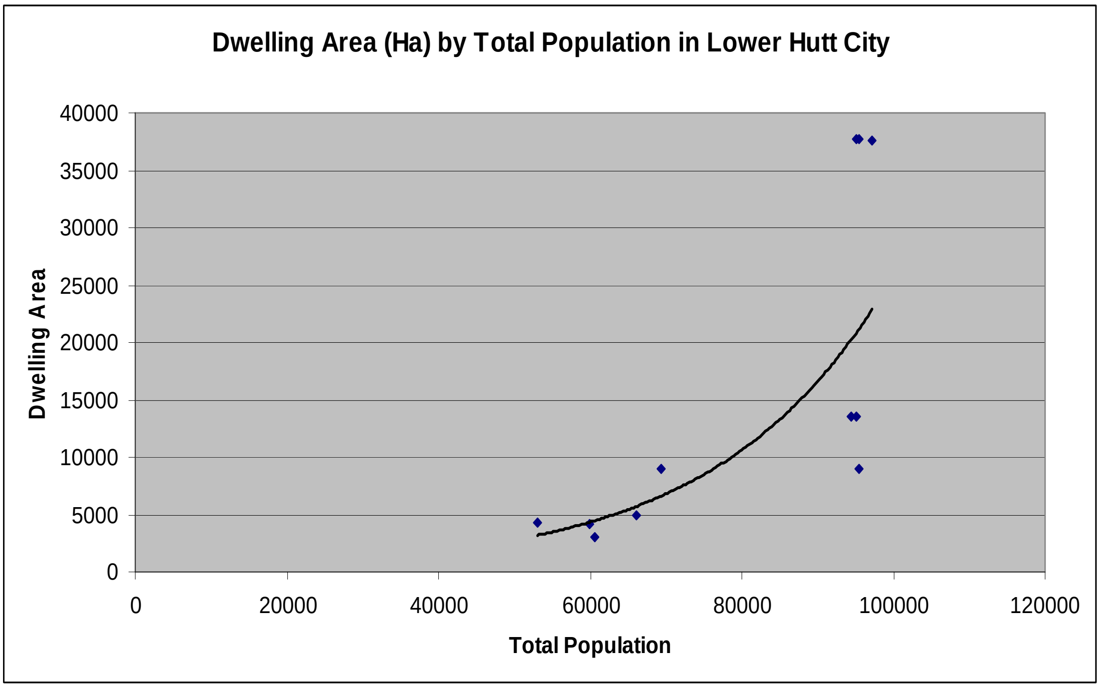
Data Analysis

Waiwhetu stream catchment area
Population / Dwelling Area (Ha) / Population Density

Year	1981	1996	2001	2006	Max
Variation					
Land Unit (1 Naenae)					
Population	9,339	7,914	7,998	8,620	-1425
Dwelling area (ha)	1003	1,068	1,073	1,100	97
Population density (p/ha)	9.3	7.4	7.4	7.8	1.9
Land Unit (2 East Epuni)					
Population	3,096	3,033	2,934	3.080	162
Dwelling area (ha)	168.6	150	146	146	-24
Population density (p/ha)	18.3	20.2	20	21	2.7
Land Unit (3 Waterloo)					
Population	3,560	4,149	4,134	4,360	800
Dwelling area (ha)	264	240	210	210	54
Population density (p/ha)	13.4	17.2	19.6	20.7	7.3
Land Unit (4 Waiwhetu)					
Population	3,177	3,585	3,591	4100	923
Dwelling area (ha)	246	265	258	267	21
Population density (p/ha)	12.9	13.5	13.9	15.3	2.4
Land Unit (5 Gracefield)					
Population	208	57	75	60	151
Dwelling area (ha)	342	413	421	421	79
Population density (p/ha)	0.6	0.13	0.17	0.14	0.47
Land Unit (6 Moera)					
Population	1,445	1,620	1,668	1,680	223
Dwelling area (ha)	60	65	65	62	5
Population density (p/ha)	24	24.9	25.6	27.1	3.1



According to these two charts, the population density goes down rapidly with year. With the equation shown, population density can be predicted for a particular year (eg., when year = 2011, population density is 2.1). These population densities are then used to predict the dwelling area which is the population divided by the population density.



Waiwhetu stream catchment area
Population projection (2006 – Base)

Year	2006	2011	2016	2021	2026	2031
Land Unit (1) **NAENAE**	8,620	8,830	9,010	9,170	9,310	9,430
Land Unit (2) EPUNI EAST	3,080	3,160	3,230	3,280	3,310	3,320
Land Unit (3) WATERLOO	4,360	4,430	4,490	4,530	4,570	4,590
Land Unit (4) WAIWHETU	4,100	4,270	4,410	4,550	4,640	4,710
Land Unit (5) GRACEFIELD	60	60	70	70	80	80
Land Unit (6) MOERA	1,680	1,700	1,710	1,710	1,710	1,690

It is clear that while population density is going down, population has continuously increased. This means that green top soil areas are being cleared for property development. This could be seen from the increase in dwelling area as well.

It could be seen that given a 25 year period the increments in the various sub catchments are marginal, nevertheless it amounts to a total increase of 236 Ha which means that there is now 236 ha less for water seepage and ground water recovery, which will yield an impact on the aquifer. Again although this amount is marginal this is a 10% variation from 25 years ago, which could be significant. This is for an approximate 10% variation in population. The next 25 years 2006 to 2031 indicates similar variation in population which then could be implied to impact similarly on the catchment reducing the seepage area by a further 10%.

The total population and dwelling area for the entire Hutt valley is as given below.

Year	Population	Dwelling Area	Density
1956	60667	3076	19.7
1961	53010	4288	12.3
1966	59908	4122	14.5
1971	66102	4927	13.4
1976	69332	8968	7.7
1981	95080	13495	7.1
1986	95432	8968	10.6
1992	94355	13508	6.9
1996	95375	37673	2.5
2001	95022	37675	2.5
2006	97149	37647	2.5
2011	102,830	48967	2.1
2016	103810	61065	1.7
2021	104320	74514	1.4
2026	104410	94918	1.1
2031	103970	103970	1

Conclusion

The results of these investigations are basically derived data, from various sources from past, as well as more recent work done on the area. The information have been systematically examined, sequentially categorised and analysed, in order to seek rational answers.

It could be seen that in catchment area under investigation while the population density is coming down the population increases, effecting the percolation area many fold, resulting in less inflow to ground flow. The last 25 years saw an decrease in green top ground area by 10%, and it is predicted that the next 25 years will have a similar effect, undoubtedly effecting inflow patterns to the ground water system thereby impacting on the aquifer.

Even though the scale of impact by demographic and catchment changes on the aquifer has not been quantified it is clear that over a 50 year period, 25 years past and 25 years future, the change in green top soils from past 10% and another forecasted 10% will significantly effect the ground water system necessitating an implementation of a catchment management strategy as well.

Basically while increase in population requires greater abstraction of ground water the decrease in population density signifies greater use of land reducing seepage area both of which are detrimental to ground water systems and has to be controlled. The decrease in population density has a lasting impact on ground water systems and priority in controlling this is essential.

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3.5 Modelling Bundaberg aquifer and catchment management strategies

The Queensland Government, Department of Natural Resources and Water have performd extensive studies on this aquifer.

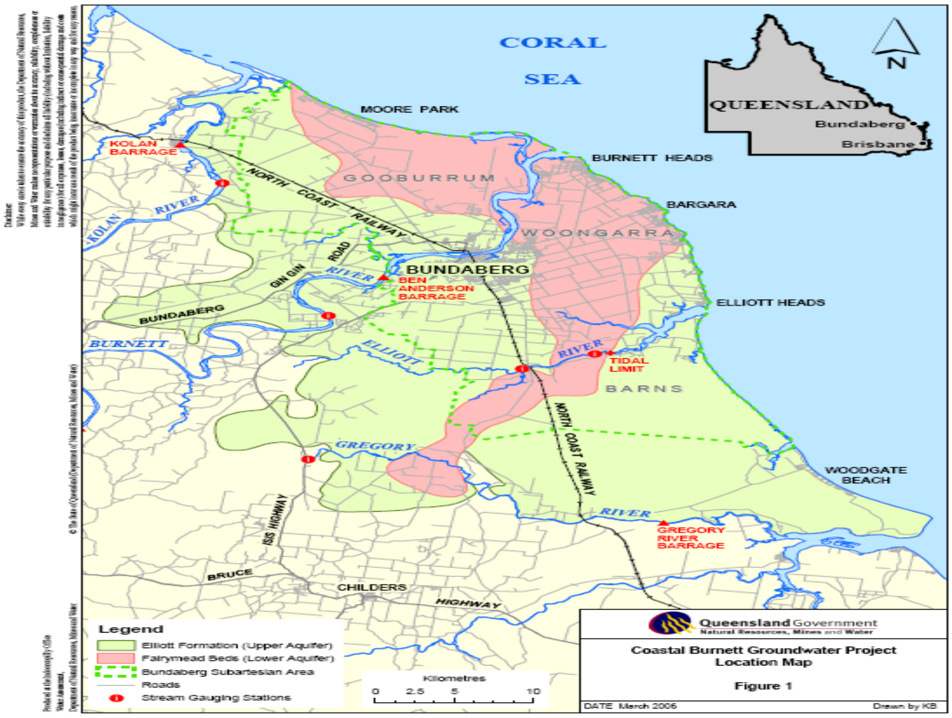
A report produced by The Queensland Government, Department of Natural Resources and Water, 2006, authored by Kiran Bajracharya, Andrew Moser, Ken Heidke, describes seawater intrusion in the Coastal Burnett Region and details the development of an instructional seawater intrusion model. Extracts of which are as follows.

The instructional seawater intrusion model has been developed using the code MODHMS (HydroGeoLogic Inc., 2003), and is based on the MODFLOW groundwater flow model (NR&M, 2005). The calibration of the seawater intrusion model involved qualitative assessments of model prediction.

It has been found that only slight changes in the extent of seawater intrusion occurred when simulated for the period of 15 years. This is also evidenced by the 8-year data from 1996 – 2003. It indicated that seawater intrusion is a long term process, requiring model simulations for very long periods of time (e.g., 100 years) to assess the pattern of significant change in concentration distribution unless major changes in extraction patterns or inflow patterns occur. Long term (100 years) scenario models have been therefore constructed from the calibrated seawater intrusion model by modifying the parameters.

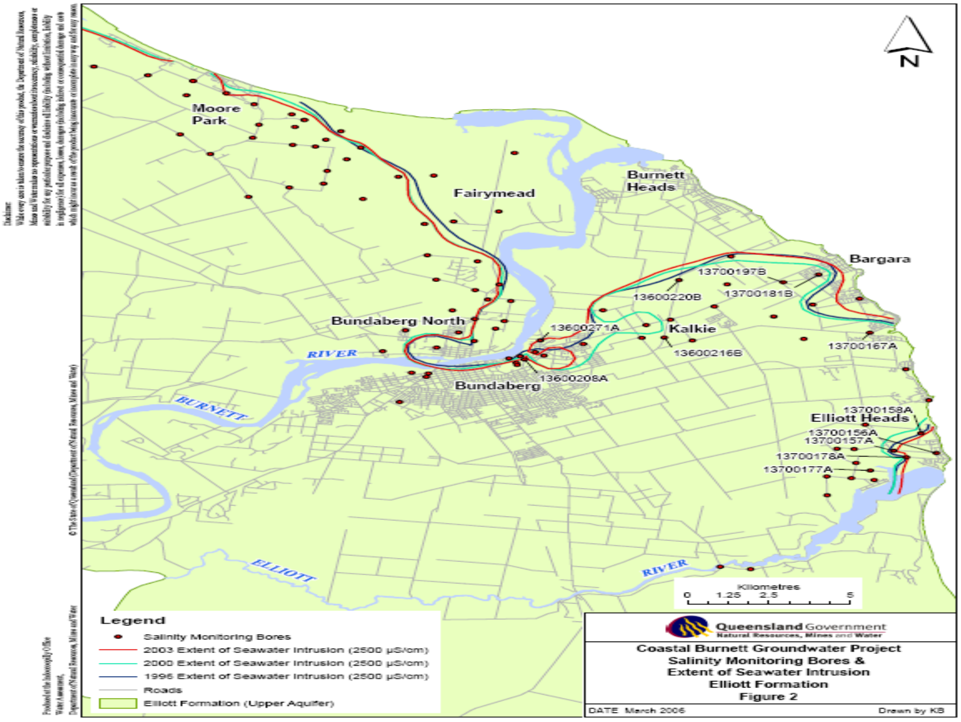
The developed model could be used as a tool for assessing relative changes in the extent of seawater intrusion associated with various management strategies. Two scenarios have been analyzed and the results indicate that usage patterns, in the long run, have an impact on the seawater intrusion.

Fig 1 Location Map – Extent of aquifer which makes up the study area



Salinity monitoring had been undertaken in some 165 bores of which 146 are still actively monitored. Figure 2 show the monitoring bores in the upper and lower aquifers. It also indicates the position of the depth-averaged 2,500 µS/cm conductivity contour for the years 1996, 2000 and 2003 in the upper and lower aquifers respectively.

Fig 2 Salinity monitoring bores and extent of seawater intrusion



Two scenarios have been run for a period of 100 years. One case is the full entitlement and the other is the present use case. Fig 3 shows the water level contours of December 2001 for the upper and lower aquifers.

Fig 3 Generated Water levels

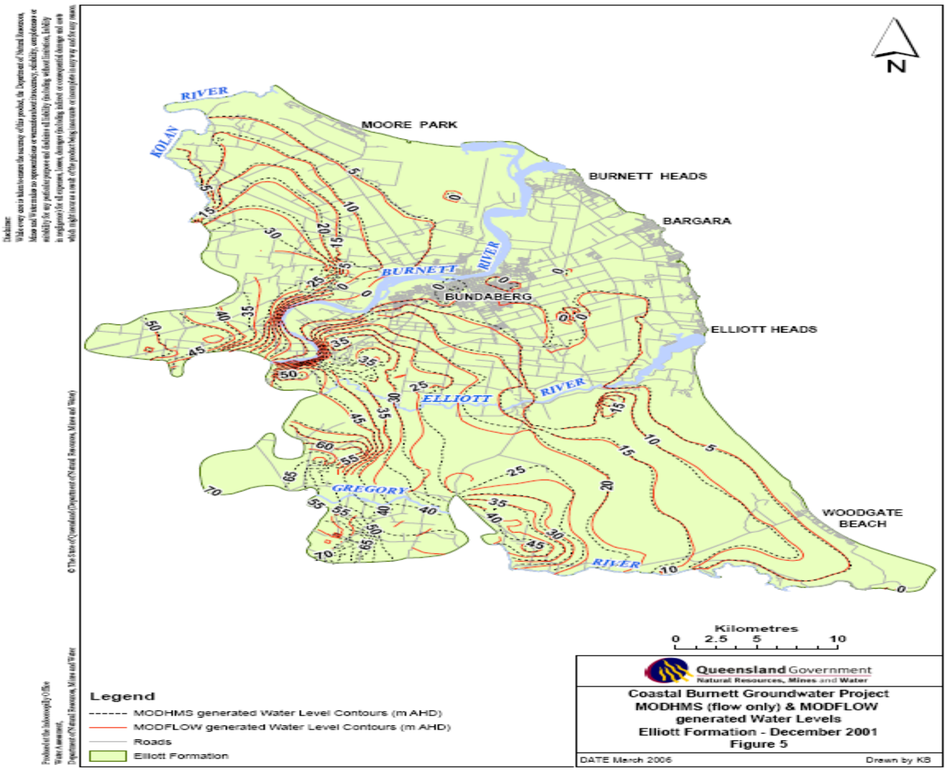
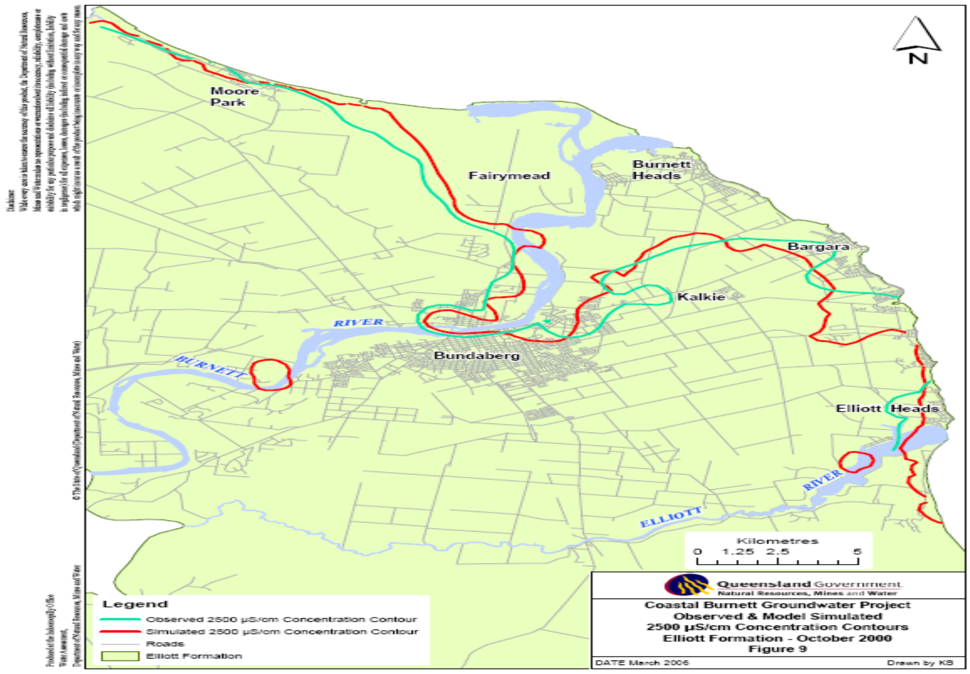


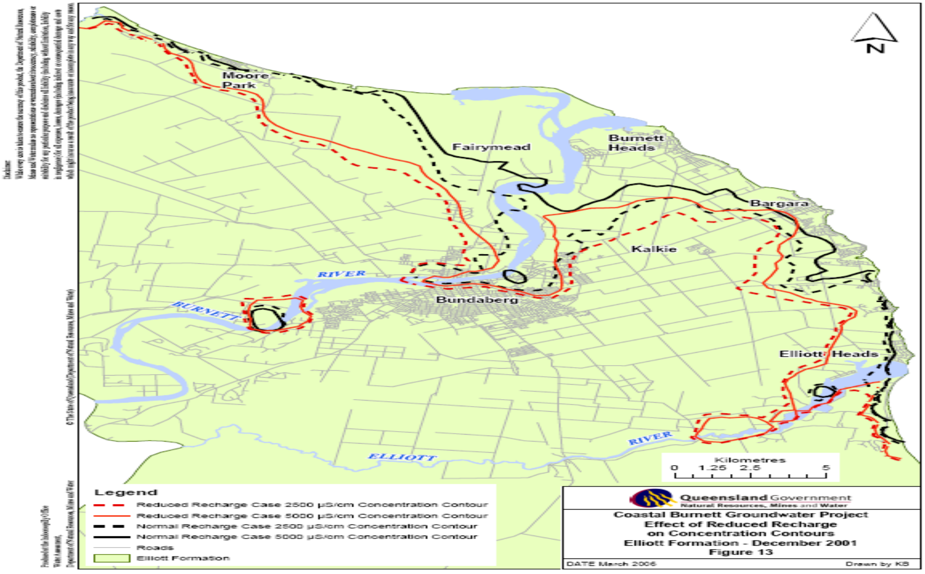
Fig. 4 show the observed and model simulated, 2,500 μS/cm contours in October 2000. The model-predictions do not accurately match observed results especially in the lower aquifer near Moore Park area, but are acceptable in the context of the calibration approach, as well as in the way the observed data have been interpreted.

Fig 4 Observed and model simulated contours



The effect of reducing recharge by 85% on the concentration contours (2,500 and 5,000 µS/cm) is shown in Fig 5 for the upper and lower aquifers, respectively. A significant decrease in recharge resulted in decreased river outflows. It shows the water level contours at the end of the 15-year simulation period for comparison purposes.

Fig 5 Effect of reduced recharge

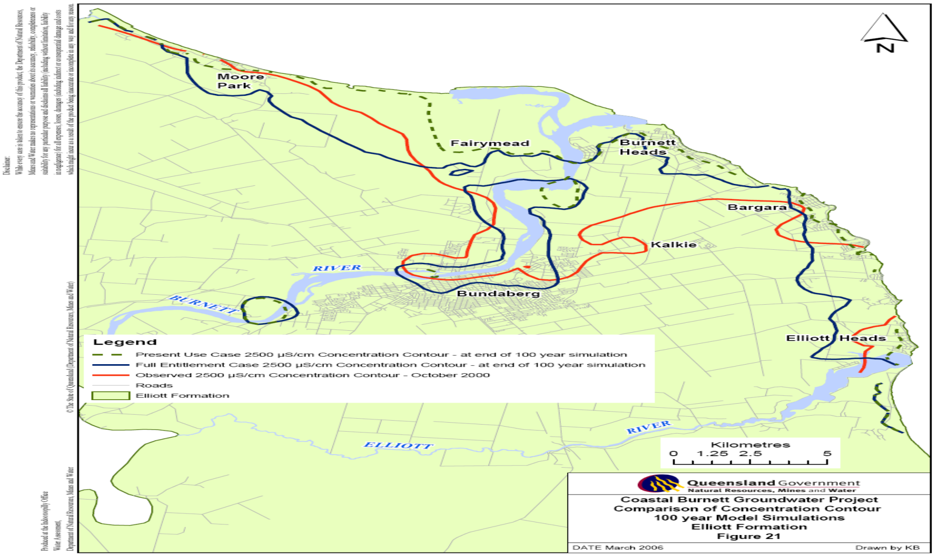


Porosity values were increased by 33% from the base values. The increased porosity on the concentration contours (2,500 and 5,000 µS/cm) are shown in Fig 6 for the upper and lower aquifers along with the concentration contours with base porosity values. As seen in the Fig, the effect of higher porosity was the salt concentration front arriving at a particular point later.

Fig 6 Effect of increased porosity

Full entitlement, or nominal entitlement, extraction data has been used to run a 100- year simulation. The 2,500 µS/cm concentration contour are shown in Fig 7 for the upper and lower aquifers respectively. Also shown, for comparison purposes, in the Fig is the interpreted 2,500 µS/cm contour observed in October 2000.

Fig 7 100 Year Model simulation



Please note that all figures above are sourced from the reports of Queensland Government, Department of Natural Resources and Water.

It has been noted that the seawater intrusion model should not be used to estimate the groundwater salinity at specific locations and not expected to reproduce vertical variability in groundwater salinity because it is a pseudo three dimensional two-layer model. Lateral movement of depth averaged concentration front in the two aquifer layers in the region can be approximated by this approach. In most cases, the model should be used to determine relative movement in the extent of seawater intrusion rather than as a tool for estimating absolute groundwater salinities.

The model used has provided a basis for the construction of long-period simulations (about 100 years), characterized by large climatic variability, as calculated from historical rainfall records. Use of the model for predictive scenarios could simulate a range of management approaches, some of which may result in large and persistent depressions in coastal water table conditions.

The study concludes that the model is considered an adequate tool for assessing relative changes in the extent of seawater intrusion associated with various resource management strategies.

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3.6 Assessment of change & potential groundwater quantity and quality & salinity in Pakistan

ABSTRACT

Indus Basin Irrigation System (IBIS) encompasses arid to semiarid climate and annual canal diversions are less as compared to evapotranspiration. This difference is also varying in different canal commands. Groundwater quality deterioration is taking place in some canal commands at alarming rates as compared to others. In this perspective, extent of land and Water resources of Pakistan linked to IBIS has been highlighted with special reference to change in groundwater quality with time. The data analysis in long perspective of surface water and ground water resources has shown that areas that were waterlogged in the past are now showing groundwater mining. Also the groundwater quality is deteriorating at very alarming rate. There is need to shift from short term to strategic planning particularly for the groundwater resources of the country which cater for about 50 to 60 % of crop water requirements in IBIS.

1. INTRODUCTION

Pakistan is basically an agricultural country whose agriculture mostly depends on flows in Indus River and its tributaries. Irrigation in the Indus Basin has a long history, stretching back to Indus civilizations of over four thousand years. Early irrigation relied on inundation canals which watered narrow strips along the river banks during the flood season. By the construction of barrages and reservoirs, increasingly more river water was diverted and more land was irrigated to increase the food production comparable with increasing population requirements.

The Tarbela reservoir, completed in 1976, added some 50% to available river water for the Rabi season. The river diversions per year vary, depending on the rainfall in the Himalayan catchments and available reservoir storages. But at present the country is in halt towards it surface water resources development, no major storage has been added to the system since 1976. The resulting balance of water development shifted to groundwater exploitation in the form of tubewell installation by government and then by farmers itself. The major portion of these huge groundwater reserves were recharged by deep perculation from irrigation system in which major developments took place from 1932 to 1976. Before the construction of major canal system in Pakistan, depth to groundwater varied from 70 t0 100 ft (Ahmad 1995).

The lands which remained waterlogged for a long time are now under water stress in form of depleting groundwater since 1990's. This major groundwater development started in 1960 with a slow pace and during a decade from now has totally changed the water and salt balance of the IBIS. This change may have an irreversible impact on agriculture production if not tackled with proper planning particularly with respect to groundwater development.

2. LITERATURE REVIEW

About a century ago, the system was originally designed for an annual cropping intensity of about 75 percent with the intention to spread the irrigation water over as large an area as possible to expand the settlement opportunities (Jurriens and Mollinga, 1996). The Indus Basin is underlain by an extensive groundwater aquifer covering about 16 million ha, of which 6 million ha are fresh and the remaining 10 million ha are saline (Haider et al., 1999).

A study undertaken in 1990 pointed out that in Punjab the volume of groundwater extracted significantly exceeds the volume of water recharged. The study estimates the difference to be as much as 27 % on a provincial basis (NESPAK/SGI 1991), but this overexploitation is concentrated in a number of fresh groundwater areas. This is in line with that as reported by Van Steenbergen and Oliemans (1997), that the share of groundwater in the supply of irrigation water has been rising from 8 % to 40 % from 1960 to 1985. Also Halcrow (2006) reported that the groundwater use by farmers has incresed from 8% in 1960 to 60% at the start of 21st century. Even so contribution of groundwater in meeting crop water requirement by and large remains an unknown quantity in Pakistan because it is unmanaged and measured fragmentarily.

According to Ahmed (1995) the quality of groundwater in the Indus Plains varies widely from place to place, both vertically and horizontally from completely fresh to extremely saline, depending on its origin, the source of recharge and the pattern of groundwater movement in the aquifer. Generally groundwater is fresh in strips along the rivers because of seepage of fresh water and deteriorates towards centers and southwest of each doab. According to Chaudhri (1993) serious salt imbalance is occurring in the useable groundwater zones of Punjab where the salt input has increased from 0.64 to 1.95 t/ac/year.

Now the increasing demand for food to cope with the ever increasing population has caused the annual cropping intensities to rise to 150 to 180 percent in different canal commands just with increasing contribution of groundwater resulting in increased concentration of salts in groundwater. So this change in groundwater environment needs to be tackled on scientific and long term basis rather than short term perspective otherwise the situation may not be reversible.

3. RIVER FLOWS AND CANAL DIVERSIONS

The river flow data of Pakistan from 1961-62 to 2004-05 was analysed giving Pre Tarbela Dam (1960-61 to 1975-76) annual average flows of 140.83 MAF and post Tarbela Dam (1976-77 t0 2004-06) annual average flows to be 139.07 MAF. The same data has been plotted in the form of western, eastern and total river flows in Figure 1. There was drought period from 1999 to 2002 which is reflected in the form of low river flows (Figure 1), less canal diversions and almost no releases below Kotri Barrage (Figure 2) and low rainfall (figure 3).

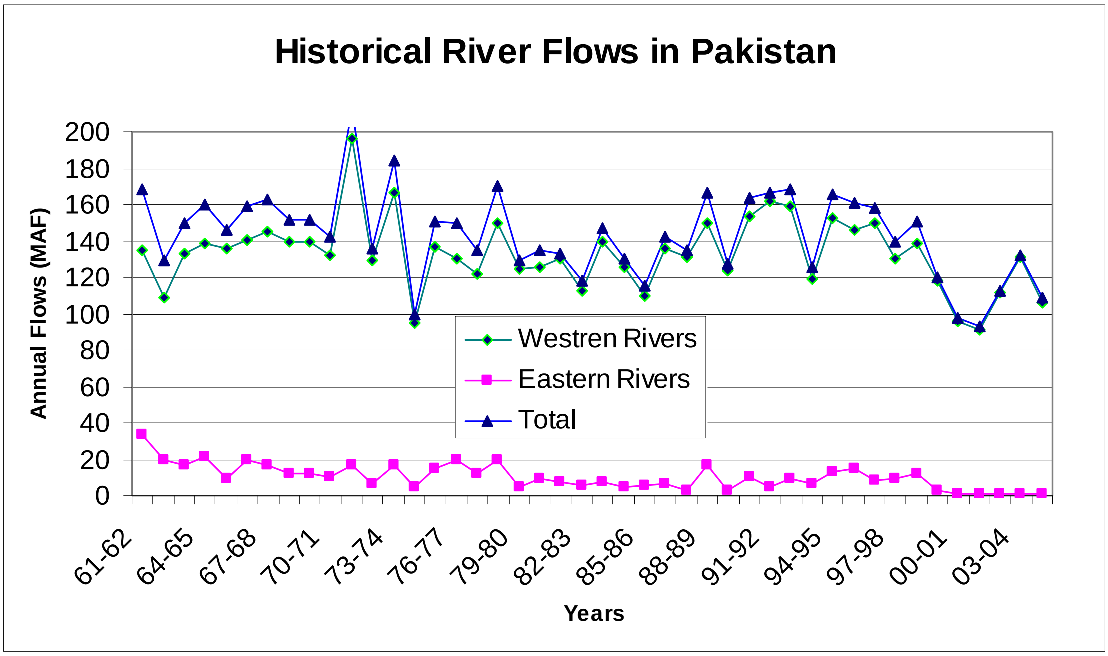

Figure 1: Historical Indus River System flows in Pakistan.

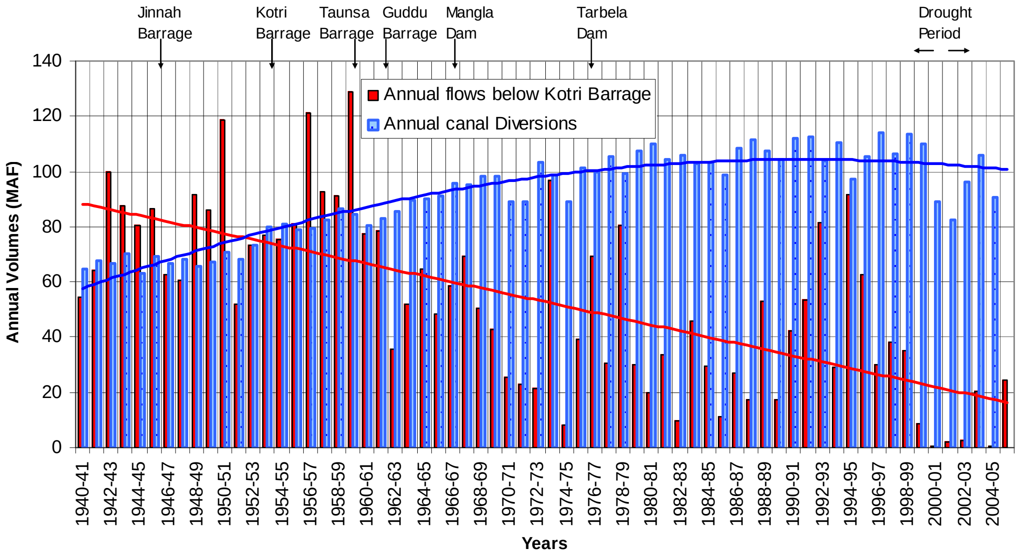

Figure 2:Historical annual canal diversions and flows below Kotri Barrage.

As shown in Figure 2, the annual water releases below the Kotri Barrage (last barrage in IBIS) to the Arabian Sea has been consistently decreasing due to successive development of barrages and reservoirs on the system. Still on an average there is spillage of above 35 MAF annually to the sea (Asrar-ul-Haq et al. 1997). The same fact has been highlighted in more detail in the Kotri Study-I (GoP 2005) in which long term downstream average flows has been calculated as given in Table 1;

Table 1: Longterm average flows downstream Kotri Barrage (MAF)

Period	Pre-Kotri	Post-Kotri	Post-Tarbela
	1937 to 1954	1955 to 1975	1976 to 2004
Kharif	71.656	56.455	31.383
Rabi	8.862	5.862	2.058
Annual	80.52	62.32	33.44

The Table 1 above shows that post Tarbela Dam, an annual average of 33.44 MAF escaped below Kotri Barrage to Sea. After leaving 8.6 MAF for releases downstream Kotri Barrage to check Sea water intrusion and other environmental uses (on fiver year average basis), as recommended by International Panel of Experts in Kotri Study-I (GoP 2005) still there is potential of 24.84 MAF on an annual average to be effectively controlled through multi-purpose storages. Besides utilization for irrigated agriculture to bring prosperity to millions of people, particularly in backward areas of Pakistan, this could provide a large chunk of cheap hydropower.

4. RAINFALL

Pakistan lies in an arid and semi-arid climate zone. Rainfall is markedly variable in magnitude, time of occurrence and its aerial distribution. However, almost two-thirds of the rainfall is concentrated in the three summer months of July - September. High intensity rainfall occurs at elevations between 2-5 thousand feet above which the rainfall decreases. During the monsoon season, the rainfall run-off is added to the discharge due to snow melt so that the total discharge increases manifold. Whereas in Indus Plain, the mean annual precipitation ranges from less than 100 mm in parts of the Lower Indus Plain to over 750 mm near the foothills in the Upper Indus Plain. The entire Indus Plains (canal command areas) receive an average seasonal rainfall of 212 mm (95% confidence interval ± 28) and 53 mm (95% confidence interval ± 8) in the *kharif* and *rabi* seasons, respectively. So the agriculture in Pakistan mainly depends upon canal irrigation. Historical annual rainfall at six selected stations representing about entire irrigation system from North to South is plotted in Figure 3. The maximum, average and minimum rainfall along with standard deviation for these stations is given in Table 2.

Table 2:The maximum, average and minimum rainfall at selected stations in IBIS.

Rainfall station	**Rainfall (mm)**			**Standard deviation**
	Maximum	Average	Minimum	
Sialkot	1887	962	383	330.3
Lahore	1233	571	277	217.5
Peshawar	907	421	174	147.7
D I Khan	615	241.5	0	123.7
Bhawalpur	671	144	0	110.2
Sibi	380	161	0	97.6

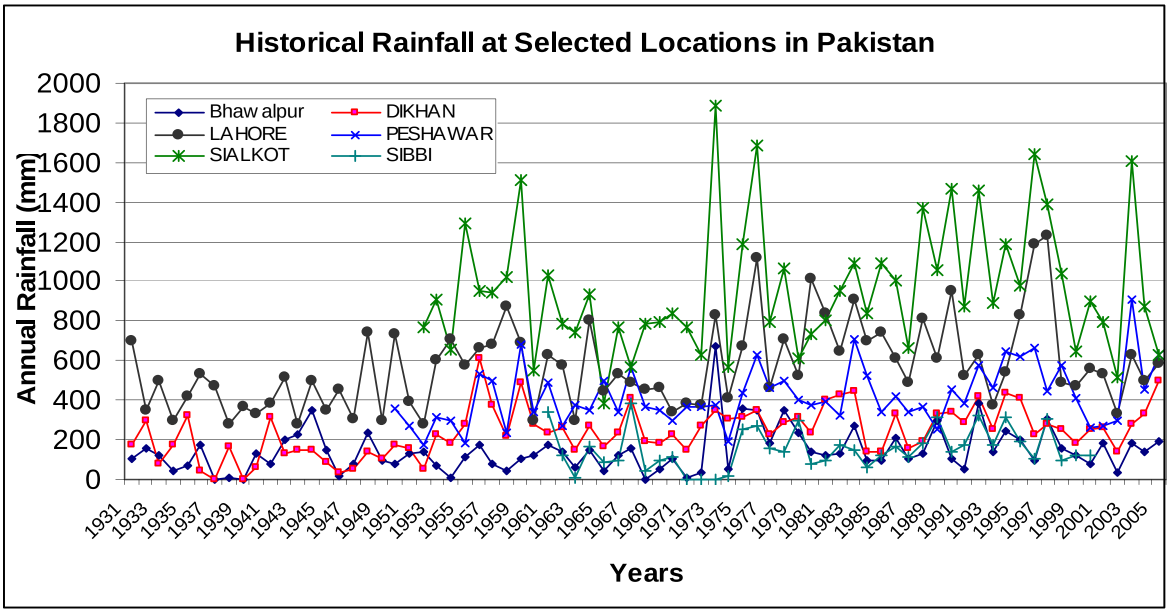

Figure 3: Historical rainfall at selected stations in Pakistan.

5. GROUNDWATER DEVELOPMENT

After the introduction of weir-controlled irrigation in 1871 (Ahmed 1993), the groundwater table started rising due to poor irrigation management, lack of drainage facilities and the resulting additional recharge from the canals, distributaries, minors, water courses and irrigation fields. On the other hand, the extensive use of groundwater for irrigation started with the installation of public tuewells in the 1960's, soon to be followed by the explosive development of tubewell installation by private farmers (some 700,000 at present and still growing at annual rate of 1-2%). The annual groundwater abstraction under the latest drought conditions (1999-2002) increased to about 55 MAF. Now a days, farmers are only left with the groundwater development choice for coping with any increased water demand due to increasing cropping intensity and other competing uses such as domestic and industrial as a result of population increase.

6. WATERLOGGING AND GROUNDWATER DEPLETION

Before the introduction of widespread irrigation, the groundwater table in the Indus Basin varied from about 40 feet in depth in Sindh and Bahawalpur areas to about 100 feet in Rechna Doab. On whole IBIS basis the area under three categories of depth to watertable i.e. 0-150 cm, 150-300 cm and more than 300 cm is compared on percentage basis for 1962-65, 1977-79 and 2002 and shown in Figure 4. According to the statistics 6, 16 and 0 % of the irrigated area was waterlogged in these three periods respectively. This show a general trend of groundwater being under stress of over development, surely there is also the impact of drought period as shown in Figure 1 and 2 depicting less river flows and canal diversions during the period. The lowering trend of water levels for individual observations is also shown in Figure 5, starting from 1990 to 2004 for Lower bari Doab canal indicating a watertable decline of 1 ft per year. This is actually the population pressure in terms of increased groundwater use for domestic, industrial and agricultural purposes. Particularly, the increased cropping intensity in agriculture sector is responsible for major depletion of groundwater mostly in fresh groundwater areas.

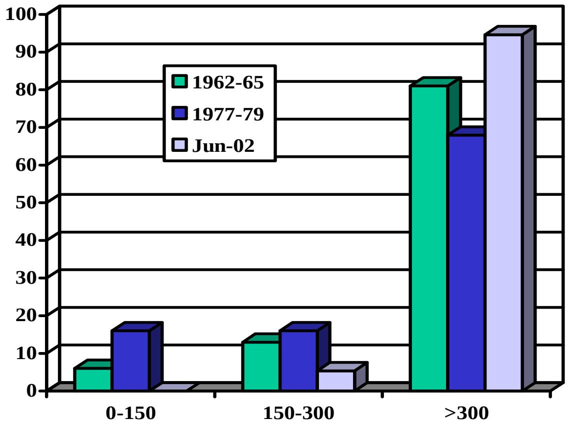

Figure 4: Historical comparison of depth to watertable in irrigated areas of Pakistan (%age area).

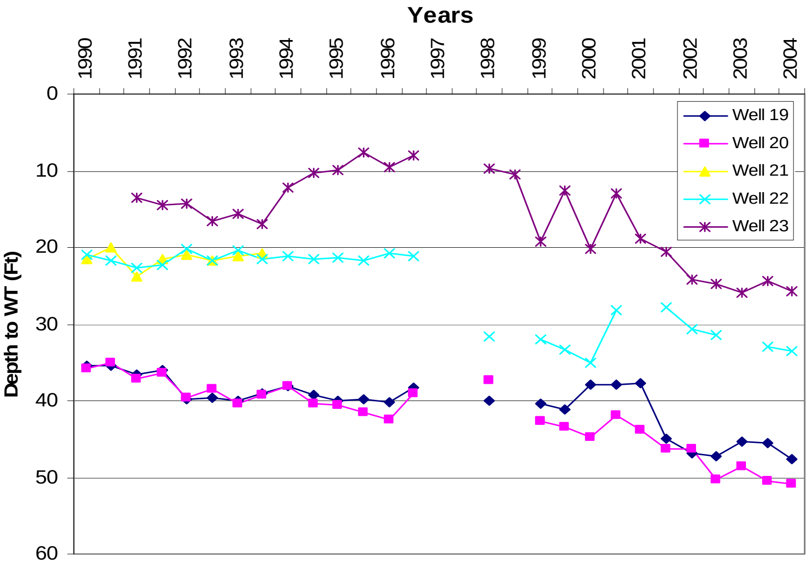

Figure 5: Falling trend of groundwater levels in Okara Zone of Lower bari Doab Canal 1990 to 2004.

7. GROUNDWATER QUALITY

Groundwater quality has the most important deciding factor in terms of its long term impact on its use and soil environment. So the groundwater quality has been looked into with historical perspective. Comparison of results of groundwater quality survey conducted during 1977-79 and 2001-02 shows the deterioration of the groundwater resources with passage of time as shown in Figure 6. Clearly the groundwater quality deterioration is proving that on aggregate salts are being accumulated in IBIS at quite an alarming rate. Once the areas that were fresh are now shifted to marginal and hazardous zones over a time span of 23 years only.

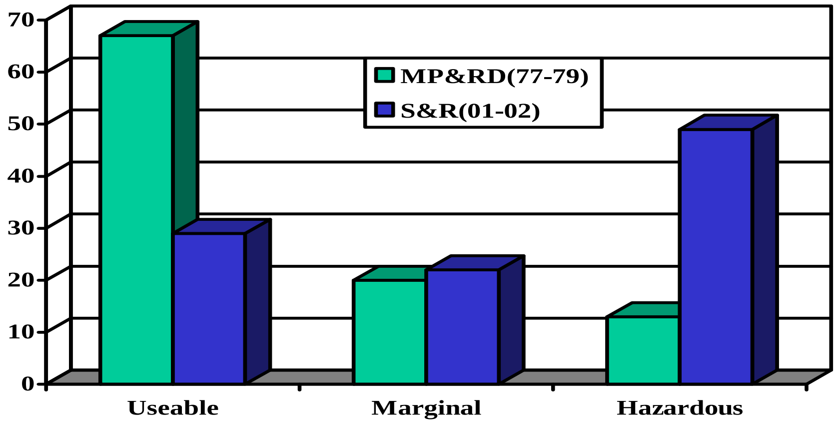

Figure 6: Comparison of groundwater quality 1977-79 and 2001-02 (%age area).

8. PROFILE AND SURFACE SALINITY:

During 2001 to 2002 a project named "Salinity Survey of the Irrigated areas of the Indus Basin" was taken up. Under this project 42 Million acres land of the Indus Basin has been surveyed and mapped with respect to profile salinity/sodicity, surface salinity and groundwater quality. The results when compared to similar surveys during previous times for profile salinity and sodicity shows that profile salinity situation is improving. The reason behind this is lowering of the groundwater levels thus providing proper drainage for leaching the salts from upper soil profile but at the same time polluting the shallow groundwater which is normally used for irrigating crops to supplement the canal supplies. The profile salinity for whole IBIS is compared on %age basis for three survey times as shown in Figure 7.

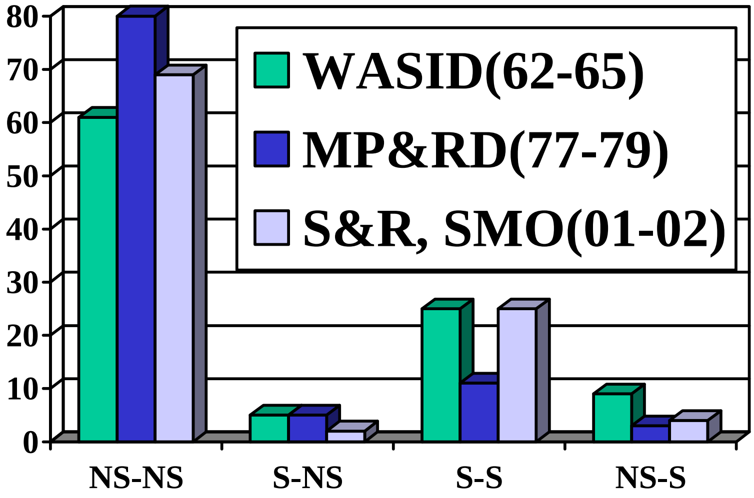

Figure 7: Profile salinity/sodicity during 1962-62, 1977-79 and 2001-02 (%age area).

The spatial distribution of surface salinity status based on 2001-03 survey is illustrated in Figure 8. The affected area and percentage of the area surveyed for each category are summarized in Table 3. Considering over all account of the Indus Basin Irrigation System, the comparison shows a remarkable improvement in S2 and S3 categories. The comparison of the present survey with that of 1979-81 survey indicates that salt affected area was 11% S2, 6% S3 and 8% S4, including 75% non saline. Where as in 2001-03 the non-saline area has increased to 77.5% and S2, S3 areas decreased to 9.5% and 4.7% respectively. There was also a nominal increase of 0.3% in strongly saline area. The results are compared in Figure 9. The province wise comparison reflects improvement in NWFP and Punjab, where as in Sindh and Balochistan there is increase in salt affected areas. Figure 8 and Table 6.1 show that most of surface salinity is in lower Indus part where the rainfall is only 100 to 200 mm.

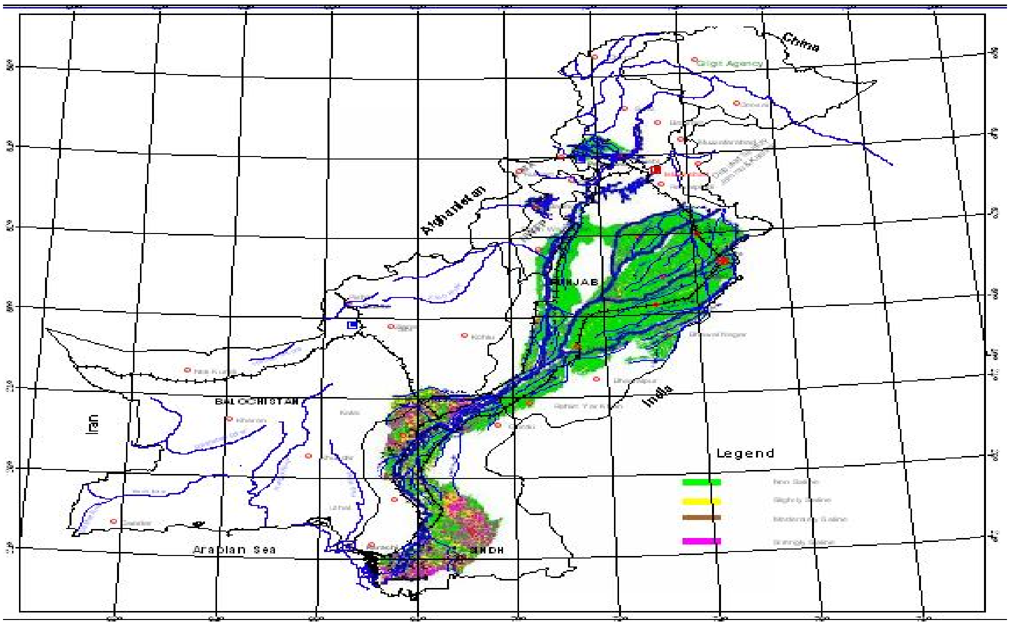

Figure 8: Surface Salinity Status of Pakistan 2001-03.

Table 6.1 Surface Salinity Status of Area Surveyed

AREA SURVEYED 1979-81(millions acre)					
Province	Non Saline (S1)	Slightly Saline (S2)	Moderately Saline (S3)	Strongly Saline (S4)	Total Area
NWFP	1.3	0.1	0.0	0.0	1.5
Punjab	21.5	1.8	1.1	0.7	25.1
Sindh Balochistan	8.0	2.7	1.5	2.5	14.7
Total	30.9 (74.8%)	4.6 (11.1%)	2.6 (6.3%)	3.3 (7.8%)	41.3
AREA SURVEYED 2001-03 (millions acre)					
NWFP	1.10	0.01	0.02	0.01	1.14
Punjab	24.18	0.95	0.46	0.40	25.99

Sindh Balochistan	7.32	3.04	1.49	3.08	14.94
Total	32.61 (77.5%)	4.00 (9.5%)	1.96 (4.6%)	3.49 (8.3%)	42.07

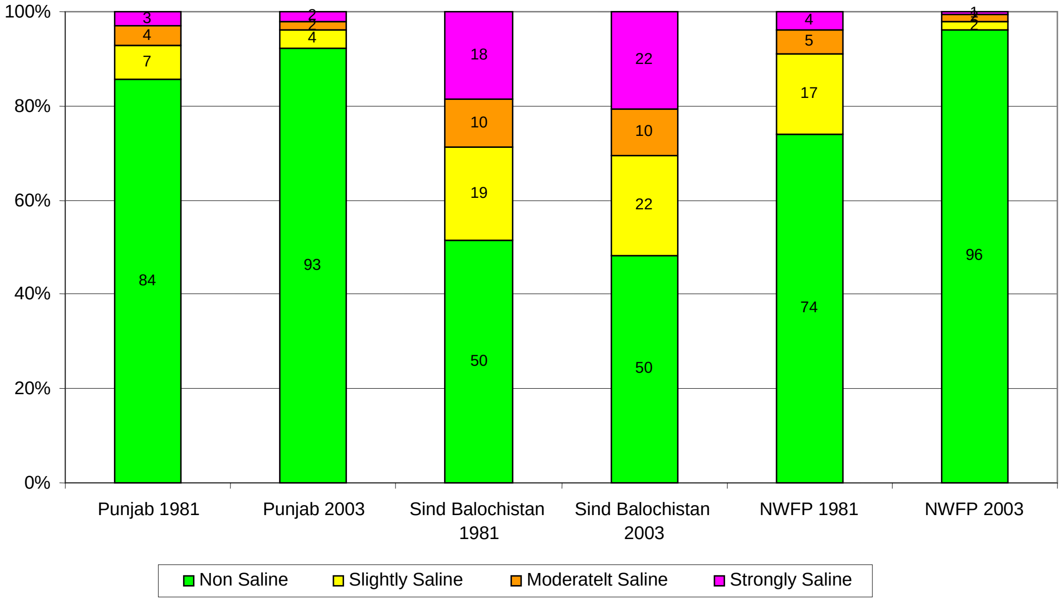

Figure 9: Comparison of Surface Salinity (survey 1979-81 and 2001-03).

9. GROUNDWATER MANAGEMENT

Groundwater use in the Indus basin has more or less reached the upper limit and there is very little potential for a further increase. On the other hand groundwater reservoir in the country has provided a reliable cushion particularly during the drought period (1999 to 2002). On an average Post Tarbela Dam canal diversions have been 104 MAF, while during the drought period (1999 to 2002) the average canal diversion were 89.4 MAF. Counting conveyance system losses to be 50%, the canal water at farm head during drought period was 44.7 MAF which is very less than the estimated annual average groundwater pumping of 55 MAF. However this groundwater pumping during drought period would have been increased to the same tune as there has been decrease in canal water diversions, because the farmers have surely responded to short canal supplies in the from of high groundwater pumping for irrigating there crops.

10. CONCLUSIONS

From the above discussion it is conclude that;

- Groundwater resources in Pakistan has been a reliable source for meeting crop water demand and has provided some degree of sustainability to crop production, otherwise in absence of groundwater storage the water stress could have resulted a very huge decline in crop production.

- More dependence of agriculture upon groundwater has caused deterioration of groundwater quality. Areas having saline groundwater have been spreading the Doabs
- Groundwater is under stress both in the from of quantity and quality due to its over exploitation as compared to recharge which mostly takes place from seepage losses in the conveyance system and during field irrigation by farmers.
- Clearly the groundwater quality deterioration shows that on aggregate salts are accumulating in IBIS at quite alarming rate. So there is need to shift from short term to strategic planning particularly for the groundwater resources of the country which cater for about 50 to 60 % of crop water requirements in IBIS.

11. RECOMMENDATIONS

- ➢ In the past, groundwater has got attention in terms of investigations and monitoring only and that too on project basis at certain times. These groundwater monitoring organizations are using very conventional methods of measurement and analysis of the information. There is no systematic procedure and protocol to acquire and disseminate and process the data such as GIS technology. It is therefore recommended that the monitoring organizations be equipped with up to date knowledge and equipment along with responsibility of future planning and research.
- ➢ There has been wastage of excess water to Sea during wet years. still there is potential of 24.84 MAF on an annual average to be effectively controlled through multi-purpose storages. Part of this can also be utilized if proper planning and infrastructure exists to spread this water in areas such as forests and barren lands. Proper sites can be developed in each canal command for spreading canal water during wet years for groundwater recharge.
- ➢ New and emerging uses of groundwater e.g. small water supply schemes along fresh water resources such as rivers and canals will have substantial impact in future on already under stress groundwater areas particularly with respect to quality deterioration of the resource with passage of time.
- ➢ There is high risk of inland saline intrusion due to increased and unplanned pumping of groundwater, therefore detailed groundwater investigation and quantification using modeling techniques needs to be carried out so as to avoid this irreversible phenomenon of like polluting the fresh groundwater.

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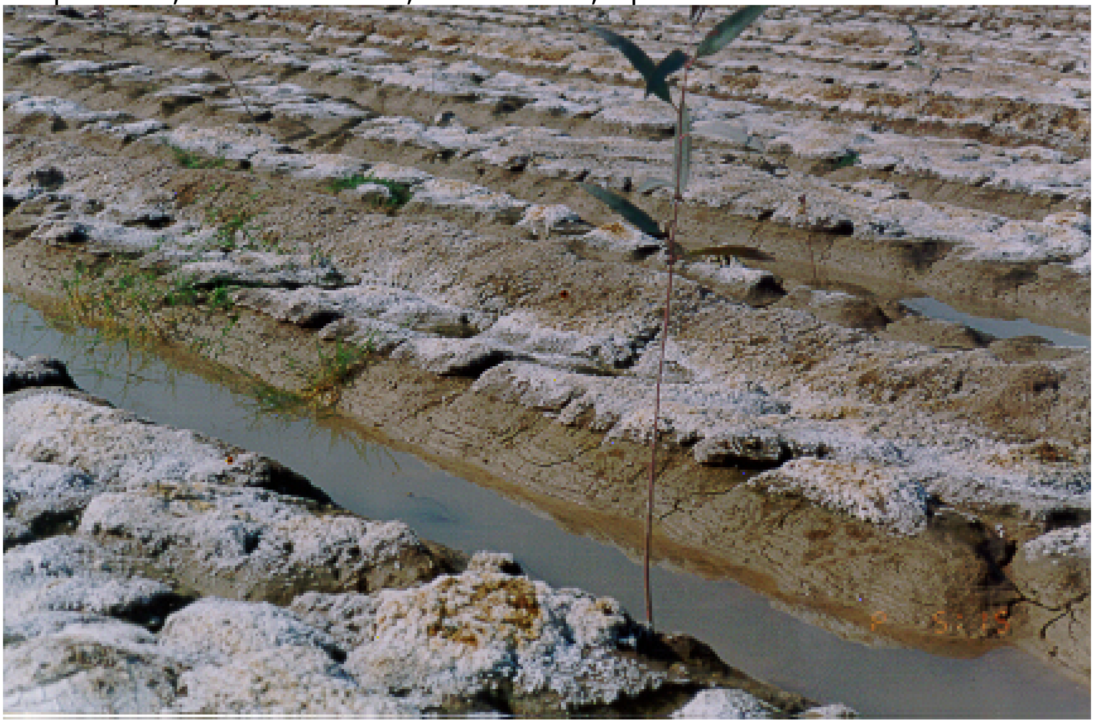


Soil Salinity due to use of hazardous quality groundwater.

3.7 Management of coastal surface waters subject to sea water intrusion

Abstract

Coastal surface water bodies hydraulically linked to the ocean are subject to seawater intrusion at varying levels. Development work in surrounding areas as well as, sedimentation changes the delicate balance required to maintain same levels of seawater intrusion. Here the Negombo lagoon is taken as a case study and investigated to identify a management strategy for the sustainence and maintenance of the delicate balance so that the optimum amount of seawater intrusion could occur. Here various dredging scenarios have been investigated and the optimum solution developed.

1. Introduction

The Negombo, Lagoon in the western coast of Sri Lanka is a coastal surface water body which maintains a delicate balance of seawater intrusion. Development in surrounding areas and sedimentation over time disturbs the natural balance causing changes to level of seawater intrusion resulting in changes to the aquatic and water quality of the water body which impacts lively hood of the area. As measure of reconvening the original salinity intrusion balance and managing the water body dredging the lagoon has been investigated.

Here by means of improving the circulation in the lagoon to minimize further siltation and to achieve favourable conditions to sustain the rich biodiversity dredging scenarios have been investigated.

2. The Study area – Negombo lagoon and its environs

The Negombo lagoon is a shallow coastal body of water located on the west coast of Sri Lanka (7^0 10' N and 79^0 50' E). It forms an integral part of the Muthurajawela marsh - Negombo lagoon coastal wetland, 6230 ha in extent (**Figure 1**). The lagoon is approximately 12.5 km in length and its width varies from 0.6 to 3.6 km (**Figure 2**). Its mean depth is estimated to be approximately 0.65 m and the surface area to be 35 km^2, thus placing its volume to be of the order of 22.5 million m^3. One of the unique features of the lagoon is that its transition to the sea consists of several narrow channels. The total cross-sectional area of the inlet channels is estimated to be 250 m^2 with a length of 2.5 km. This area of transition also serves as a principal anchorage for a large fleet of fishing vessels of different types.

The exchange of water in the lagoon is influenced by the tides from the ocean side and fresh water supply from the inland side. The tide is semi-diurnal and the tidal range in the lagoon varies in the order of 0.07m at neaps to 0.2m at springs, these values being about one third of tide at sea. Thus the volume of water stored and released varies between 1.5 million m^3 and 7 million m^3 per tide. Fresh water enters from the southern end of the lagoon through Dandugam Oya, Ja Ela and several streams from the Muthurajawela marsh. The supply of fresh water varies from virtually zero during the dry seasons to more than 100 cumecs during the rainy seasons. The lagoon and the entire wetland are separated from the sea by a narrow stretch of land consisting of fragile coastal dune system situated on beach rock formed during sea level changes over geological periods of time. The coastal conservation of this dune system plays a vital role in the long term stability of the lagoon.

The Negombo lagoon and its coastal environment has had a long association with tourism and the fishery industry. One of Sri Lanka's leading beach resorts is located north of the Negombo lagoon inlet. The lagoon inlet serves as a principal coastal fishery anchorage for a fleet of fishing vessels and the lagoon estuarine fishery supports at least 3000 families from around 25 villages dispersed at the perimeter of the lagoon. Haphazard expansion of piers and landing points have contributed towards alterations in the flow patterns leading to sedimentation in the channel segments thereby affecting the control of flow into and out of the lagoon. Large quantities of solid and liquid waste are dumped at various locations in the lagoon resulting in pollution problems. This has resulted in the loss of vital functional parts of the eco-system including the flow channels and nursery areas. The principal challenge is the restriction of mechanical dredging to minimize the influence of turbidity and the preservation of the mangroves on the edges of the lagoon.

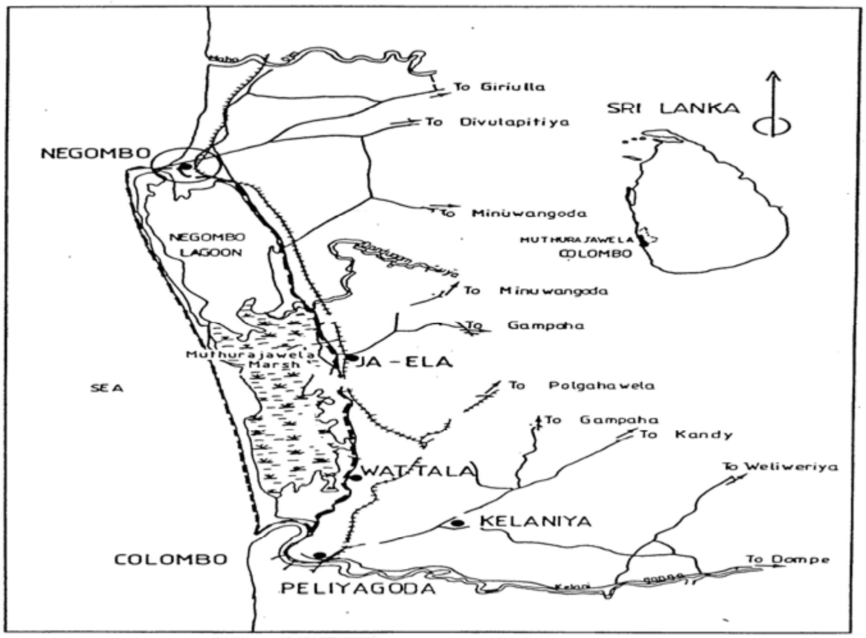


Figure 1 : Muthurajawela Marsh - Negombo Lagoon

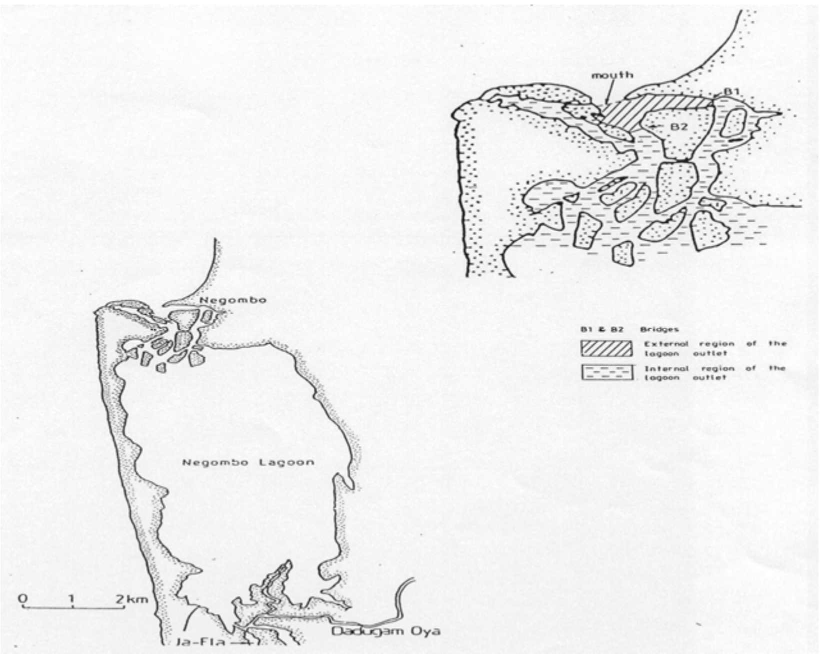


Figure 2 : Negombo Lagoon

It is evident that unplanned development along the waterfront, reduction of tidal flow, siltation and pollution are major problems affecting the Negombo Lagoon. These have contributed to the overall degradation of the aquatic environment at the tidal inlet and within the lagoon. If this siltation continues it will in the long-term, adversely affect the lagoon environment, in particular, its biodiversity.

3. Study methodology

Planning and implementing engineering interventions at the Negombo lagoon inlet and assessing its impact on the environment require as detailed an understanding as possible of the system to be managed. A review of natural conditions and human/development activities identified some of the problems, which affect the lagoon environment. It was clear that siltation of the lagoon and its inlet was a major issue, linked to most problem areas. In this context it was evident that the method of approach adopted should identify the lagoon inlet as an integral part of the aquatic system consisting of the main body of the lagoon on one side and the ocean on the other side. It is important to note that the entire tidal exchange between the ocean and the lagoon is restricted to flow beneath the two bridges at the inlet. The region between the bridges and the mouth is used extensively by fishing vessels and waves from the ocean propagate into this area.

The investigative strategy requires both qualitative and quantitative information leading to a clear understanding of natural changes of inlet stability. It also requires methods of predicting the manner in which the hydraulic behaviour would respond to changes introduced by proposed engineering interventions. The priority need is to assess the likely impact or efficiency of the proposed interventions so that different options can be evaluated objectively one against the other. In order to achieve this objective it is necessary to be able to simulate existing conditions within the system of interest and to predict, in quantitative terms, within acceptable levels of accuracy, the consequences of such interventions. In this context it is recommended to apply reliable mathematical models which is a powerful technique capable of integrating, by means of mathematical equations, the many diverse processes involved in the functioning of aquatic systems, thereby simulating such systems and predicting quantitatively the effects of changes in these systems.

The hydraulic behaviour of a tidal inlet can be investigated in three stages. In the first stage an initial but sufficiently detailed assessment of the physical processes occurring at the inlet can be made by studying existing information.
This includes,
1) Historical information and data from different investigations carried out in the study area. These include information on previous schemes in the area and their impact on neighbouring regions.
2) Results of semi-quantitative conceptual models and preliminary modelling studies that rely on an understanding of the varying processes in the natural systems that affect the hydraulic regime.
3) Using results from case studies of similar situations from which likely impact of change can be inferred.

In the second stage attention is focused on planning and implementing field investigations to strengthen the existing information / data bank. The depth of these investigations will depend entirely on the outcome of the first stage. A preliminary analysis of data indicates that although a large data bank exists for the Negombo Lagoon, most of the data have not been collected from a viewpoint of engineering studies and hence the same cannot be used directly for computations associated with the hydraulic behaviour for the inlet. The principal shortcomings of the data from an engineering viewpoint are the limited frequency of collection (sampling frequency), the limitations with respect to the points at which the data has been collected (spread of data points) and the absence of an interconnected grid for the sampling points. Sampling points at the bed have only been identified on plan and not related to the bathymetry. In order to study the hydrodynamic processes associated with sedimentation it is necessary to collect specific data at pre determined sampling frequencies over a particular time interval (for example spring tidal cycle).

In the third stage detailed mathematical modeling is implemented. Once the existing physical processes are fully understood and modeled, engineering interventions for improving the environment can be formulated. The intervention should then be modeled to determine their efficiency and the input on the hydraulic regime. Such studies could be used to assess the impact of intervention on the aquatic and neighboring environment.

The terms of reference has restricted the interventions to optimum dredging with the minimum environmental impact, to be carried out in the channel network within the outlet. In this context the approach adopted for the study comprises investigating a range of options with respect to dredging giving due consideration to the depth of dredging, improved efficiency in circulation and environmental issues.

4. Field investigation

Extensive field investigations which were carried out comprises two components namely field surveys and deployment of data recording equipment at identified locations along the lagoon water body. Tables 1 and 2 summarize the two components. Most recording equipment were deployed beyond the minimum required period. This enabled each of the parameters to be determined under varying combinations of the boundary conditions. Some instruments were in place for a long time so that the acquired data bear more meaning in the subsequent applications in the study. Such data banks provide a wider understanding of critical parameters and could be related to the long-term behaviour of the lagoon.

Table 1 : Summary of Field Survey Activities

Horizontal and Vertical Control Surveys
Topographic Survey of the lagoon periphery including islands/ shoals
Bathymetric Survey
Drogue Studies
Bed Sediment Sampling
Core Sediment Sampling
Flow, Salinity, Suspended Sediment measurements in the entrance channels
Discharge measurements in Dandugam Oya

Table 2 : Summary of Deployment of Recording Equipment

WTG-Water Level Gauge (at lagoon entrance)
WTG- Water Level Gauge (in the main water body of the lagoon)
Salinity Meter (at the lagoon entrance)
Salinity Meter (at the lagoon southern end)
Current Meter with Salinity Sensor (at the westward lagoon channel)
Current Meter with Salinity Sensor (at the lagoon main water body)
Anemometer (wind measurements)
Tide gauge (at the southern end of the lagoon)

5. Numerical modeling

Objectives of numerical modeling investigations were,

1. To evaluate the existing circulation pattern and associated salinity levels at various stages of the flow
2. To predict the circulation pattern and salinity levels for different dredging scenarios.
3. To extract following information
    Volume of water exchange and variation of current
    Residence time of water at selected areas
    Variation of water depth at typical and extreme spring and neap tides
    Projected movement of fresh water and silt after rainfall events and in dry season etc.

4. To assess the variation of water level due to influence of fresh water flow and flooding.

To address the above issues, the following basic models of the MIKE21 Modelling System will be used.

One dimensional Hydrodynamic (HD) model

Two-dimensional Hydrodynamic (HD) model with other modules such as Sediment Transport (ST) and Advection Dispersion (AD).

A two dimensional hydrodynamic (HD) model of the lagoon and entrance channels formed the basis of the most important modelling activity. An advection-dispersion (AD) model and a sediment transport (ST) model were built on top of the HD model to investigate the transport of salinity and sediment.

5.1 Model Description

MIKE 21 HD is the hydrodynamic module within the MIKE 21 modelling system and is used for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady, two-dimensional flows in one-layer (vertically homogeneous) fluids and has been applied in a large number of studies. MIKE 21 HD is based on the numerical solution of full non-linear equations of conservation of mass and momentum integrated over the vertical to describe flow and water level variations. MIKE 21 HD makes use of a so-called "Alternating Direction Implicit (ADI)" technique to integrate the equations for mass and momentum conservation in the space-time domain.

MIKE 21 ST is the sediment transport module for the assessment of the sediment transport rates and related initial rates of bed level changes of non-cohesive sediment (sand) due to currents or combined wave-current flow. MIKE 21 ST calculates sediment transport rates on a rectangular grid covering the area of interest on the basis of the hydrodynamic data obtained from a simulation with MIKE 21 HD together with information about the characteristics of the bed material. MIKE 21 AD simulates the spreading of a dissolved or suspended substance in an aquatic environment under the influence of the fluid transport and associated natural dispersion processes. The substance may be a pollutant, which may be treated as conservative or subject to linear decay: salt, heat and dissolved/suspended contaminants. Similarly to the HD module, the concentration of the substance is calculated in each point of a rectangular grid covering the area of interest.

5.2 Boundary Conditions for Hydrodynamic Modelling

Different types of boundary conditions applied in hydrodynamic modelling are described below. The wind velocity, tidal flows and river discharges were used to force the hydrodynamic model. Full scale measurements programme was carried out to obtain the information for model forcing and for model calibration. Figure 3 gives the deployment locations of the instruments.

5.2.1 Tidal Boundary conditions

Accurate definition of the open sea tidal constituents at model boundaries is essential for the verification of the tidal propagation pattern in the area of interest. The constituents adopted in the present study were extracted from a previous performed tidal hydrodynamic study in which the already established open sea tidal constituents were further refined. The established tidal constituents for the northern and southern boundaries of the Regional Model are listed in Table 3.

Table 3: **Derived Tidal Constituents for the Northern and Southern Boundaries of the Regional Model.**

Model Boundary	Derived Amplitudes of Tidal Constituents (m)				Derived Phase of Tidal Constituents (deg.)			
	M2	S2	K1	O1	M2	S2	K1	O1
North-Kalpitiya	0.175	0.12	0.085	0.03	53	118	65	55
South- Galle	0.16	0.11	0.05	0.02	51	95	20	72

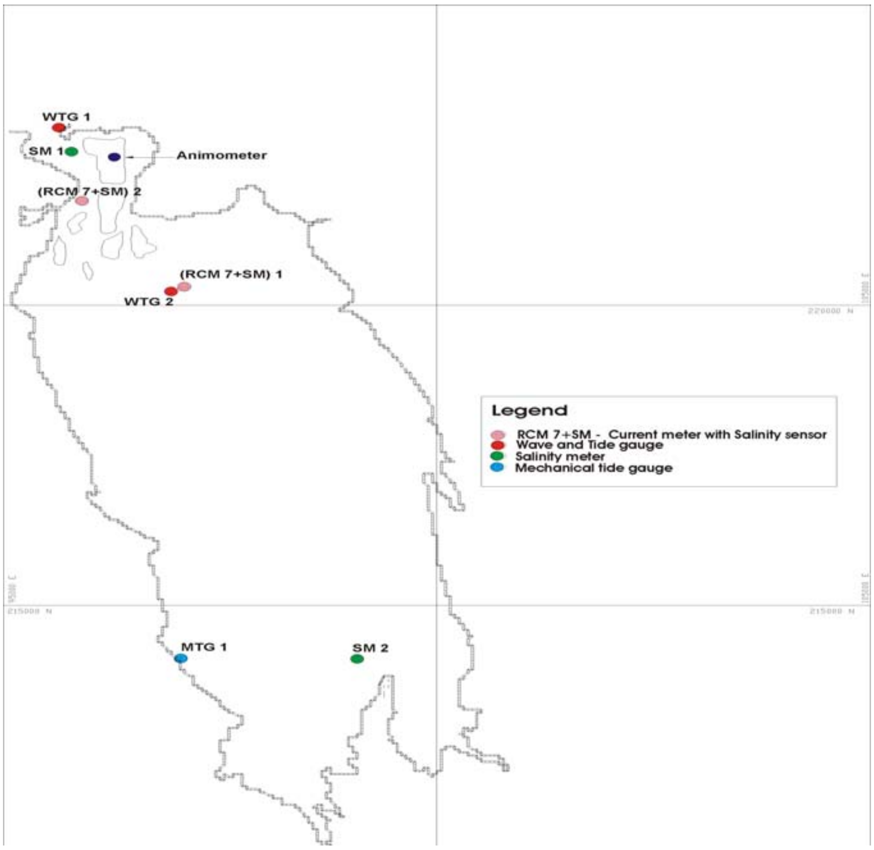
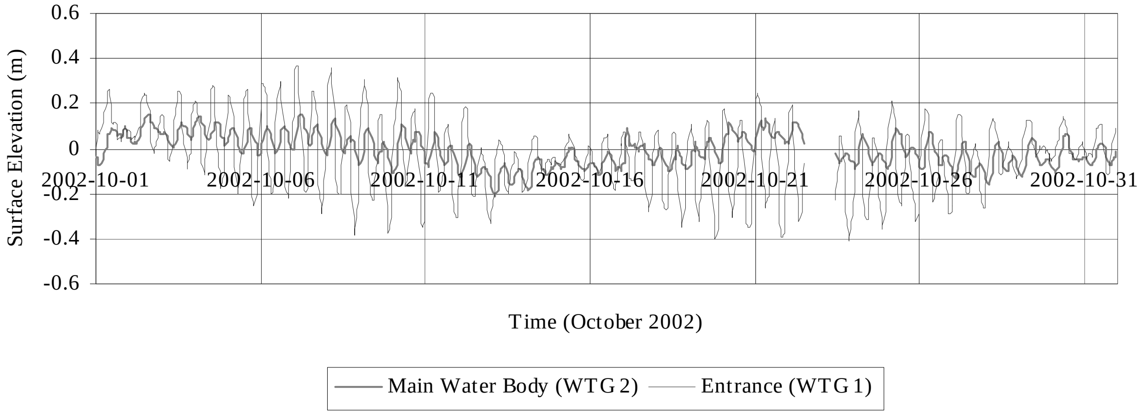


Figure 3 : Deployment locations of the instruments

The tidal constituents used in the study were calibrated with the measured surface elevations at the lagoon entrance(Location –WTG1). The measured surface elevations at the entrance (WTG1) together with a location just inside the lagoon mouth (WTG2) is given in figure 4.

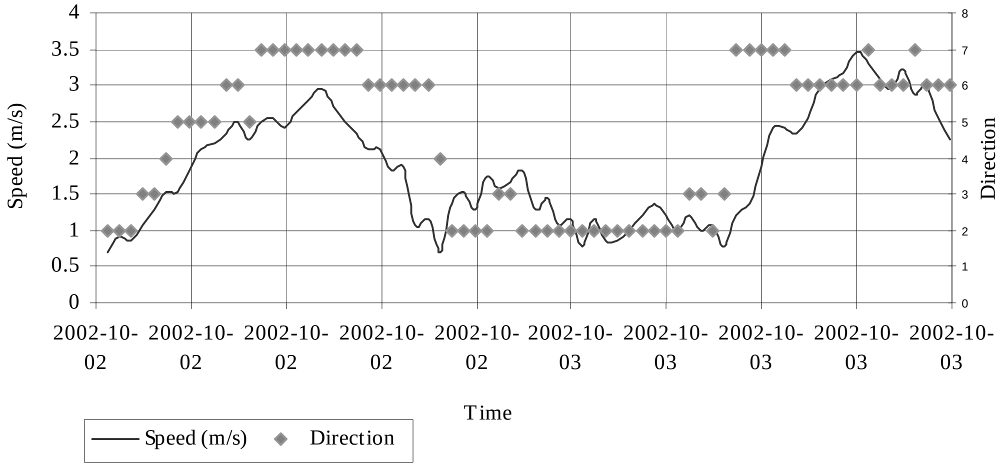
Figure 4 : Measured surface elevation at the lagoon entrance (WTG1) and lagoon main water body (WTG2)



5.2.2 Wind Boundary conditions

Wind measurements were carried out in one of the lagoon islands as indicated in figure 3. In all computations time varying wind field was used, however wind was assumed to be uniform in space. Figure 5 gives a typical measurement of wind speed and direction. Simplified wind fields were developed using this information for model forcing. Direction sector 1: 0-45^0, 2: 45-90^0, ………….7: 270-315^0 and 8: 315-360^0.

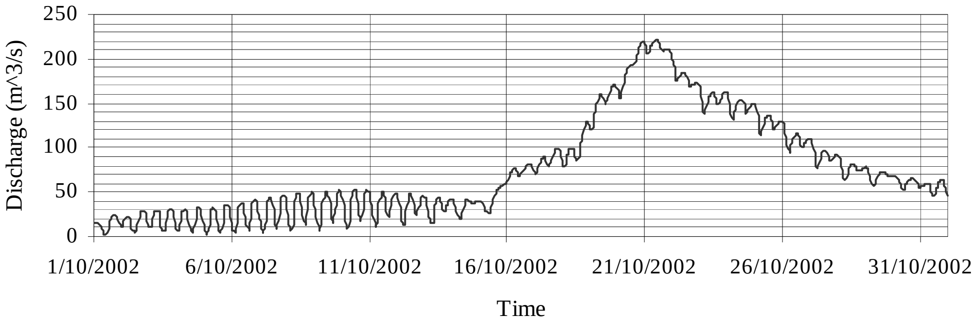
Figure 5 : Measured wind speed and direction at the lagoon entrance



5.2.3 River Discharge

Cumulative discharge from Dandugam Oya, Ja-ela and Hamilton Canal was used as a single point source for model forcing. This information was available from the JICA Master Plan Study of Storm Water Drainage in Colombo Metropolitan Area. Figure 6 gives the predicted fresh water inflow into the lagoon during the month of October, 2002.

Figure 6: Predicted cumulative discharge from Dandugam oya, Ja-eala and Hamilton canal



6. Results from modeling study

6.1. Lagoon entrance channels

Average depth of the channels vary from about 0.5 m to 3.5 m. The length of the lagoon entrance channels is about 2.4 km and the cross sectional area varies from 500-650 m^2. Figure 7 gives the lagoon entrance channels showing the channel sections selected for model outputs. These model outputs are for the same period selected for model calibration.

Figure 8 gives the plan view of the entrance channels showing maximum flood discharges for the existing condition. It can be seen from the figure that there are three dominant flow paths (3-6-11, 3-5 and 3-14-9-12) which carry almost 90% of the flow.

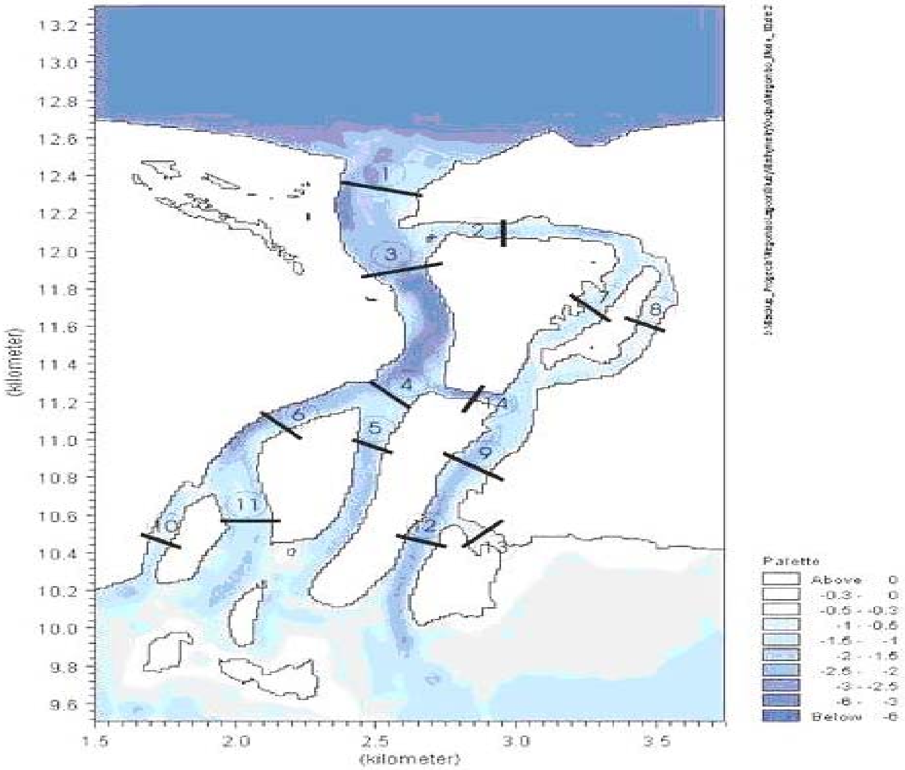


Figure 7 : Lagoon inlet showing the selected channel sections for model studies

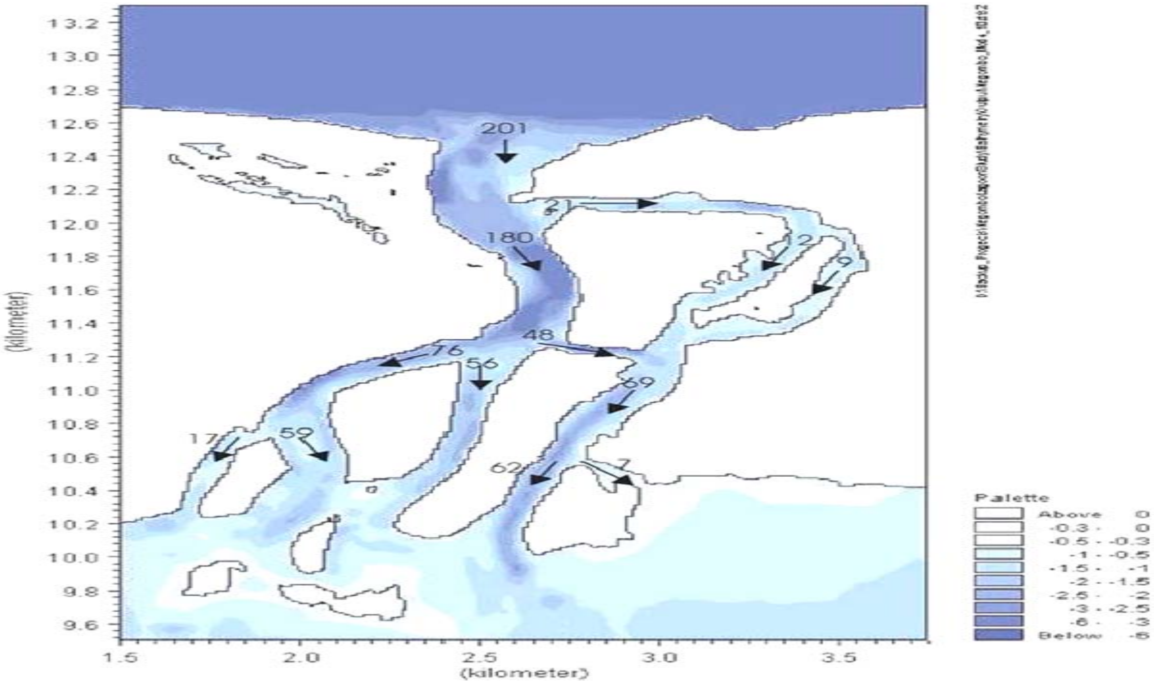


Figure 8: Maximum flood discharges (m^3/s) for existing condition

7.2 Dredging Scenarios

The inlet of the Negombo lagoon and the lagoon itself is subjected to sedimentation. As a result the water exchange between the sea and the lagoon has decreased, which is harmful for fresh-salt eco-system of the lagoon. The objective of the present study is to improve the circulation in the lagoon so that further siltation of the lagoon can be minimized and the water quality can be improved.

In the present study, 8 options were considered. Water exchange and the long-term sedimentation are considered as the most important criteria in the selection of the most feasible option. Stake net fishing in the lagoon entrance channels and other types of lagoon fishing and also the other user effects are given due consideration. Water circulation can be improved through the increase in the dredging quantity, which in turn will increase the cost involved.

Option 1

In this option channels 2 and 7 are dredged up to a depth of 1.5 m. There is a 33% increase of discharge in channel 2 and 92% increase in discharge in channel 7. Discharge through channel 8 has reduced by 44% and through the main channel 3 by about 3%. This option involves a total dredging volume of 60,000 m^3 and the total increase of discharge through the entrance channel system is only by 1%.

Option 2

In this option channels 2 and 7 are dredged up to a depth of 2.5 m. There is a 100% increase of discharge in channel 2 and 217% increase in discharge in channel 7. Discharge through channel 8 has reduced by 56% and through the main channel 3 by about 7%. This option involves a total dredging volume of 220,000 m^3 and the total increase of discharge through the entrance channel system is by 4%.

Option 3

In this option channels 2,7,9 and 12 are dredged up to a depth of 2.5 m. There is a 152% increase of discharge in channel 2 and 292% increase in discharge in channel 7. Channels 9 and 12 experiences an increase in discharge of 45% and 50% respectively. Discharge through channel 8 has reduced by 33% and there is only a minor effect to main channel 3. This option involves a total dredging volume of 350,000 m^3 and the total increase of discharge through the entrance channel system is by 14%.

Option 4

In this option channels 2,7,9,12 and 13 are dredged up to a depth of 2.5 m. There is a 176% increase of discharge in channel 2 and 333% increase in discharge in channel 7. Channels 9 experiences an increase in discharge of 62% and there is no significant change of flow in channel 12. Discharge through channel 8 has reduced by 33% and there is only a minor effect to main channel 3. This option involves a total dredging volume of 540,000 m^3 and the total increase of discharge through the entrance channel system is by 19%.

Option 5

In this option channels 6 and 11 are dredged up to a depth of 2.5 m. There is a 45% increase of discharge in channel 6 and 69% increase in discharge in channel 11. Discharge through the other 2 western channel segments 5 and 10 reduces by 11% and 41% respectively. There is a varying percentage reduction 5%-29%, through the eastern channel system and also reduction in flow through the cross channel 14 towards the eastern channel system. This option involves a total dredging volume of 315,000 m^3 and the total increase of discharge through the entrance channel system is by 9%.

Option 6

In this option both eastern and western channels are dredged up to a depth of 2.5 m. There is a 181% and 333% increase of discharge through two northeastern channels 2 and 7. Southeastern channel, number 9, provides an increase of 59% and there is no significant change in channel number 12. Channel 13, which provides water to the northeastern part of the lagoon water body, provides an increase of discharge from 7 to 47 m^3/s, a 571% increase. In the western channel segment, main channels 3 and 4 gives and percentage increase of 17 and 21 and the branches 6 and 11 provide a percentage increase of 45 and 66. Channels which are not subjected to dredging indicate decreases in discharge. This option involves a total dredging volume of 900,000 m^3 and the total increase of discharge through the entrance channel system is by 34%.

Option 7

In this option both eastern and western channels are dredged up to a depth of 2.5 m and channel 12 was blocked to obtain a higher discharge through channel 13 in view of getting more water to the presently stagnant northeastern part of the lagoon main water body. Discharge through the channel 13 has increased from 7 to 78 m^3/s, a 1014% increase but the total increase of discharge through the entrance channel system has dropped to 25% from 34% (option 6).

Table 4 gives the summary of maximum flood discharges for the existing condition and different dredging scenarios and table 5 gives the percentage increase/decrease of discharge as a result of dredging. Positive values indicate the percentage increase whereas negative values indicate the percentage decrease in discharge. Existing condition is denoted by 0.

	Dredging Scenario								
	Channel Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Main entrance channel	**1**	201	203	210	230	240	220	270	252
Western channel segments	**3**	180	175	168	177	182	200	211	202
	4	132	128	130	130	128	160	160	171
	5	56	52	54	54	53	50	50	55
	6	76	76	76	76	75	110	110	116
	10	17	17	18	17	18	10	12	12
	11	59	59	58	59	57	100	98	104

Eastern channel segments	**2**	21	28	42	53	58	20	59	50
	7	12	23	38	47	52	11	52	45
	8	9	5	4	6	6	9	7	5
	9	69	75	80	100	112	60	110	81
	12	62	67	73	93	64	55	63	3
	13	7	8	7	7	48	5	47	78
	14	48	47	38	47	54	40	51	31

Table 4: Maximum flood discharges (m^3/s) for different dredging scenarios

	Dredging Scenario								
	Channel Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Main entrance channel	**1**	-	1	4	14	19	9	34	25
Western channel segments	**3**	-	-3	-7	-2	1	11	17	12
	4	-	-3	-2	-2	-3	21	21	30
	5	-	-7	-4	-4	-5	-11	-11	-2
	6	-	0	0	0	-1	45	45	53
	10	-	0	6	0	6	-41	-29	-29
	11	-	0	-2	0	-3	69	66	76
Eastern channel segments	**2**	-	33	100	152	176	-5	181	138
	7	-	92	217	292	333	-8	333	275
	8	-	-44	-56	-33	-33	0	-22	-44
	9	-	9	16	45	62	-13	59	17
	12	-	8	18	50	3	-11	2	-95
	13	-	14	0	0	586	-29	571	1014
	14	-	-2	-21	-2	13	-17	6	-35

Table 5: Percentage (%) increase/decrease in flood discharge for different dredging scenarios.

8 Summary and conclusion

Comparison of Option-6 and the Existing Condition

The alternative proposals for dredging have been proposed for the management of the lagoon. It could be seen that option 6 yields the best results.

Figure 9 gives the variation of surface elevation at Point 4 for the dredging option 6 and for the existing condition. All other selected points inside the lagoon also showed similar variations in the surface elevations. It can be seen from the figure that there is about 45-60% increase in tidal range in the lagoon water body. Existing condition gives a time lag of 4 hours and as a result of dredging time lag reduces up to about 2.5 hours, which contributes to the increase in tidal range mentioned above. An increase in tidal range is apparent at points 2 and 3 as well. A clear reduction of time lag cannot be seen, as these points are located very close to the lagoon mouth. An increase in longitudinal component of velocity by about 65-75% and a reduction in the transverse component can be seen at point 4.

Points 4A, 5, 5A, 6, 6A, 7 and 7A experiences a 25-50% percentage increase in longitudinal velocity whereas no significant increase in transverse velocity can be seen. It has to be noted here that even though the percentage increase in velocity is high, magnitude of these velocities are very small.

Figure 10 gives the comparison of longitudinal velocities at points 5 and 5A, before and after dredging. It can be seen from the figure that the longitudinal velocity increases both at points 5 and 5A as a result of dredging. The percentage increase in velocity at point 5 is 40% and in point 5A it is 75%. Higher percentage increase at the eastern side of the lagoon body can be seen as a result of dredging the channel 13, which supplies water to this area. It is also clear from the figure that the circulation in the eastern side of the lagoon will improve up to the present conditions in the western side.

Table 6 gives the cross sectional area, maximum flood flow discharge and maximum flood velocity for the existing condition and option 6. Table also gives the percentage increase /decrease in discharge and velocity as a result of dredging. It is clear from the table that there is a percentage increase in discharge in all channels except 5, 8 and 10, which are not subjected to dredging. Increase sedimentation in these channels could be expected as a result of the decrease in velocity. Dredging of these channels would not contribute greatly for the increase in total volume exchange but will be included in the dredging programme due to the stakeholder requirements. Channels 11 and 12 experiences increase in discharge and a decrease in velocity as a result of dredging. This small reduction in velocity could not expect to give any adverse effects in relation to sedimentation. There is a 18% reduction of velocity in main entrance channel but the magnitude of predicted velocity is still high enough to prevent increase in sedimentation. Figure 11 gives the cumulative exchange of water into and out of the lagoon. Flow into the lagoon is taken as positive. There is a 25-50% increase in volume exchange into and out of the lagoon.

Figure 9: Variation of surface elevation at Point 4

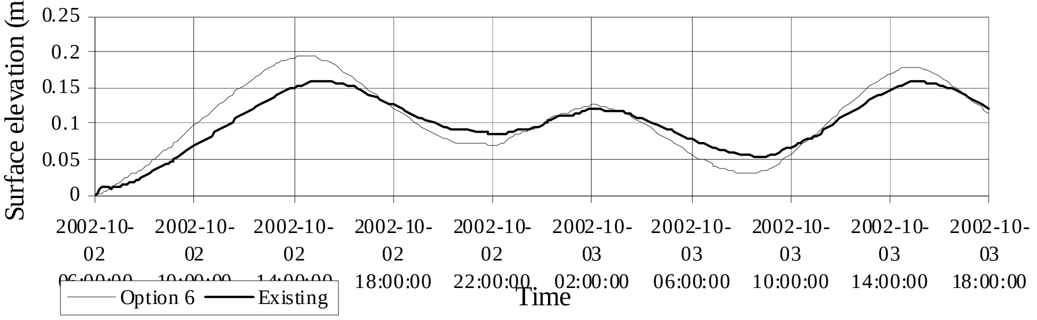


Figure 10 : Comparison of longitudinal velocities at Point 5 and 5A

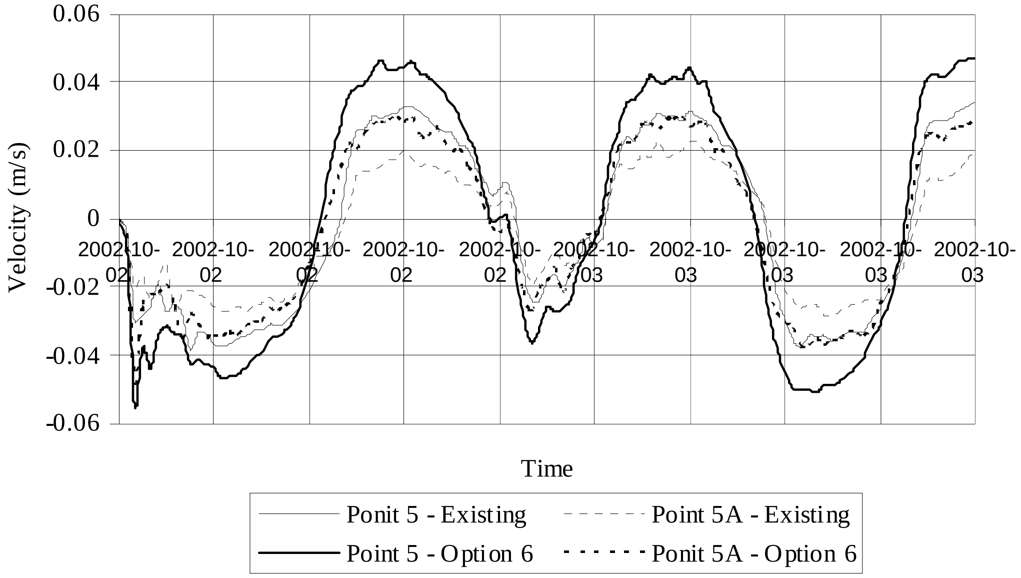
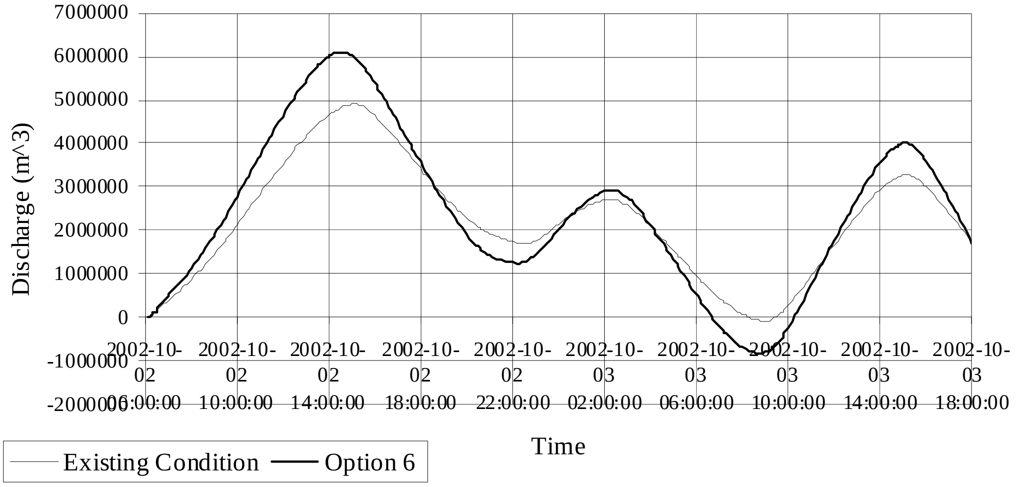


Figure 11: Comparison of Cummulative exchange of water into and out of the lagoon



Figures 12, 13 and 14 give the velocity vector plots of the lagoon, lagoon entrance channels and lagoon main water body at the maximum flood velocity. It has to be noted here that all surface elevation and velocity variations discussed, corresponds to selected early spring period together with a minimum fresh water inflow into the lagoon. A spring period will provide higher surface elevation variations together with increase velocities whereas a neap period will provide smaller surface elevation variations together with smaller velocities.

	Channel Number	**Existing Condition**			**Option 6**				
		Cross section	Discharge (m^3/s)	Velocity (m/s)	Cross section	Discharge (m^3/s)	% increase in discharge	Velocity (m/s)	% increase in velocity
Main entrance channel	**1**	517	201	0.39	821	270	34	0.33	*-18*
Western channel segments	**3**	474	180	0.38	434	211	17	0.49	29
	4	349	132	0.38	349	160	21	0.46	21
	5	188	56	0.30	188	50	*-11*	0.27	*-10*
	6	228	76	0.33	254	110	45	0.43	30
	10	77	17	0.22	77	12	*-29*	0.16	*-27*
	11	228	59	0.26	392	98	66	0.25	*-4*
Eastern channel segments	**2**	82	21	0.26	133	59	181	0.44	69
	7	100	12	0.12	211	52	333	0.25	108
	8	76	9	0.12	76	7	*-22*	0.09	*-25*
	9	249	69	0.28	370	110	59	0.30	7
	12	196	62	0.32	214	63	2	0.29	*-9*
	13	38	7	0.18	96	47	571	0.49	172
	14	117	48	0.41	117	51	6	0.44	7

Table 6 : Comparison of Discharge, Velocity and Cross sectional areas in entrance channel segments for Existing condition and Dredging Option 6

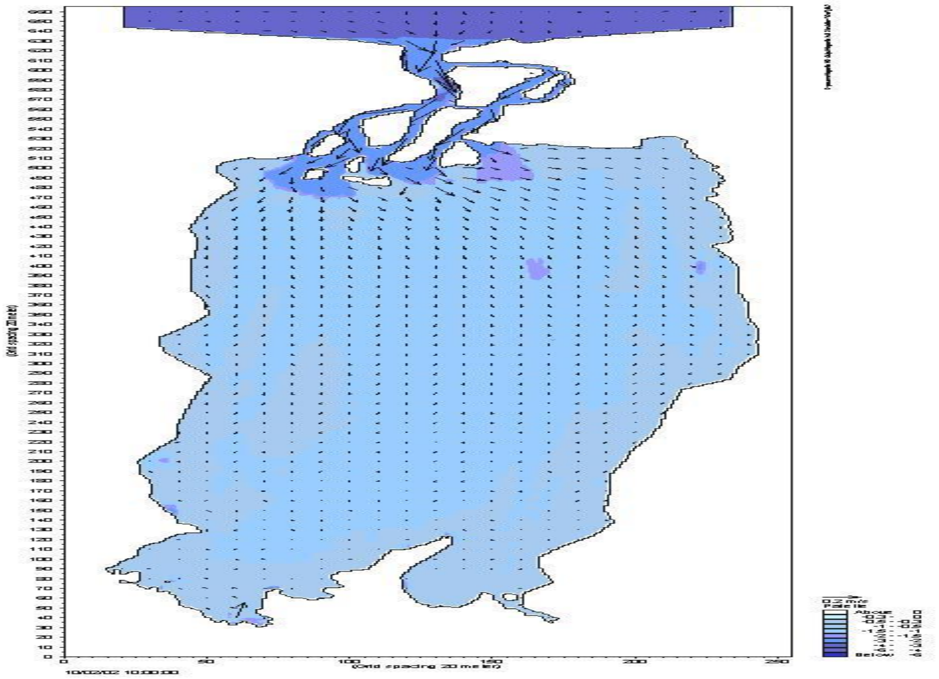


Figure 12 : Velocity vector plot of the lagoon at the maximum flood velocity

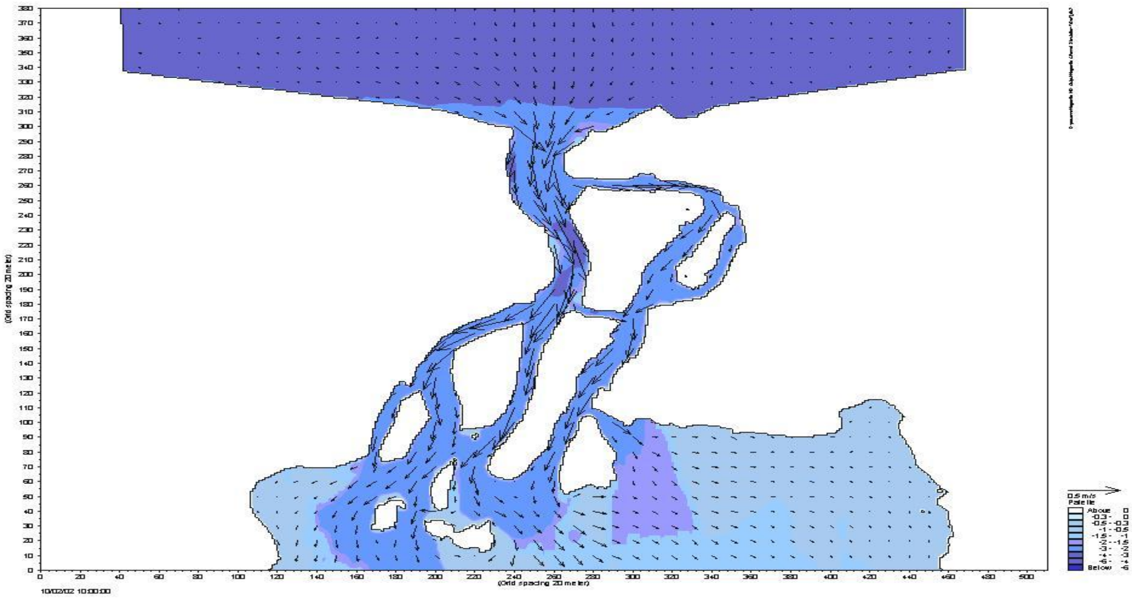


Figure 13 : Velocity vector plot of the lagoon entrance channels at the maximum flood velocity

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3.8 Multiple objective management of saltwater intrusion in coastal aquifers using linked simulation optimization-methodology development and performance evaluation

Abstract

Multiple objective management of Coastal aquifers is a challenging task, especially due to the difficulties in accurately modeling the physical processes and then developing an economically efficient optimal management strategy. A set of different methodologies are developed for multiple objective management of coastal aquifers. One important issue in developing management models for coastal aquifers incorporating the density dependent flow and transport processes is the computational feasibility.

A linked optimization simulation model for multiobjective management of saltwater intrusion in coastal aquifers is developed. The numerical simulation model incorporates density dependent three dimensional saltwater intrusion process in coastal aquifers. The nondominated Pareto optimal front is generated for efficient management with two conflicting objectives: maximization of withdrawal from production wells and minimization of pumping from barrier wells. The developed methodology is tested for an illustrative coastal aquifer study area. The performance evaluations show potential applicability of developed methodology for multiobjective management of saltwater intrusion in coastal aquifers.

Introduction

Management of saltwater intrusion in coastal aquifers is a critical issue of modern times. Different management alternatives are available for controlling saltwater intrusion in coastal aquifers (Willis and Finney, 1988; Maimone, 2002). This study examines two different alternatives: (a) a planned pumping strategy, and (b) planned extraction from barrier wells. A methodology for multiple objective management of saltwater intrusion in coastal aquifers utilizing numerical simulation linked optimization is developed and evaluated. The main aim is to demonstrate the computational feasibility of using a multiobjective saltwater intrusion management model which is based on the simulation of the density dependent saltwater intrusion process.

Comprehensive review of saltwater intrusion modeling, management and monitoring methods can be found in Bear *et al.* (1999), Cheng and Ouazar (2004), and Dhar (2008). Different management objectives reported in the literature include, maximization of total pumping rate (Shamir *et al.*, 1984; Hallaji and Yazicigil, 1996; Cheng *et al.*, 2000; Mantoglou et al. 2004; Abarca *et al.*, 2006; Karterakis *et al.*, 2007), minimization of the pumped water salinity (Das and Datta, 1999a, 1999b), minimization of volume of saltwater into the aquifer (Finney *et al.*, 1992; Emch and Yeh, 1998), minimization of draw down (Hallaji and Yazicigil, 1996), minimization of deviation from the target concentration, pumping and recharge rate (Abarca *et al.*, 2006), minimization of distance of stagnation point (Strack, 1976) from coast (Park and Aral, 2004). Pumping or injection costs are also included in different studies, *e.g.*, Emch and Yeh (1998), Reichard and Johnson (2005), Ferreia da Silva and Haie (2007). However, only a few works considered multiple objectives of operation at a time (Shamir *et al.*, 1984; Emch and Yeh, 1998; Das and Datta, 1999a; Park and Aral, 2004).

Few recent studies concentrated on the use of more complex meta-models, like Artificial ;Neural Network, e.g., Bhattacharjya , 2003; Rao et. al., 2004; and Bhattacharjya and Datta (2005).

Over the years different versions of genetic algorithm have been used in saltwater intrusion management, e.g., structured messy genetic algorithm (Cheng *et al.*, 2000), real coded genetic algorithm (Bhattacharjya and Datta, 2005), simple genetic algorithm (Cheng *et al.*, 2004; Qahman *et al.*, 2005), real coded progressive genetic algorithm (Park and Aral, 2004).

Available literature suggests that there is scope for development of methodologies incorporating explicit multiobjective solution algorithms which can generate the nondominated front in a single run for multiobjective management of saltwater intrusion in coastal aquifers, incorporating density dependent flow and transport processes. Thus a three-dimensional density dependent flow and transport simulation model FEMWATER (Lin *et al.*, 1997) is linked with the evolutionary algorithm: Non-Dominated Sorting Genetic Algorithm-II, in short NSGA-II (Deb, 2001).

Methodology

A methodology is developed for deriving multiple objective optimal management strategies for saltwater intrusion in coastal aquifers, incorporating the physical processes involved either in the form of numerical simulation model or as a meta-model.

Numerical Simulation Model

The proposed methodology utilizes a simulation model linked to the optimization model, or a meta-model trained using the simulation model, also linked to the optimization model. Although, it is possible to use any numerical simulation model for simulating the physical processes, FEMWATER was chosen to simulate the coupled flow and transport process in the coastal aquifer. The three dimensional finite element based model FEMWATER solves the governing equations for the flow and transport processes in the saturated-unsaturated porous media.

Management Model

Any meaningful strategy must incorporate within the management framework, the physical processes involved. The basic goal of this study is to develop multiobjective optimization based management model for saltwater intrusion management, using linked simulation-optimization. The aim is to search for feasible set of pumping values which can be safely sustained in a coastal aquifer. This can be achieved by formulating and solving a two conflicting objective optimal management model. The model formulation utilized in this study is: maximize the total pumping from production wells, and minimize the extraction from barrier wells, while maintaining the spatiotemporal salinity within permissible limits. Barrier wells alter the hydraulic gradient near the ocean face. This impact can be utilized in the management of saltwater intrusion. The formulation can be mathematically represented as:

$$Maximize\ f_1(Q) = \sum_{i \in \mathcal{S}^Q} \sum_{k \in \mathcal{S}^T} Q(\mathbf{x}_i, t_k) \tag{1}$$

$$Minimize\ f_2(q) = \sum_{j \in \mathcal{S}^q} \sum_{k \in \mathcal{S}^T} q(\mathbf{x}_j, t_k) \tag{2}$$

Subject to:

$$\mathbf{c}(\mathbf{x}, t) = \mathbf{g}(\mathbf{Q}, \mathbf{q}) \tag{3}$$

$$c(\mathbf{x}_l, t_k) \leq c_{\max} \quad, \forall k \in \mathcal{S}^T, l \in \mathcal{S}^O \tag{4}$$

$$Q_L(\mathbf{x}_i, t_k) \leq Q(\mathbf{x}_i, t_k) \leq Q^U(\mathbf{x}_i, t_k) \ , \forall k \in \mathcal{S}^T, i \in \mathcal{S}^Q \tag{5}$$

$$q_L(\mathbf{x}_j, t_k) \leq q(\mathbf{x}_j, t_k) \leq q^U(\mathbf{x}_j, t_k) \ , \forall k \in \mathcal{S}^T, j \in \mathcal{S}^q \tag{6}$$

All symbols are defined in NOTATION section. The simulation model is represented within the optimization model formulation by the binding constraint (4). This binding constraint can be replaced by an externally linked numerical simulation model. Three-dimensional finite element based numerical simulation model FEMWATER or meta-model is utilized to provide information about response of decision variables. The constraint set (4) restricts the concentration at observation locations within permissible limits. Constraint set (5) and (6) specifies the feasible range of pumping values for the production and for the barrier wells.

Optimization Algorithm

Saltwater intrusion process is highly nonlinear in nature. Generally multiobjective saltwater intrusion formulations are solved by essentially converting it into a modified single objective problem which is solved iteratively (Emch and Yeh, 1998; Das and Datta, 1999a, 1999b). But the converted model produces Pareto optimal solutions one at a time. The optimization model requires information from the flow and transport simulation models for each iteration. Thus equivalent conversion of the problem becomes inefficient in generating the Pareto front. Population based evolutionary multiobjective optimization (EMO) algorithms are efficient in generating the required Pareto front in a single run. These algorithms are also effective in solving problems with nonlinearity, nonconvexity and discontinuity.

Physical Process Based Linked Simulation-Optimization Model

The numerical simulation model used is FEMWATER. The evolutionary multiobjective optimization (EMO) algorithm NSGA-II first generates the initial population of spatiotemporal pumping values using Latin Hypercube Sampling (LHS) strategy. Each set of generated spatiotemporal pumping values are sent to the simulation model which has been implemented for the study area. The simulation model is then solved to obtain resulting temporal concentrations at each specified control points in the aquifer. The concentration values are utilized by NSGA-II to calculate the constraint violation for each population.

Application of Developed Methodology

In order to evaluate the application potential, the proposed methodology is applied to an illustrative study area (Figure 1). The three-dimensional coastal aquifer is having an area of 2.52 Km^2. Dimensions of the aquifers are 1800 m (length) × 1400 (width) × 100 m (depth). The right-hand boundary is the ocean face. The aquifer is assumed to be homogeneous and isotropic in terms of aquifer parameters (hydraulic conductivity, longitudinal dispersivity, transverse dispersivity). The left boundary is taken as inland face which allows freshwater entry to the aquifer system. Remaining three sides (front, back and, bottom) are assumed as impermeable. Flow boundary conditions are taken as Dirichlet condition. For inland face, linearly varying heads are assigned with values 1.66 m near front face and 1.74 m near back face. No fluctuation of seawater surface is assumed. The ocean face boundary is assigned hydrostatic head values. Initial water level in the aquifer is assumed to coincide with the ground surface.

Initially the aquifer is assumed to be at zero concentration state. Dirichlet boundary condition is assigned for concentration along inland and ocean face with the values 0 and 35,000 mg/l respectively. For rest of the boundaries, concentration mass flux is assigned a zero value. All the boundary conditions are considered as time invariant. Parameter values as specified are given in Table 1.

The optimal management policy determines the transient pumping strategies for eight production wells (PW1 to PW8) and three barrier wells (BW1 to BW3). Locations of the wells are shown in Figure 1. Pumping wells are having 10 m screen interval with top screen and bottom screen levels at -40 m and -50 m, respectively. Total of three time periods each having a value of 183 days is considered for management purpose. The time step used for simulation purpose is much smaller. It is assumed that pumping rates do not change during a particular management period. The upper and lower limits for pumping rates are specified as 10,000 m^3/day and 0 m^3/day, respectively.

The formulated management model deals with two objectives which are conflicting in nature. The objectives considered here are maximization of total water extraction from production wells, and minimization of pumping from barrier wells. In order to increase the extraction from production wells while maintaining the salinity standards, it is required to increase the pumping from the barrier wells. In general, a multiobjective optimization typically has two distinct goals, orthogonal to each other: (a) find solutions as close to the actual nondominated front as possible, and (b) find solutions as diverse as possible (Deb, 2001).

Physical Process Based Linked Simulation-Optimization Model

The generated front for the two-objective optimization model is obtained using linked simulation-optimization with NSGA-II. Figure 2 shows initial population which is generated using Latin Hypercube Sampling (LHS) strategy. It is worthwhile to mention that, although these solutions are well spread in the objective space, all are infeasible. Figure 5 also shows considerable improvement in terms of the objective function value for generations 100, 200, and 300. Further, for generations 400-500-600-700 the rate of improvement in the objective function value decreases. The success in achieving the second goal of diversified solutions is also tested.

As shown in Figure 2 for generations 800 and 1500, the objective function values improve with the number of generations, and the solutions also diversify further. In this study, the NSGA-II algorithm is run for a population size of 24 and for 1800 generations. The final front is shown in Figure 4. Real coded version of NSGA-II is used, as this version shows much faster convergence compared to the binary coded one. The GA parameters are varied for testing the sensitivity of the solutions. But no significant improvement is observed. Linked simulation optimization carries the curse of computation burden with it. Each run, with 24×1800 function and constraint evaluations require around 30 days in 2.4 GHZ Oeptron AMD machine with 4GB RAM. Also the computational complexity dictated the choice of the number of generations. Thus the resulting front may not be the Pareto optimal front, or the true nondominated front, but a near nondominated one.

In order to validate the results, two points **14** (109792.8, 13924.03) and **11** (107801.80, 10141.89) are chosen on the final front. In solution **14**, 13924.03 m^3/day total pumping from barrier wells is required to maintain the water quality standards, while pumping 109792.8 m^3/day from the production wells. If the total pumping from production wells is decreased to 107801.80 m^3/day (solution **11**), consequently total pumping from barrier wells can to be increased to 10141.89 m^3/day to satisfy the permissible concentration constraints. It is evident that for any improvement in one objective, the other has to be sacrificed, as expected for a multiobjective problem with conflicting objectives. In this study, except vertical recharge which is small in quantity, no special recharge mechanism is applied for management. Figure 3 shows convergence of concentration values for production wells PW6, PW7 and PW8.

Summary and Conclusions

An effective and computationally feasible linked optimization-simulation based methodology is developed to address optimal management of saltwater intrusion in coastal aquifers. The developed methodology is generic in nature. Any suitable numerical

simulation model can be utilized for simulation the density dependent flow and transport processes.

The following conclusions can be drawn: The simulation based linked multiobjective management framework for saltwater intrusion in coastal aquifers using the NSGA-II algorithm results in an efficient and direct approach to solve multiobjective problem without treating it as a modified single objective problem, solved iteratively. Two different objectives of management: maximization of pumping from production wells and minimization of pumping from extraction barrier wells are considered.

The limited performance evaluations show the potential applicability and computational feasibility of the proposed methodology. It is expected that further computational efficiency can be achieved by using a meta model as an approximator of the numerical simulation model for simulating the physical processes in the aquifer. These issues are examined and further studies are given in details in Dhar (2008) and Dhar and Datta (2008a,b).

NOTATION

The following symbols are used in this paper:

c = material concentration in aqueous phase;

$\mathbf{c}(\mathbf{x},t)$ = concentration vector function;

$c(\mathbf{x}_l,t_k)$ = concentration at spatial location *l* at the end of time t_k;

$c_{\max}$ = maximum permissible concentration;

d_l^p = desired or target value of the *l*-th output for *p*-th pattern;

$f_1(Q)$ = first objective function;

$f_2(q)$ = second objective function;

$\mathbf{g}(\mathbf{Q},\mathbf{q})$ = numerical simulation model;

i = signifies spatial location for production well;

j = signifies spatial location for barrier well;

k = signifies temporal location for well;

l = signifies spatial location for observation well;

N_L = number of outputs;

P_t = total number of patterns;

$Q(\mathbf{x}_i,t_k)$ = pumping rate from production well at spatial location *i*;

$Q^U(\mathbf{x}_i,t_k)$ = upper value of pumping rate from production well at spatial location *i*;

$Q_L(\mathbf{x}_i,t_k)$ = lower value of pumping rate from production well at spatial location *i*;

$q(\mathbf{x}_j,t_k)$ = pumping rate from barrier well at spatial location *j*;

$q^U(\mathbf{x}_j,t_k)$ = upper value of pumping rate from barrier well at spatial location *j*;

$q_L(\mathbf{x}_j,t_k)$ = lower value of pumping rate from barrier well at spatial location *j*;

$\mathcal{S}^O$ = set of observation locations;

$\mathcal{S}^Q$ = set of production well locations;

$\mathcal{S}^q$ = set of barrier well locations;

$\mathcal{S}^T$ = set of all time periods;

t = time;
$\mathbf{x}$ = spatial coordinates;
y_l^p = *l*-th output for *p*-th pattern from network;
ρ = water density at chemical concentration *c*;
ρ_0 = referenced water density at zero chemical concentration.
ε = density reference ratio.

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Table 1: **Different aquifer and discretization parameters**

Parameter	**Unit**	**Value**
Hydraulic conductivity in x-direction, K_{xx}	**m/d**	**25.00**
Hydraulic conductivity in y-direction, K_{yy}	**m/d**	**25.00**
Hydraulic conductivity in z-direction, K_{zz}	**m/d**	**0.25**
Longitudinal dispersivity, a_L	**m**	**50.00**
Lateral dispersivity, a_T	**m**	**20.00**
Molecular diffusion coefficient, a_m	**m^2/d**	**0.69**
Soil porosity, n	**-**	**0.20**
Density reference ratio, ε	**-**	**8.40×10^{-7}**
Vertical recharge	**m/d**	**5.47×10^{-4}**

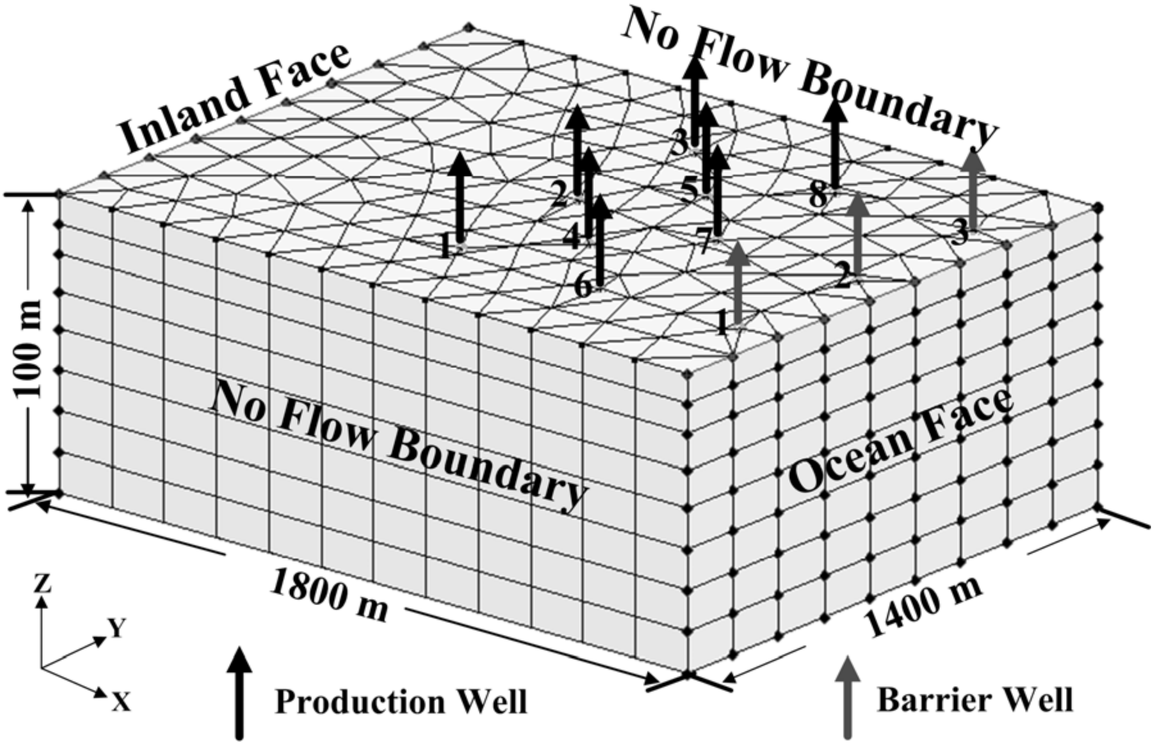

Figure 1: Illustrative study area

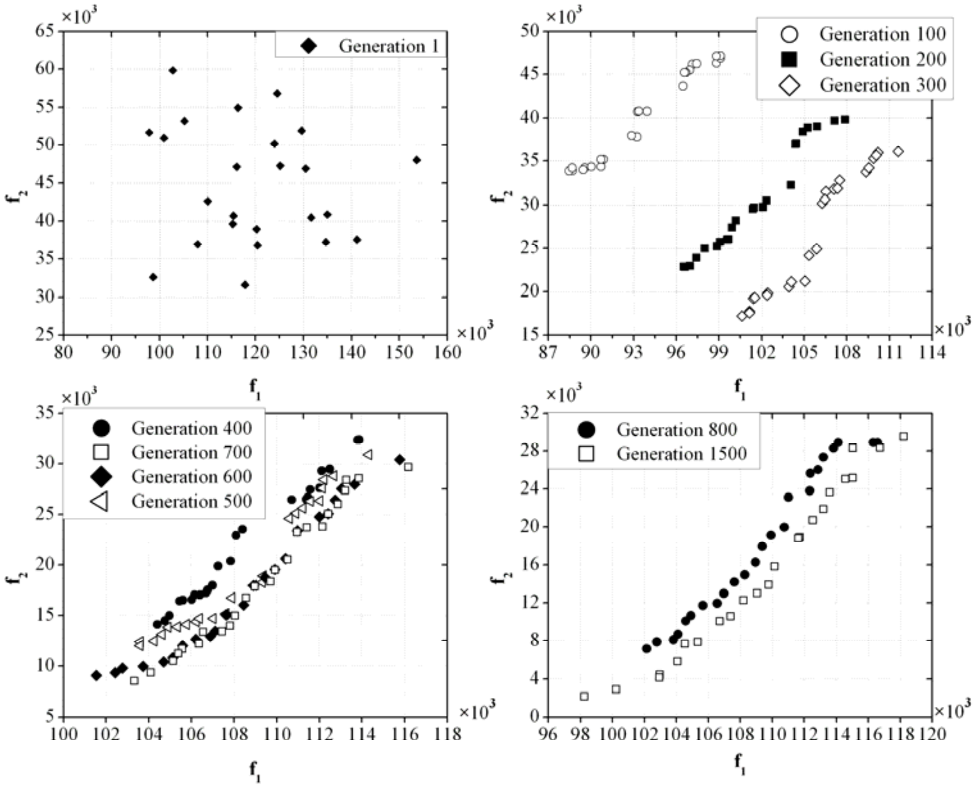

Figure 2: Results corresponding to different generations

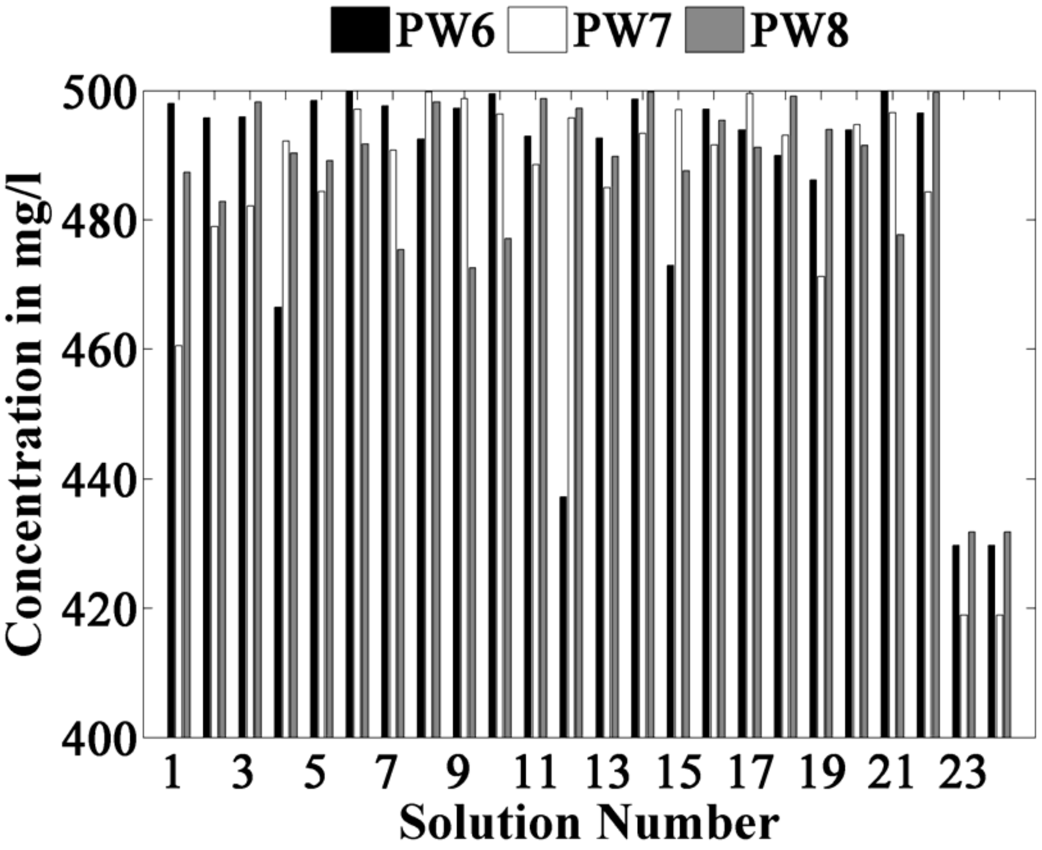

Figure 3: Maximum actual concentration corresponding to each point of final front from physical process based approach

3.9 Exclusion of salt water in low lying coastal areas -A case study of the southern province of Sri Lanka.

1. INTRODUCTION AND OBJECTIVES OF THE STUDY

Recently considerable attention has been focused on issues relating to environmental degradation of coastal ecosystems. In particular, critical evaluations have been made on development activities related to estuaries, marshes, lagoons and in general coastal wetlands. Adverse impacts which have been created as a result of hydraulic works have been highlighted. This identifies a strong demand to develop well-formulated environmental management programmes for coastal ecosystems. Such programmes should give priority to the continual existence of the natural estuarine environment and consider both the resources of an estuarine ecosystem and its uncontrolled exploitation. Within this framework the programme should be able to identify and assess the impact of human intervention and natural changes which are likely to take place.

The objective of this study is to investigate within an integrated management framework the problems associated with salt-water exclusion and drainage in the Galle District of the Southern Province of Sri Lanka. Salt-water exclusion and drainage are two important phenomena which should be incorporated in an environmental management programme of an estuarine ecosystem. In this context the analysis of the problem of salt-water intrusion and flooding as well as its impacts on the environment and overall mitigation should not be considered in isolation but in association with other related phenomena. In effect, a clear understanding of the overall issues is required in order to examine the likely impacts of individual activities and the interaction among the various systems and resources. In view of these considerations, the approach to this investigation included the identification of overall issues relating to the estuarine environment and its management prior to study of the specific estuaries in the Galle District. By adopting this approach it was expected to make use of the positive advantages of operating within an integrated management framework.

2. MECHANICS OF SALT-WATER INTRUSION

2.1. Estuary behaviour

Where rivers carrying fresh-water discharge into the ocean, the sea-water tends to propagate into the estuarine system, affecting the quality of the water in low-lying regions. Thus, the problem of salt-water regulation is very relevant in an estuarine environment where the environment is alternately subjected to large influences of fresh-water, particularly at low tide and more saline conditions during high tides. Depending on specific environmental conditions the saline water will mix to a smaller or larger degree with the fresh-water. The resulting sea-water intrusion can render the quality of the water in the low-lying areas unsuitable for domestic, agricultural, industrial and other uses, thus causing adverse impacts on the community. The sea-water intrusion itself can extend to a considerable distance upstream and the whole process could be very complicated in the presence of interconnected water bodies.

Most rivers enter the sea where there is enough tidal rise and fall to modify flow near their mouths. River mouth areas are defined as specific geographical zones situated at places of river inflow into recipient basins (that of the oceans) and as zones of dynamic interaction, mixing of river water and sea-water, and the deposition of river and marine sediments.

As a hydrographic system a river mouth area can be divided into two parts:

1. the river part, where fluvial hydrological regime predominates, though the influences of the sea may occur actively in the form of tidal and storm surge water level variations and intrusion of salt-water; and
2. the coastal part, where a marine hydrological regime predominates, though the influences of the river may occur actively in the form of significant fresh-water discharge.

The part of the river system in which the river widens under the influence of tidal action is the estuary. The estuary cannot be considered in isolation. The entire system has many inter-dependent parts, extending from the landward limit of the tidal rivers forming it to a point offshore beyond which the effect of an individual estuary on water circulation and sediment movement can no longer be discerned. The behaviour of the estuary is influenced by the circulation of water and solids in the sea, as well as by the entire tidal part of the river system.

Estuaries are governed by tidal action at the sea face and by river flow. These are the main interdependent variables. The boundary shape of the estuarine system is determined by the geomorphology of the land and the properties of all alluvial materials that form the bed and banks of the channels. Usually, the overall boundary shape changes only slowly, though there may be rapid local or short-term adjustments. The geomorphology of an estuary basin is, essentially, a fixed boundary condition, but the channels as modified by flow can be regarded as a variable boundary. The behaviour of an estuary is influenced by the circulation of water and solids in the sea, as well as by the whole tidal part of the river system. Sea-borne sediments stirred up by tidal currents and wave action can enter an estuarine system from beyond any immediate zone influenced by the estuary.

2.2. Surface and density gradients

Tidal rise and fall of the water surface at the entrance of an estuary causes surface gradients which result in the propagation of gravity waves into the estuary. The rate of propagation depends primarily on the depth of water and in consequence on the tidal range at the mouth. The tidal wave travels more slowly as the depth decreases and consequently the wave form becomes distorted as it travels inland.

The equilibrium of an estuary can only be maintained if the quantities of solids, fresh-water and minerals in solution each remain in balance. Fresh-water entering an estuary must leave at the same rate averaged over a period of several weeks if this system is in equilibrium. Rainfall, evaporation and percolation all take part in the process but seldom contribute significantly to the balance of flow of fresh-water, except during times of very low river flow.

The inevitable movement of fresh-water away from an estuary mouth into the sea is accompanied by movement of saline water entrained with it. This saline water must be replaced if equilibrium is to be maintained. In such a situation, the exact quantity of salts entrained with fresh-water and removed from a given region in unit time must be replaced by an equal influx of water and dissolved salts. Because there is a small increase of density with salinity at a particular temperature, the fresh-water moves on the surface away from an estuary mouth, whereas the saline water moves towards it near the sea-bed.

Within an estuary, the effect of density gradients is considerable. There are two important aspects to be considered with respect to density gradients.

Firstly, there is tendency for net landward movement of sediment to occur over the middle reaches because the flood tidal velocities are stronger than those of the ebb.

Secondly, superimposed on this effect, the density difference between the water at the seaward end of an estuary and water entering from rivers causes net landward movement of water near the estuary bed and a compensating seaward movement near the water surface. This can cause fine sediments to be carried landwards in suspension to a point of zero net movement, which is near the landward limit of density gradients. Water is predominantly fresh upstream of this point.
When river flow is high this position of zero net movement is moved sea wards and, conversely, when the flow is small it moves landwards.

The effect of density gradients on flow in an estuary depends on the level of turbulence that occurs. If turbulent mixing is so intense that there is only a small difference in density over the depth at any point, there must be a horizontal gradient of density ranging from 1000 kg/m^3 at the upper tidal limit to the density of sea-water (1026 kg/m^3) at some distance offshore. The horizontal force due to such a density gradient increases with depth below the surface and is always directed in the direction of decreasing density. It therefore gives rise to a small landward force, zero at the surface and reaching a maximum at the bed.

2.3. Estuarial dynamics and salt-water intrusion

The flow regimes in estuaries are governed by distinct dynamic influences, which determine the direction and magnitude of velocities at different elevations and at different distances from the mouth.

Some of the important dynamic factors are summarised as follows:

1. the effect of the tide throughout the salinity intrusion length as a function of the forcing tide at the entrance;
2. the effect of gravitational forces caused by density variations between fresh-water from upstream and saline water entering from the sea; and
3. the gravitational forces needed to produce a net seaward transport of fresh-water.

At low rates of flow, mixing between fresh river water and sea-water only occurs at a narrow interface between the two layers. Almost complete separation can then exist between the fresh and saline water. Never the less, at the interface between them, some mixing will occur. To maintain equilibrium, this salt would have to be replaced from the only possible source and there would be landward movement of saline water in the lower layers. The situation can be summarized using the principle of continuity or conservation of matter. These principles show that entrainment of salt over a distance in a river must result in landward flow of salt in the lower layer, gradually decreasing in quantity as it penetrates inland.

Between the two extremes of well-mixed flow, and stratified flow, there can exist any degree of mixing. The two extreme cases are (1) the strata of the lighter fresh-water being distinct from the heavier salt-water underneath (this occurs when tidal motion is minimal so that mixing is effected only by the fresh-water outflow of the river) and (2) density changes exists throughout the depth and length of the river. When tidal oscillations are large, compared with the river discharge, the turbulence present in the stratum close to the bed causes greater mixing at the interface of fresh and salt bodies.

The density difference between out flowing fresh-water and the sea- water itself causes the former to override the latter, which, in turn, penetrates up the river in the form of a saline wedge.

3. PARAMETERS RELATED TO SEA-WATER INTRUSION AND CHANGES WHICH INFLUENCE THEM

3.1. Impact assessment of sea-water intrusion and related parameters

There are many important parameters which have a close relationship to the intrusion of salt-water. Changes of these parameters will contribute significantly towards changes in the behaviour of salt-water intrusion. These parameters are subjected to change by (or respond to) either man-made or natural actions. In the context of the present study, five important parameters which need to be considered are as follows.

1. Configuration of the river outfall
2. Configuration of the estuarine system
3. Fresh-water discharge
4. Tidal exchange
5. Water quality

3.2. Change caused by development activities

With regard to the use of natural resources of an estuarine ecosystem it is possible to identify many activities of economic development. Of these the following six groups of activities are of significance to the aquatic systems considered in this study.

1. Agriculture
2. Fisheries
3. Utilisation of natural resources
4. Industries
5. Human settlement
6. Transportation

These activities are either aimed at controlling sea-water intrusion or are likely to cause important impacts on the mechanics of sea-water intrusion.

Thus these activities can have an impact on any of the five principal areas identified in the previous section.

The quality of the water in an estuarine system is not only affected by sea-water intrusion but also by the adverse effects of the disposal of sewage and pollutants. From the study of estuarine systems it has been observed that the effects of pollutant inputs are normally significant and long-lasting. These inputs are not limited to human sewage and chemical disposal from industrial plants but also include the run-off of chemical fertilisers, pesticides from agriculture and irrigation sectors and concentrated drainage of acidic waters leached from reclaimed lands. In particular, estuaries receive pollutants from the fishery industry.

It is emphasised that in order to evaluate the impact of development activities on an estuarine system it is necessary to consider all important activities. However, the study of such impacts in an estuarine ecosystem is very complicated. In view of the complexity of the problem and the large number of factors involved, it is a difficult task to address all interactions which are likely to take place in the system. Hence, attention is focused on issues relating to water resources which can be analysed within the framework of hydraulic engineering and practice.

3.3. Changes caused by natural actions

There are two groups of changes caused by natural actions.

1. Changes in flow discharge
2. Changes in topographical conditions

Changes in discharge can manifest itself either in the form of quantity of water inflow/outflow or through change of water levels. The first groups would thus include the variation of fresh-water, river discharge, rainfall, evaporation, variation of tidal fluctuation and changes in water levels caused by meteorological factors. The second group is principally associated with river and tidal movement of sediment at the outfall itself and in the estuarine system as a whole. Nearshore coastal processes which are influenced greatly by wave action also play an important role in the erosion and accretion processes within estuarine systems.

3.4. Estuarine configuration, tidal range and storage

The configurations of the river outfall and of the estuary itself are two important parameters related to sea-water intrusion. In relation to these two parameters there are two important impacts to be discussed:

1. increase in tidal storage and tidal range upstream; and
2. decrease in tidal storage and tidal range upstream.

Storage areas located within the tide-affected zone can be increased by the effects of natural changes or hydraulic works. The increase in storage area by natural factors may appear in the form of destruction of natural habitat or existing dunes or the increase of ocean sea-water levels by wind set-up or storm surges. It is noted that the effects of increase in the tidal storage areas on the extent of sea-water intrusion become important only when such an increase is significant in comparison with that of the existing tidal prism.

Activities aimed at improving flow conditions for either drainage and navigation will normally contribute to an increase in tidal range upstream. The increase in tidal range upstream can be effected by the removal of sand bars at river outfalls, deepening of channels by dredging for navigation and by the excavation of new channels or enlargement of existing channels for drainage improvement. The latter will also have a positive impact towards improving considerably the drainage of inland areas, thus protecting such areas from flooding.
The reductions in tidal storage can be carried by natural changes such as sand-bar formation and other sedimentation processes. The reduction is often effected by human actions such as the introduction of flow control structures and tidal flood defense structures. The closure of a river mouth or the construction of sluices will have two major effects, namely a relative increase in fresh-water input and a reduction in the tidal storage areas in the system.

Decrease in tidal range upstream is caused by obstruction to tidal flows which are normally created by natural factors such as sedimentation processes. Estuary sedimentation is influenced by both fresh-water flow and tidal flow. Sediment laden flow enter estuaries from inland (fresh- water) and nearshore areas (sea-water) and is subjected to sedimentation. A large reduction in velocity at the river outfall combined with strong influence of flocculation results in the deposition of sediments.

3.5 Relative fresh-water inflow

The physical phenomenon of sea-water intrusion is influenced by the input of fresh-water from the upstream of the river and of sea-water under the influence of tidal fluctuation. The extent of intrusion and also mixing types can normally be related to the input of fresh-water relative to the tidal prism. It could therefore be expected that a substantial change in the relative fresh-water input by either man-made or natural actions will contribute towards significant changes of sea-water intrusion.

The input of fresh-water and sea-water could be analysed by considering the relative increase/decrease of fresh-water flow. The relative increase of fresh-water inflow to a given aquatic system will result from a reduction of tidal inflow or an absolute increase in fresh-water inflow. With regard to the reduction of tidal inflow it is observed that, except for the change of configuration at the river outfall by natural factors or human actions as already discussed, the most important reduction will result by change that take place from spring to neap tide. The increase of fresh-water inflow can be caused either by natural factors such as flood water from the upstream basin and rainfall or by human activities such as controlled flow resulting from regulation of upstream reservoir.

Relative reduction of fresh-water inflow to a given aquatic system may correspond to an increase in tidal inflow or an absolute reduction in fresh-water inflow. The increase in tidal inflow is normally caused by natural factors such as the spring tides or wind set-up and storm surges. The reduction in fresh-water inflow can be caused by natural factors such as prolonged drought, evaporation and by fresh-water abstraction for irrigation and other water supply purposes.

4. INTRODUCTION TO THE STUDY AREA

The Southern Province of Sri Lanka is one of the nine Provinces which is managed by a separate Provincial Council. The Province covers three districts, namely Galle, Matara and Hambanthota. The Government of Sri Lanka has given a high priority for the development of this Province and accordingly the Government formulated a development strategy for the Province. Based on the recommendations of the development strategy, several priority programmes were selected for immediate implementation with financial assistance from international donor agencies.

Salt-water exclusion and drainage are two areas which need to be attended. The intrusion of salt-water in the low-lying coastal areas has made it impossible for the people to use the land for any productive agricultural purposes. Although in the early 1970s salt-water exclusion and drainage schemes were constructed, these schemes have not performed well, leading to collapse. Thus there is a strong demand for the rehabilitation by adopting a new approach. The schemes which were included in the study are listed below.

1. Dedduwa Scheme 1000 ha
2. Dedduwa-Rantotuwila Scheme 800 ha
3. Madu Ganga Scheme 800 ha
4. Madampe Scheme 1700 ha
5. Hikkaduwa Scheme 1200 ha
6. Moragoda Ela Scheme 170 ha
7. Nugaduwa- Kaduruduwa Scheme 180 ha
8. Waggalamodera Scheme 600 ha
9. Koggala Scheme 400 ha
10. Goviyapana Scheme 320 ha

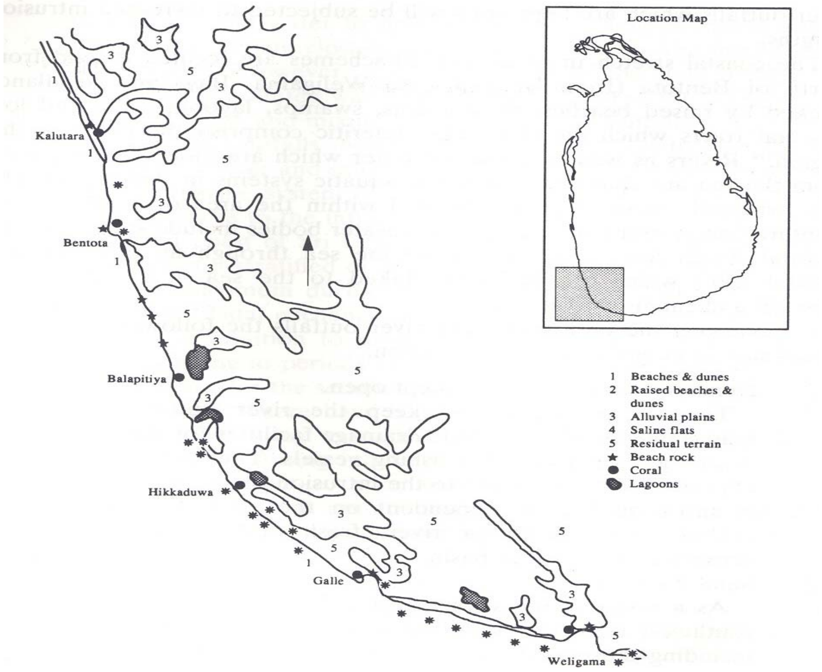

Figure 1 illustrates the southwest region of the island in which the proposed schemes are located.

5. IMPORTANT ISSUES RELATING TO THE OVERALL PERFORMANCE OF THE OUTFALLS UNDER STUDY

The study area is located in the southwest region of the island and as a result of wave action in the nearshore region there exists a strong net littoral drift directed towards the north. This contributes to the movement of sand from south to north. Hence, during the dry seasons when river discharges are low, most of the river outfalls are closed partially or completely. Therefore, in order to keep the river outfalls open it is necessary to make use of estuary control structures such as groynes to be located at the outfall itself or to undertake periodic dredging of the sand bar. It is also noted that river outfalls are also used for the mooring of fishing vessels. They provide a safe anchorage for small craft and as such there is strong demand to keep the river outfalls open while also maintaining sufficient depth for the free movement of vessels.

The tidal variation around the coastline of Sri Lanka is comparatively small (< 1 m) and hence the salinity distribution will be closer to stratified or partially mixed. The salt-water wedge has been clearly observed in many estuarine water bodies. The mechanics of salt-water intrusion and the factors which influence the process have been outlined in the previous section. Of the many parameters, the mean depth and river discharge have a considerable influence on the intrusion length. Increase of the mean depth and lower fresh-water discharge contribute to greater intrusion length along a river. Hence, it could be expected that, during dry seasons, river outfalls which are kept open will be subjected to increased intrusion lengths.

The coastal stretch in which the 10 schemes are located extend from north of Bentota (from Beruwala) to Weligama. Bays and headlands backed by raised beaches, flood plains, swamps, lagoon, lakes and low residual tracts which are commonly lateritic comprise the coast in this region. Rivers as well as bodies of water which are more or less cut off from the sea are characteristic of the aquatic systems in this region. The two principal rivers which are located within the area of study are the Bentara Ganga and Gin Ganga. Other water bodies include smaller rivers, lagoons which have direct access to the sea through an entrance and coastal lakes which are indirectly linked to the sea, if at all, usually through a channel or river.

In reviewing the performance of river outfalls the following important issues should be given due consideration.

1. <u>Demand for outfalls to be kept open.</u>
There is a demand to keep the river outfalls open at a reasonable depth to provide drainage facilities for flood water and to provide navigation for fishing vessels. The river outfalls being kept open will contribute to the intrusion of salt-water. The length of intrusion will be dependent on the tidal fluctuation at the outfall, mean depth of river, fresh-water discharge and the geometry of the water basin.

2. <u>Sand-bar formation.</u>
As a result of the strong littoral drift which prevails along the southwest coastline, sand-bar formation occurs at most outfalls including those at the major river outfalls. This is a hazard for navigation and prevents the drainage of flood water. In order to prevent sand-bar formation it is necessary to

construct estuary control structures at the outfall, with due attention being focused on the stability of the adjacent coastline. Even in the presence of estuary control structures there have been many examples where sand bars have formed in between the structures because of strong littoral and on-offshore movement of sediment. Waves which break carry the sediment towards the estuary, thus forming a sand bar commencing towards the landward end of the control structure. Sand bars could be removed manually or mechanically by using a dredger. If this is adopted it is necessary to do so at periodic intervals in order to prevent the reformation of sand bars. Presence of sand bars at outfalls have contributed to the flooding of inland low-lying areas during heavy rainfall. There have been many occasions where sand bars have been forced open in order to release flood water to prevent major flooding of inland areas. Partial or complete closure will reduce or prevent the intrusion of saline water. However, it can also lead to the development of stagnant and polluted water bodies at the head of the estuary.

3. Tidal exchange and mixing processes of open outfalls.

The river outfalls being kept open will contribute to the exchange of river and saline water leading to the development of a saline estuarine system of ecological importance. Tidal exchange will contribute to the intrusion of salt-water and in the case of the southwest coast of Sri Lanka this would on most occasions be in the form of a stratified or partially mixed condition. Intrusion will be at its maximum during low river discharges under spring tide conditions. Tidal exchange also contributes to siltation within the estuary (in addition to sand-bar formation at the outfall itself). Corresponding to periods of lower velocity of the tidal cycle there is a tendency for the sediments in the tidal flood water to settle on the river bed. There have been many cases where sedimentation has occurred along estuaries. Pollution resulting from fishing vessels and the fishing industry as well as domestic and industrial effluents contribute to poor water quality conditions within an estuary. Some of the pollutants may travel upstream during high tide (flood tide) and may not necessarily be flushed out during low tide.

4. Important features of the aquatic system.

The layout of an aquatic system, including the shape (in plan view), interconnections between water bodies, differences between the relative depths (in cross-sectional elevation) and the characteristics of flow also play a vital role with respect to salinity intrusion and retention. In the case of a typical river not having major tributaries discharging their water within the saline intrusion zone, it is very likely that the salt-water wedge will move upstream and downstream the estuary over a length which could be predicted. However, the presence of tributaries and interconnections with lakes and other water bodies of complex geometry generate complicated intrusion patterns which are not amenable to easy theoretical analysis. Under such circumstances the ability of the aquatic system to flush out the saline water is poor-leading to salinity retention which in turn has a negative impact on low-lying agriculture.

5. Environmental considerations.

From an environmental point of view there is a strong demand to maintain the saline estuarine system to obtain the desired ecological balance. There have been strong opposition by environ- mentalists against schemes which prevent the tidal exchange of fresh and saline water. It has been clearly pointed that the existence of many unique marine habitats depends on the presence of the natural tidal exchange which takes place at estuaries. The diversity and adaptation of estuarine life were discussed previously.

6. Prevention of salt-water intrusion.

Prevention of salt-water intrusion can be achieved by the use of flow control structures having gates which could be controlled automatically (hydrostatic pressure) or manually. The flow control structure could be located in the neighbourhood of the outfall or at locations along tributaries from which water is used for agricultural purposes. If the flow control structure is located at the outfall, salt-water will be prevented from entering the usual estuarine region, thus allowing no opportunity for tidal exchange and mixing processes. This would have adverse impacts with respect to the ecological balance of the traditional saline estuarine system. Under these conditions the flow control structure should be designed so that it would be able to discharge floods without causing flood damage to low-lying areas further inland. For this purpose it may be necessary to have the additional use of pumps to discharge large quantities of water to the sea. The flow control structure would also prevent the free movement of fishing vessels, which under such circumstances may only be achieved by the use of lock gates. In contrast, if the control structures are located along tributaries, it would permit the presence of a saline estuarine system having tidal exchange and mixing of fresh and saline water along the main body of the river. Under these circumstances the main body of the river will be subjected to saline intrusion and hence any fresh water intake structure cannot be located along the main river without a clear understanding of the salt-water intrusion characteristics. Control structures located along the tributaries should also be in excellent working condition because any malfun- ctioning would lead to the intrusion of saline water from the main river which will have a varying degree of salinity depending on the tidal cycle. The relative merits and demerits of the different types of flow control structures is discussed below with reference to the observations made from field visits.

7. Impact on nearshore coastal stability.

Rivers play an important role with respect to the stability of the shoreline by providing an appreciable sediment input to the nearshore regions. For example, a particular stretch of coastline can achieve a state of stable dynamic equilibrium by having received a steady sediment load from the estuary of a nearby river, as one of the sources of sediment contributing to the 'sediment budget' of that coastal stretch. Therefore, a change in that source of sediment can lead to an imbalance of the 'sediment budget' which can result in coastal erosion. There have been many examples where the reduction of the sediment load such as that arising from excessive sand mining in estuarial regions has contributed to excessive erosion of nearby coastal regions. This aspect should be given due consideration in the design of flow control structures which are constructed across an outfall. There- fore, it is evident that gates placed across the full width of an estuary is not only undesirable from an environmental point of view but also contributes to an imbalance of the nearshore sediment budget. Most of the estuary control structures which have been constructed to prevent the formation of sand bars are of the form of a pair of groynes which are constructed perpendicular to the beach on either side of the outfall. These groynes act as littoral barriers leading to the accumulation of sand on one side and severe erosion on the other side. If groynes are to be used they cannot be designed to act in isolation. It is therefore necessary to adopt a field of groynes as opposed to a pair and the design should consider in detail the nearshore hydrodynamics of the coastal region as well as the sediment load discharged from the river.

6. FIELD INVESTIGATIONS

6.1. Description of outfall sites

Field visits were undertaken on several occasions to study the performance of the outfalls and to assess their impact on salt-water intrusion. A brief description is made here of the important aspects.

The outfall of the Bentara Ganga is stable, having a wide opening to discharge the river water. Bentara Ganga is one of the principal rivers in that area and the coastal regions in the vicinity of the outfall is fairly stable, indicating a balance in the sediment budget. The open outfall would no doubt contribute to the intrusion of salt-water into the far internal regions, as confirmed by the pump operators of the Irrigation Department (ID).

The outfall of Aluthwela Ela is constantly subjected to siltation and the ill has constructed a side channel with a vertical lift gate for the control of flow to discharge flood water at a location near a rock outcrop. The prevailing turbulence prevents the formation of the sand bar at that location.
The outfall of Madu Ganga is protected by two rock armoured groynes. In spite of the presence of the control structures, sand-bar formation takes place. The Madu Ganga estuary is used extensively for the anchorage of fishing vessels and as such there is a strong demand to keep the outfall open for the safe passage of vessels. The closure of the outfall has caused considerable inconvenience to the fishermen. This location is one of the sites to be investigated by the Ministry of Fisheries for possible development as an anchorage with supporting facilities.

A concrete-lined channel located north of the Madu Ganga at Karij- japitiya is also used for the purpose of drainage of flood water. Here again the outfall has been located at a site within a rock outcrop where sand-bar formation does not take place because of high turbulence of the flow field. The channel is highly polluted and the lining is also damaged at certain locations.

The outfall of Madampe Ganga is protected by the construction of two rock armoured groynes. A high degree of turbulence is present, with waves breaking on natural rock formation at the seabed. Just upstream of the groynes is located a hydraulic structure consisting of 14 lift gates, spanning the entire width of the river. When closed this structure prevents the flow of salt-water into the estuary. The structure itself has been subjected to general deterioration, but the gates are in working order.

The outfall of the Hikkaduwa Ganga is protected by two groynes consisting of rock and cylindrical rings made of concrete. In spite of the groynes, sand-bar formation takes place near the landward end of the groynes. When the sand bar is not present, considerable amounts of salt-water would enter the aquatic system at high tide. South of the outfall is located an anchorage for the mooring of fishing vessels. Considerable erosion had taken place north of the outfall, and this has been controlled by the use of revetments and groynes.

The Moragoda Ela discharges into the Galle Harbour and thus the outfall itself is not protected. This stream is heavily polluted and silted closer to the outfall.

Discharges of flood waters into fishery or commercial harbours is not desirable because it can lead to siltation of the harbour.

The drainage from the Nugaduwa-Kaduruduwa Scheme is discharged into the bay of Galle at its southern end and the outfall at this location is not protected. The outfall region has been subjected to siltation, thus controlling the flow at this location.

The discharge from the Mihiripenna Ela is released through a sub- merged culvert near a rock outcrop. Here again the high level of turbulence prevents the formation of sand bars. A vertical lift gate has been used to control the flow. A large pump has been installed originally to discharge flood water and at present it is in a state of neglect and disuse.

The outfall of Koggala Lake is not protected and subjected to very severe sand-bar formation. A rock armoured revetment is located along the coastline just south of the outfall and there are sandy beaches towards the north. During the last few years there have been pronounced changes in the pattern of formation of the sand bar. Many attempts have been made to discharge the flood water including the channelling of the same via a canal to a location north of the existing outfall (which is located directly in front of the bridge). However, these attempts have not been successful, leading to the formation of a large sand bar near and under the bridge.

The drainage of the Goviyapana Scheme is discharged at a location south of Ahangama. The outfall is protected by two rock armoured groynes which have performed well from a coastal engineering point of view in that the groynes have not generated adverse impacts on the neighbouring coastline. However, in spite of the presence of the groynes, sand-bar formation takes place closer to the landward end of the groynes.

6.2. Flow control structures for the prevention of salt-water intrusion

Attempts to prevent the intrusion of salt-water have been made by the use of flow control structures located either at the outfall itself or along the tributaries from which water is used for agricultural purposes. Two types of flow control gates, namely automatically controlled and manually controlled, have been used. On several locations, pumping schemes have been incorporated to supplement the discharge of flood water, particularly in the vicinity of outfalls.

From the field investigations it was clearly observed that both automatic and manually operated gates used in the schemes have been subjected to severe deterioration. The same is also applicable to the pumps and the associated pipelines. Flow control structures and pumps need regular maintenance, in the absence of which deterioration sets in rapidly. The use of pumps to discharge flood waters has not been successful. The cost of operation of these pumps has increased considerably. Therefore, the use of pumps to discharge flood water is considered uneconomical in the current context.

With reference to the two types of flow control gates, it is observed that individuals with specific interest can easily interfere with the operation of automatic gates, thus making these structures ineffective. The use of locking devices in manually operated gates prevents such interference. The manual operation of opening and closing of the gates is time- consuming. If, for example, a number of gates are present at a particular location, it may well be that saline intrusion can take place if the gate operation is not properly planned. When a single person has to operate a large number of gates at a particular location it becomes difficult to control the flow effectively within a restricted time period.

From the information made available by the gate operators, a certain amount of seepage has taken place around and under some of the control structures. This problem has to be rectified in the design of structures to be adopted in the future.

7. CONCLUDING REMARKS

The demand to keep the river outfalls open at a reasonable depth to provide and maintain

1. drainage facilities for flood water,
2. access for fishing vessels, and
3. an ecological balance by having a fresh/saline aquatic system is justified.

The sand-bar formation caused by strong littoral drifts as well as on-offshore sediment transport along the southwest coastline is considered a major problem in keeping the outfalls open. Sand-bar formation could be prevented or restricted by the construction of estuary control structures. These structures which are usually constructed perpendicular to the beach have to be designed with due consideration to the stability of the adjacent coastline. The construction of isolated structures which obstruct the littoral movement of sand could generate coastal erosion on a large scale. Hence, in order to achieve a stable coastline it may become necessary to construct additional structures on either side of the outfalls to control the littoral movement in an acceptable manner.

It is a point of interest to note that on certain locations innovative schemes have been used whereby the inland drainage has been channelled near a rock outcrop where sand-bar formation does not take place because of high turbulence of the natural flow field. Unfortunately such natural features are not readily present near river outfalls.

Prevention of salt-water intrusion can be achieved by the use of flow control structures having gates which could be controlled automatically or manually. These structures could be located in the immediate neighbour- hood of the outfall or at locations along tributaries from which water is used for agricultural purposes. In view of the need to keep river outfalls open for reasons specified earlier, it is observed that flow control structures should be located along the tributaries as opposed to their being located at the outfall itself.

Both automatic and manually operated flow control gates and pumps which were used to discharge flood water have been subjected to severe deterioration. The absence of planned maintenance and the hostile marine environment have contributed towards achieving this state. The use of pumps to discharge flood water has proved to be uneconomical. However, in the absence of such devices to discharge heavy floods which take place, the inundation of low-lying areas in the regions neighbouring the outfalls is unavoidable.

From the study it is observed that most of the structures could be rehabilitated, after which a well-formulated maintenance programme should be implemented with the effective participation of the farming community. However, in justifying the rehabilitation of a specific scheme, due consideration should be given to detailed cost-benefit analysis together with socio-economic, environmental and other related issues such as alternative employment opportunities. In contrast, it is important to appreciate the practical difficulties associated with the operation and maintenance of flow control structures as well as problems relating to community participation in such projects. The exclusion of salt-water in low-lying coastal areas is a difficult task and in this respect the concept of drainage at very low elevations needs to be analysed in detail. It is also observed that, while higher elevations are more suitable for planned agricultural development, attention should be focused on alternative land use in low-lying areas. The continuous problem of sand-bar formation and its prevention should be investigated from a coastal engineering point of view.

The investigations relating to the 10 schemes described in this study clearly identified the relevance of adopting a coordinated approach in understanding the problems associated with exclusion of salt-water and drainage in low-lying agricultural schemes. By conducting preliminary investigations of 10 schemes as opposed to that of one or two schemes, it was possible to obtain a clear insight to the common problems associated with the schemes. The problems of salt-water exclusion and drainage are two important issues which need to be carefully addressed in the overall management of low-lying coastal areas. For effective management, these issues should not be considered in isolation but in association with other issues, such as those discussed in section 5, which will have direct and indirect impacts on salt-water exclusion and drainage. This identifies the importance of developing an integrated management framework incorporating the relevant issues.

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3.10 Ground water behaviour in subsurface area of underground dams

ABSTRACT

As there exists situations where coastal aquifers need to be exploited at least at levels below through flow [1], there is a need to develop management techniques that facilitate this. Construction of underground dams is one such technique that allows abstraction but prevents the saline wedge intruding particularly when the cone of depression is at its lowest. Here, ground water behaviour in subsurface area of underground dams have been investigated. Figures based on the calculation results of the saturated and unsaturated analysis in three dimensions by Finite Element Method are sequentially plotted in transient time and thereby ground water movement in areas of underground dams have been investigated. It has been found that while there is a strong dependence on initial and boundary conditions as well as goodness of model calibration, it can be concluded that the proposed technique could be used for planning, designing and managing underground dams for salinity control.

Key words : Numerical Modelling, Salinity Intrusion

INTRODUCTION

Management of salinity intrusion by controlling hydraulic gradient is common practice. This is usually adopted either by reducing abstraction or moving abstraction wells upstream. However there exist situations where it is necessary to exploit the ground water system due to insufficient surface flows. This is further exacerbated when the through flow or a percentage of the through flow, of the ground water system is high enough to cope with the requirements. The case of Miyako Island is one such situation. Here the through flow is high enough to cater to the catchment demands. Nevertheless due to the cone of depression created during abstraction and the occurrence of the resulting reverse gradient, salinity intrusion tends to occur.

Therefore it is evident that alternate management techniques need to be investigated and hence here construction of underground dams for management of such situations has been investigated. In order to study the behaviour of aquifers subject to salinity intrusion but managed by underground dams, initially here numerical modelling of groundwater subject to underground dams was performed [2]. The Sunagawa underground dam in the Miyako island was used as a case. The results given below indicate ground water behaviour in subsurface area of underground dams. From this analysis it is evident that while there is a strong dependence on initial and boundary conditions as well as goodness of model calibration, it can be concluded that the proposed technique could be used for planning, designing and managing underground dams for salinity control.

CASE STUDY

The target area is the Sunagawa underground Dam in Miyako Island of Okinawa Prefecture in Japan. The maximum height of the body is approximately 46 meters and the length of the body is approximately 1500 meters.

Here an interesting part of the west edge has been studied. In the figures, the maximum height is approximately 10 meters and its visible length is approximately 50 meters.

The stratum of this island is composed of Ryukyu limestone and tertiary Shimajiri mudstone formations.

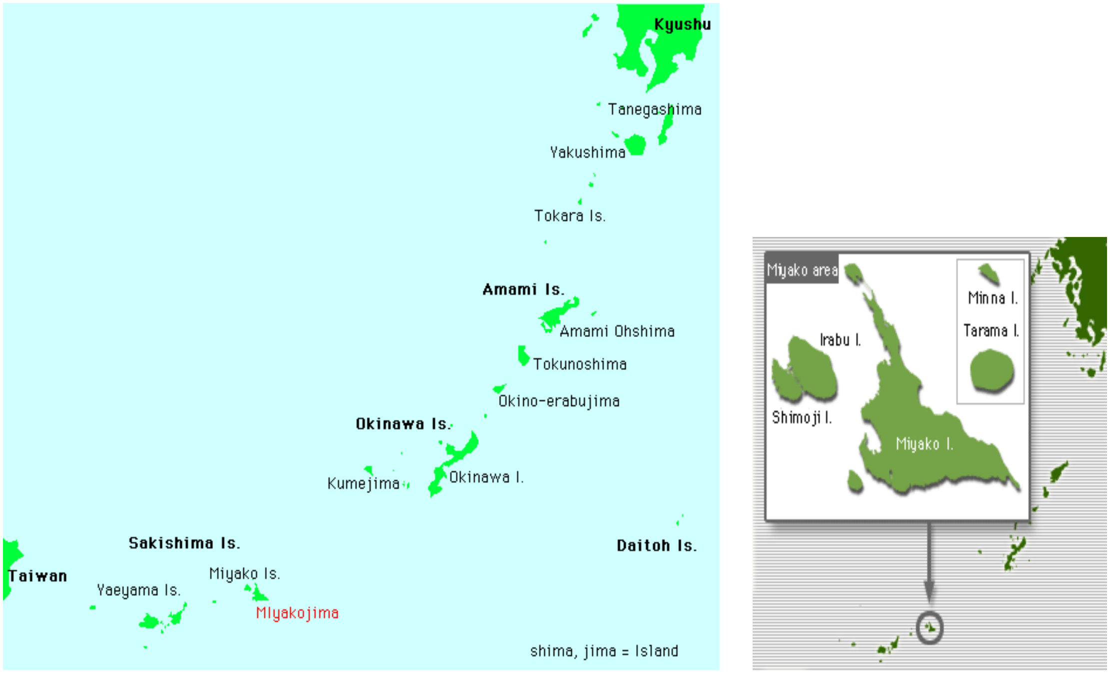
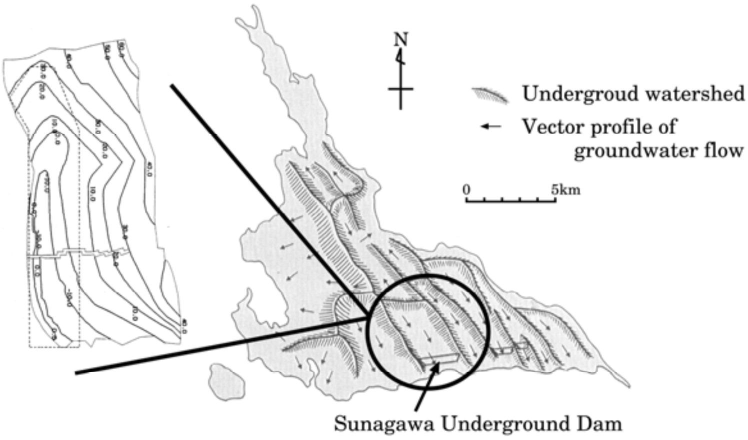


Fig – Sketch of Sunagawa Underground Dam in Miyako Island, Okinawa Prefecture.



DATA PRESENTATION

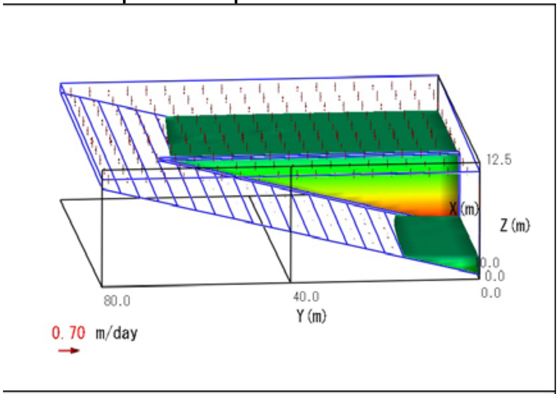
The following figures show groundwater behaviour flowing in the subsurface area of an underground dam body of concrete in the west edge and its environs. These figures based on the calculation results of the saturated and unsaturated analysis in three dimensions by FEM sequentially illustrate in transient time ground water movement. The images illustrate per day changes.

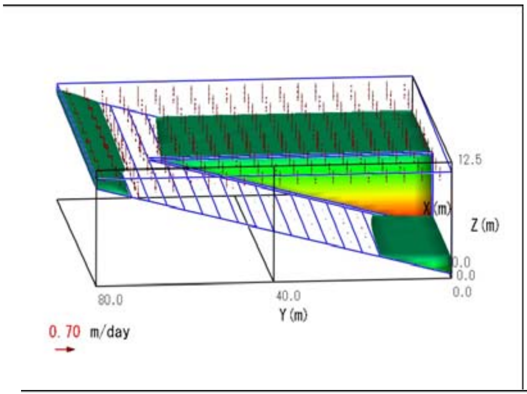
GW flows from north to South. Underground dam body builds along the east-west direction across the main flow direction. In these figures, this part of the body is located at and around west edge. The arrows in red show water movement. It begins with infiltrated water from rainfall, comes to unsaturated flow in the vertical direction, and flows into groundwater reservoir filled with water in soils. After that, groundwater gradually overflows to the downstream area beyond the underground dam body. Color graduations of water give saturation degrees of the water contents, in which green means 1 in completely saturated soils and 0 means near shifting to red via yellow in unsaturated soils.

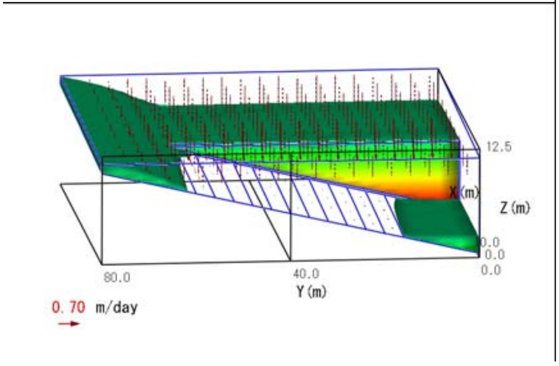
Graduation depicts the value of the pressure heads. Green means zero because groundwater table faces on the atmosphere and the pressure heads on it equals to the pressure of the atmosphere, i.e. zero. Transparent area in soils have negative pressure heads because of unsaturated conditions.

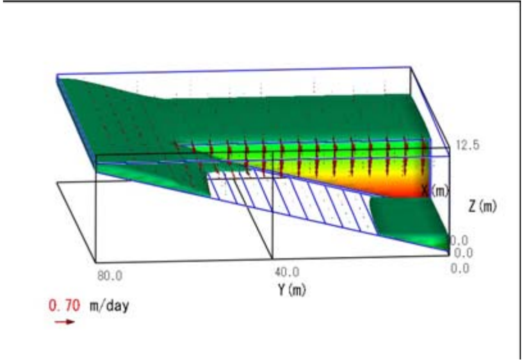
It could also be seen that flowing water detouring the dam body over the west edge of the analytical domain. This is also interesting behavior. Flow to the downstream of dam body is composed of not only overflow but also detouring flow. The fact will be key to planning of counter measures against seawater intrusion problems.

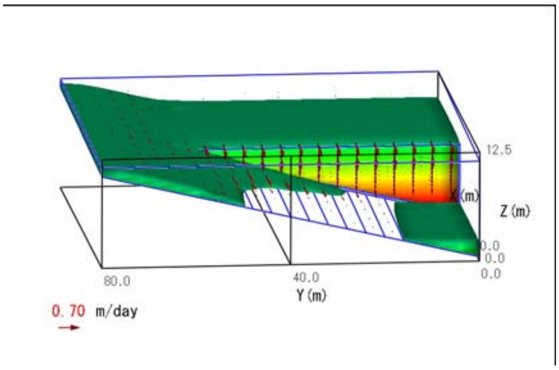
The input parameters are saturated hydraulic conductivity and porosity in space. The unsaturated model parameters are also needed. Actual rainfall and evapotranspiration data are used.

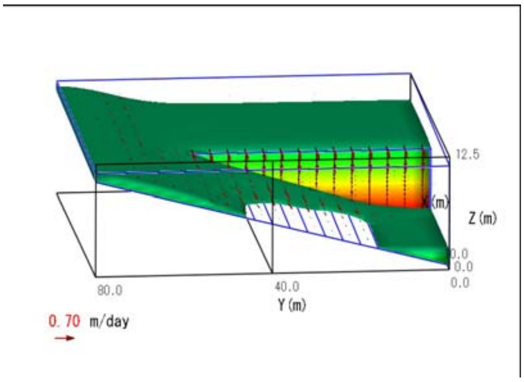












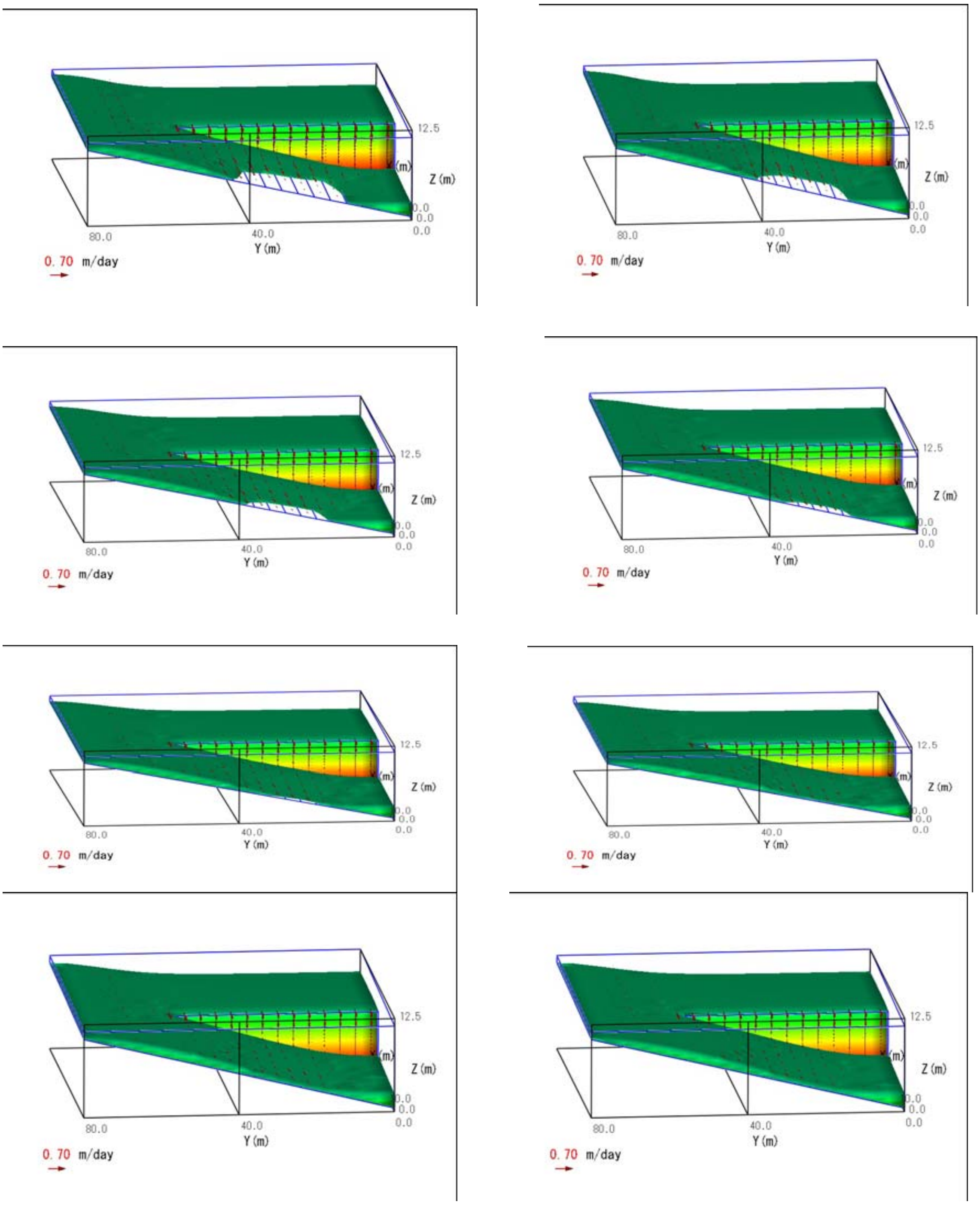
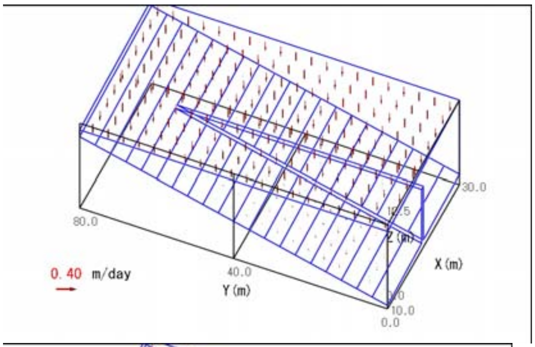


Fig – Daily ground water movement

Similarly the velocities of the ground water have been plotted. These have been plotted in order to show and grasp the featured velocity profiles in the frame box similarly with under ground dam..

In north part, there is groundwater reservoir. Water in down stream area of South part flows into Sea.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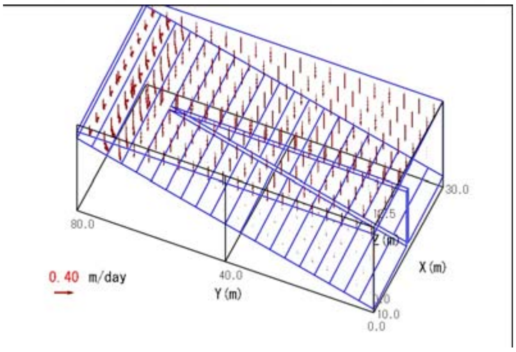
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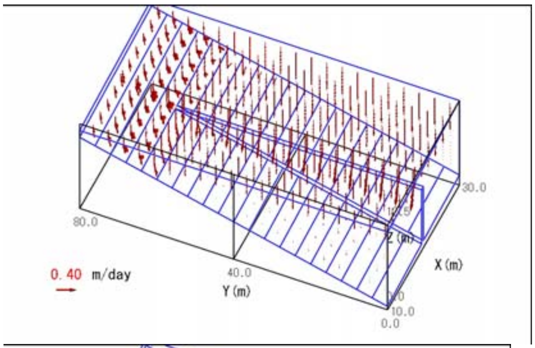
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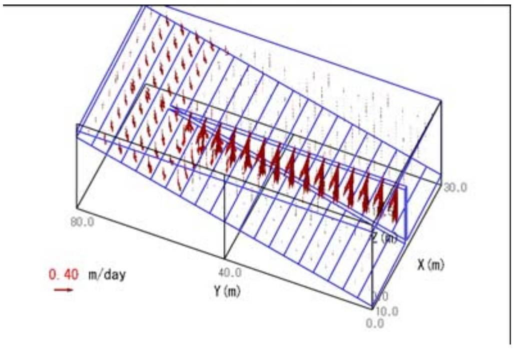
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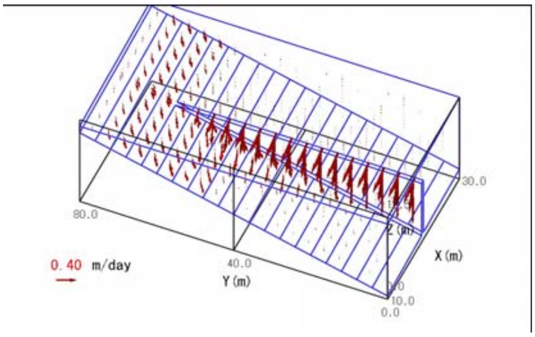
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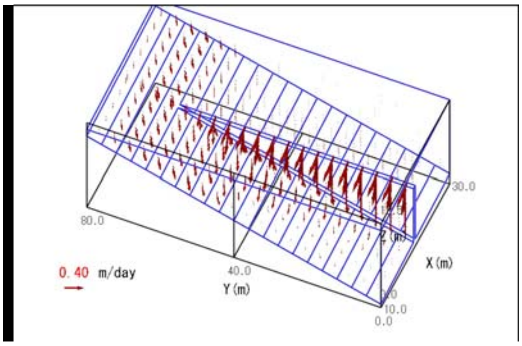
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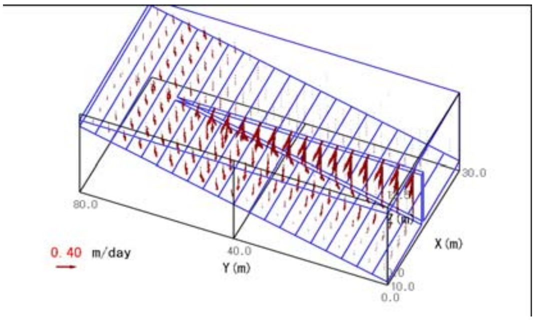

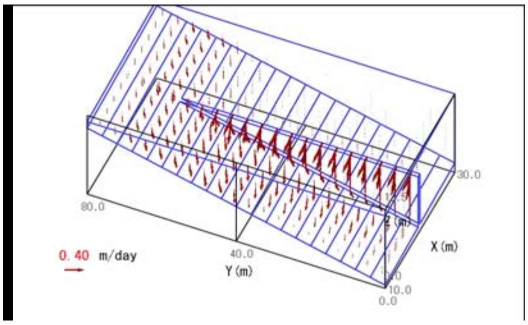

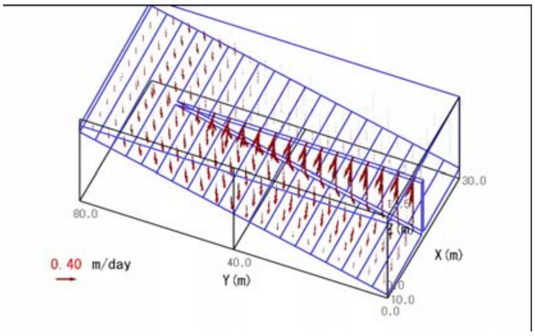

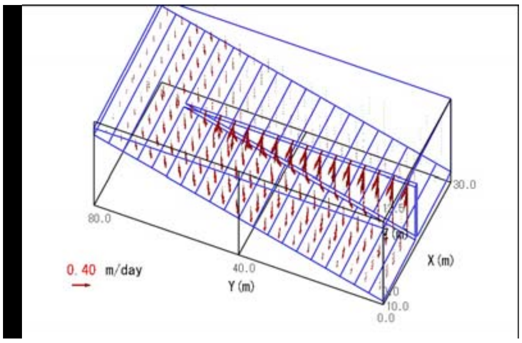

SUMMARY AND CONCLUSION

Ground water behaviour in subsurface area of underground dams have been investigated. Figures based on the calculation results of the saturated and unsaturated analysis in three dimensions by Finite Element Method are sequentially plotted in transient time and thereby ground water movement in areas of underground dams have been investigated. It has been found that while there is a strong dependence on initial and boundary conditions as well as goodness of model calibration, it can be concluded that the proposed technique could be used for planning, designing and managing underground dams for salinity control.

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4.0 Conclusions

This study set out to ,

1. Forecasting salinity intrusion in key Asia Pacific sites, which it did in many locations (Wellington, Bundaberg, Andra Pradesh, Sri Lanka) as detailed in section 3.1, 3.2, 3.3 and 3.7. It could be clearly seen that all these sites are susceptible to salinity intrusion and they have to managed.
2. Developing a methodology for multiple objective optimal management and this is detailed in section 3.8.
3. Developing technical & social management strategies such as management of spatial and temporal variation of abstraction quantity, management of recharge via construction of recharge wells, recharge ponds, recharge zones etc., is as detailed in sections 3.2, 3.3, 3.4, 3.4, 3.5 and 3.6
4. Increasing the profile & awareness of change in coastal zones and inland waters. This was achieved by media releases, presentations at local and international conferences, seminars and workshops.
5. Establishing links and networks with policy makers in relevant countries. This was achieved by working jointly with regional councils in each country, establishing links and networks with policy and decision makers relating to this issue in each country.
6. Disseminating information to policy makers. Again this was achieved by presenting research papers at local as well as international conferences, conducting seminars and workshops.

5.0 Future Directions

It has been found that there is a need to establish precise linkages between overall catchment change characteristics, and both surface flow and ground water flow regimes as well as volumes. Catchment change characteristics bought about due to demographic changes as well as global change.

Further there is a need to investigate more in detail the effect of global change on temperature variation, seawater level rise and its effect on salinity intrusion.

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Appendix

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