Development and Test of a Functional Relationship on Groundwater Salinity Reduction

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ABSTRACT

The study was undertaken to develop and test a functional relationship that would determine the effect of spatial change and time on salinity concentration using the data obtained from the freshwater recharging process. Thirty wells — 5 deep wells (injection wells) and 25 shallow tubewells (observation wells) were installed in the study site, 7.5 ha, at Brgy Sulongan, Pasuquin, Ilocos Norte. In site measurement of salinity in terms of electrical conductivity (EC) was measured daily from April to August 2011. Groundwater table depth was monitored simultaneously with EC. Freshwater injection was conducted in three batches: single well, three-well, and five-well processes at 50 m^3 per well. EC and groundwater table depth were monitored before and after the freshwater recharging activities using the Salinity-Conductivity-Temperature (SCT) meter. Functional relationships between the para-meters monitored were developed using linear and non-linear models.

Results showed that during the single-well injection process, its sphere of influence was only at the point of injection. This meant that the hydraulic barrier formed had pushed more saltwater landwards, thus an increase in groundwater salinity in the study area was observed. The second freshwater addition was similar to the first. The third process, that is, five-well freshwater addition of a total of 250 m^3 to the injection wells, demonstrated the best results. The hydraulic barrier formed a wider sphere of influence to the saline concentration of the experimental area that halted the movement of saltwater landwards. The salinity concentration decreased and was considerably maintained at low levels in the whole area. Equation 3 described that during weeks without freshwater injection, groundwater withdrawal is higher; groundwater salinity decreased with time as influenced by groundwater withdrawal. Equation 4 illustrated the condition of the study area during weeks with freshwater injection and depicted that when there is simultaneous injection of freshwater to the injection wells, a hydraulic barrier is built up, preventing saltwater intrusion landwards, thereby decreasing salinity level (< 10000.0 mg/L) in the study area. Further, the relative location (L) of the installation of the injections wells to the sea was significant in the formation of the hydraulic barrier that prevented saltwater migration inlands.

It was concluded that salinity concentration of groundwater in the area is above the 1000 mg/Li threshold limit for freshwater. The use of a five-well simultaneous recharging process at a rate of 50 m^3per day per well demonstrated the best method of mitigating saltwater intrusion inland. The procedure formed a hydraulic barrier at the widest sphere of influence. Groundwater salinity changes with time during weeks without freshwater injection. During times with freshwater injection, groundwater salinity was affected by time and vertical grid in the study area.

***KEYWORDS**: Salinity, groundwater table depth, single-well, three-well, five-well, hydraulic barrier*

INTRODUCTION

Coastal zones normally enjoy a milder climate than do inland areas at similar latitudes due to the heat regulating effect of the sea. As a result of these climate characteristics, they have greater potential for communication and transport (by sea routes), human settlements and socioeconomic prosperity. Thus, it is common to find on coastal delta or alluvial plains the establishment of significant human settlements, with a high level of agricultural activity, which is favored by the fertility of the soil.

The high level of demand for water in these areas often means that such aquifers are exploited intensively, which leads to the appearance of salt-water intrusion and endangers the sustainable use of the resource.

According to Custodio[3], in a coastal aquifer, there exists a natural equilibrium between the fresh groundwater that is discharged to the sea and the salt water of marine origin that presses towards the aquifer. This equilibrium is normally shaped like a wedge, resting on the base of the aquifer, because of its greater density. The penetration of this wedge depends on the characteristics of the aquifer, i.e., its geometry and its hydraulic properties (permeability, piezometric level, etc.), and this penetration is inversely related to the flow of fresh water discharged into the sea.

Though this occurs naturally, this can be altered by human-induced activities, especially intensive pumping of groundwater resources for agricultural activities and the enhanced usage for industrial and domestic purposes. These events would result to seawater going landwards. Heavy usage of groundwater is evident in the study area considered because of needed irrigation water especially during the dry season. The cropping pattern being practiced is predominantly rice-garlic-vegetables.

Land preparation for rice is also becoming dependent on pumping of groundwater since the onset of the rainy season usually starts late, that is, July or August. Farmers would always want to start early in land preparation and other related activities so that they will also harvest on time. Just after rice production, garlic and other dry season cash crops would be planted simultaneously. These cash crops are planted to supply the vegetable needs of nearby and distant provinces. All of these crops require sufficient amount of freshwater for better yield. Farmers invest capital on the use of shallow tube wells (STW) for groundwater pumping to sustain their crops. This would usually mean intensive use of groundwater resources.

Yahaya[1] stated that it is a form of general linear modeling and a statistical technique that can be used to analyze the relationship between a single dependent (criterion) variable and several independent (predictor) variables. In his study, he further illustrated the procedure in selecting the best model in estimating the salinity in terms of EC levels based on the hydrochemistry properties and nature effecting factors using multiple regressions. There were six independent variables and two dummy variables considered in this data set. The Multiple Regression (MR) models were involved up to first-order interaction and there were 57 possible models considered. This study is the extension of prior research which had generated 63 possible models, by using the same technique but no interaction involved between the independent variables. The process of getting the best model from the total of 120 possible models had been illustrated. The backward elimination of variables with the highest p-value was employed to get the selected model.

On a personal interview, some farmers and residents are already aware of the consequences of the encroachments of seawater to their STWs. In fact, they have already observed and reported that some of their existing STWs are already abandoned because of high level of salinity.

Actual field studies on remediation such as the reduction of saltwater intrusion using fresh-water injection technology has not been done yet, hence this study.

OBJECTIVE

The study was undertaken to develop and test a functional relationship to determine the effect of spatial change and time on salinity concentration using the data obtained from the freshwater recharging process.

METHODOLOGY

The Study Area

The study site is located at Barangay Sulongan, Pasuquin, Ilocos Norte. It is basically a rain-fed agricultural area and is one of the eight coastal barangays of Pasuquin, llocos Norte located, 18.22^{o}N and 120.36 ^{o}E, 142.0 nautical feet at about 350.0 m from the coastline of the China Sea. It is about 1.7 km from the town proper.

The location of the 7.5 ha production areas where the five IWs and 25 OWs were installed and observed starts at the southwestern most part to the northwestern most part parallel to the China Sea going to the southeastern most going eastwards perpendicular to the seashore. The first row is the

5 IWs located at lower elevations and the succeeding rows are the 25 OWs at higher elevations.

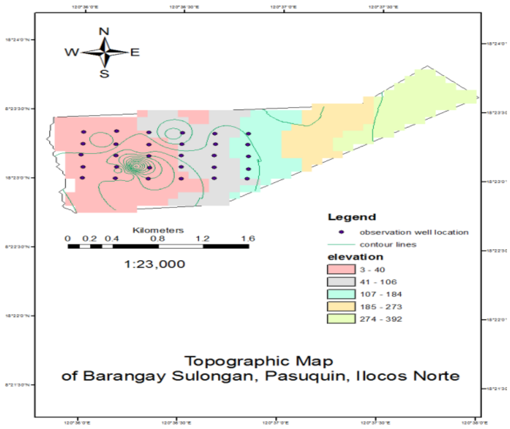

Figure 1. Location of the 5 IWs and 25 OWs in the study area.

The area was selected considering the following: (a) coastal area involved in farming, (b) with a pre-determined salinity level beyond the threshold limit of 1000.0 mg/L, (c) has an adjoining service area of 7.5 ha and 350.0 m from the coastline, and (d) has an available source of freshwater for the recharging process.

Installation of Injection Wells (IW), Observation Wells (OW) and Extraction Well (EW) in the Study Area

An inventory of existing shallow tube well (STW) and deep well (DW) in the area was done. There were 10 STWs and five DWs existing in the area where the initial salinity and groundwater table depth status was gathered and recorded.

A matrix of five (5) IWs, and 25 OWs were installed and drilled manually, 350.0 meters from the coastline, 100.0 meters and 30.0 meters apart from each other, parallel and perpendicular to the seashore, respectively, using a locally manufactured and operated drilling rig. The IWs were made of 1.0 meter diameter cement casing while the OWs were cased with 0.051 m diameter PVC pipes. The EW was an existing DW 30.0 meters from the OWs used for water extraction simultaneously conducted with freshwater injection process. An existing farm ditch between well groups C and D was laid out by the farmers to convey water from the irrigation canal of the Estancia–Sulongan Communal Irrigation System. This same farm ditch was used during the freshwater injection process.

For an orderly data collection and monitoring, the wells were grouped according to direction, that is, from west to east and from south to north.

Group A- IW1,OW1,OW6, OW11, OW16, OW21
Group B- IW2, OW2, OW7, OW12, OW17, OW22
Group C- IW3, OW3, OW8, OW13, OW18, OW23
Group D- IW4, OW4, OW9, OW14, OW19, OW24
Group C- IW5, OW5, .OW10, OW15, OW20, OW25

Group I- IW1, IW2, IW3, IW4, IW5
Group II- OW1, OW2, OW3, OW4, OW5
Group III- OW6, OW7, OW8, OW9, OW10
Group IV- OW11, OW12, OW13, OW14, OW15
Group V- OW16, OW17, OW18, OW19, OW20
Group VI- OW21, OW22, OW23, OW24, OW25

Determination of the Effects of Freshwater Injection to the Study Area

This was determined by conducting the processes of recharging the five IWs following the procedure done by Chew[2] to test the best time to form a hydraulic barrier that would possibly halt the occurrence of saltwater intrusion landwards.

The first injection of freshwater was done in IW4 during week 2 at a rate of 50 m^3 per well. The freshwater came from the nearby Sulongan- Estancia -Caruan Communal Irrigation System which was conveyed via an irrigation canal to a farm ditch going to IW4. A pump set was used to inject the freshwater to IW4.

The second injection was done simultaneously in three IWs (IW3, IW4 and IW5) during week 8, also with the same rate of 50 m^3/well. Three pump sets were simultaneously used to draw and add water from the same farm ditch to the three IWs.

The last injection was done simultaneously in the five IWs (IW1 to IW5) during week 11 using five pump sets at the same injection rate as before.

While injection of freshwater is going on, extraction was also conducted from the chosen extraction deep well within the experimental area at the same rate of 50 m^3 per day using another pump set to determine its effect on groundwater table depth and salinity level of the IWs and OWs in the study area.

Data gathering on water table depth and EC was done before and after each freshwater injection process in all the IWs and OWs using the SCT meter. This was made to monitor any possible change in EC and groundwater table depth.

The effects of the freshwater injection processes done were interpreted by plotting the gathered groundwater salinity values against the time of observation in graphical presentation.

Development of the Functional Relationship

Multiple linear and non-linear regression models were tested in order to relate to the change in salinity with respect to time and space.

Actual groundwater salinity levels gathered from weeks 1 to 14 from all the wells were regressed with groundwater salinity as the dependent variable, while the independent variables were time of freshwater injection (T); horizontal (H) grid and relative location (L) of the study area. That is:

$$S = f(T,H,L) \quad (1)$$

Where:

S = groundwater salinity, mg/L

T = time of observation, week

H= perpendicular distance from the seashore, m

L = relative location or the parallel distance from the seashore, m

A scatter diagram was plotted to determine the trend of the data as to whether the salinity levels change linearly or non-linearly with respect to the well locations. The regression model that best fitted the trend of the data was then used to determine the intercept and the coefficients of the independent variables.

The functional relationship during weeks (Weeks 1, 3, 4, 5, 6, 7, 8 and 9) without freshwater injection, likewise during weeks with freshwater injection (weeks 10 to 14) were developed respectively using multiple linear regression-stepwise method in Statistica 7.0. The groundwater salinity of OWs 1 to 25 was regressed to the time of injection (weeks), the perpendicular and the parallel distances from the seashore of the study area. Before regression processes were done, the three variables considered were subjected to significance test, specifically the functionality of the coefficient r. The variable that has the highest r value was considered as the first variable to be inputted to the equation developed.

In the stepwise analyses, groundwater salinity was considered as the dependent variable while time of freshwater injection, perpendicular and horizontal distances from the seashore of the study area were the independent variables. The data considered during weeks without freshwater injection were the salinity values of weeks 1 to 9, except those at group D where IW4 belongs and were observed during week 2 when the single–well injection was done. Also, salinity values at groups C, D and E where IW3, IW4 and IW5 were analysed during week 8 when the three-well injection happened. The goal of the analyses was to determine which of the independent variables would give a significant p-value to groundwater salinity. A p-value of 0.05 was used as the cut-off for statistical significance.

The observed values of groundwater salinity were compared with the predicted ones by the developed functional relationship using t-test.

RESULTS

Effects of Recharging the Injection Wells (IWs) in the Study Area

The status of the groundwater salinity level of the 5 IWs and 25 OWs of the study area posed an alarming status that is beyond the WHO threshold limit of 1000.0 mg/L. This was the basis of conducting the freshwater injection process and evaluating its effects in the reduction of the groundwater salinity level.

Effects of single–well injection process

Figure 2 shows the effects of the single-well freshwater injection in the study area which was done on the third day or during week 2 at IW4.

Apparently, there was an increased salinity concentration on the fourth and fifth days (Figure 2) which was even higher than during days without freshwater injection. That is, the increase was from the point of injection where IW4 belongs. IW4 to OW24 increased in salinity level. This would mean that the hydraulic barrier created by the addition of 50.0 m^3 pushed more salt ions within the edges of IW4 and remained high until Week 2.

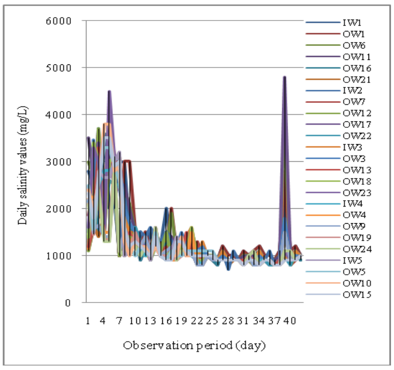

Figure 2. Effects of single-well freshwater injection to the study area during week 2 at IW4.

Twelve days after the single-well injection (May 17), the trend was already decreasing except for OW24 under group D, where the highest salinity level (3000.0 mg/L) was recorded. This would indicate that there might be other factors causing the high groundwater salinity level at OW24. This OW is located at the north eastern part of the study area where dry season cash crop such as peanut was the standing crop. There may be intensive use of groundwater resource in this part to meet the water requirement for peanut (400-700 mm /total growing period). Note that higher groundwater pumping causes higher salinity concentration.

The decreasing trend, however, continued until 40 days (June 26) after all wells were already full. The scenario might be the result of minimal groundwater extraction because it was the peak season for harvesting peanut.

The same situation of the increase in salinity level at the point of injection only was reported by Chew[2]. The process done with single well injection proved detrimental to the whole study area because higher levels of groundwater salinity were observed from all the wells. Further, the injection process would also indicate that the freshwater added to only a single well is not effective in creating a hydraulic barrier that should have halted the movement of saline waters landwards.

Effects of three-well freshwater injection process

The second freshwater injection was due on June 29, 2011 (Week8) in IWs 3, 4 and 5. An apparent salinity increase was observed during weeks 9 and 10 particularly at well groups A and B.

The 150 m^3/application of freshwater injected to IWs 3, 4 and 5 had its decreasing salinity effect near the point of injection only, which includes the OWs aligned to them. This also means that the effects of the freshwater injection pushed more saltwater inland specifically to well Groups A and B. However, the trend was decreasing, and was generally within the threshold limit of 1000.0 mg/L (Figure 3). The result might be related to the decrease in groundwater pumping since the dry season crops were harvested when the injections were done.

Chew[2] reported that the scenario can be further explained that because of hydraulic barrier formed at the three locations, the elevated pressure serves as a driving force that pushed salt ions to the edges of the groundwater system in the area. This was deemed responsible in the migration of salts through the effects of diffusion and dispersion that cause the increase in saline concentration.

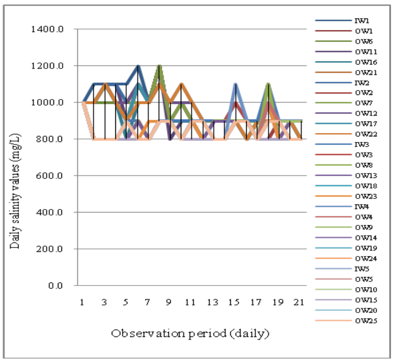

Figure 3. Effects of three-well freshwater injection to the study area during week 8 at IW3, IW4, IW5.

Effects of the five-well freshwater injection process

Figure 4 shows the salinity level of the study area after the addition of freshwater simultaneously to the five injection wells done on July 20, 2011 (Week 11). A decreasing trend in salinity concentration was observed eleven days (July 27) after the five well injections and continued up to 23 days (August 19) after injection. The groundwater salinity values gathered from all the wells during these weeks were already far below the threshold limit of 1000.0 mg/L set by the WHO. The trend was maintained considerably in the whole area.

The aquifer behavior on the simultaneous addition of 50m^3 / application / well of freshwater formed a hydraulic barrier with a wider sphere of influence to the salinity concentration of the experimental area. This would also explain that during this time, the area received a total amount of 4.0 mm of freshwater from this injection compared to the single well injection which had a smaller amount of 0.8 mm and to the three well injection processes with 2.4 mm. With the combined sphere of influence, the hydraulic barrier formed was able to halt the movement of saltwater landwards.

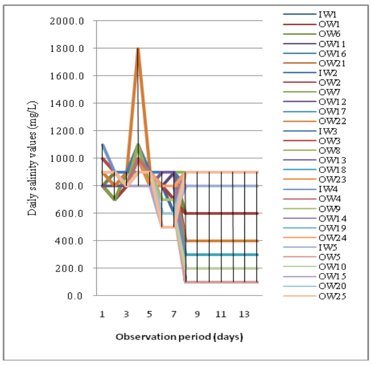

Figure 4. Effects of five-well freshwater injection process to the study area done at IW1, IW2, IW3, and IW4 during week 11

The figure depicts the saline concentration over time. This shows that the joint effect of the five injection wells was able to arrest the movement of saltwater inland and that a general decline in salinity concentration was observed.

Likewise, the figure also shows that simultaneous injection of freshwater in all injection wells seemed to be more effective than either the single well or the three-well injection processes.

Salinity as a Function of Time and Spatial Variation during Weeks without Freshwater Injection

As presented in Table 1, time without freshwater injection showed a highly significant relationship with groundwater salinity (β= -169.523, t= -13.68 and p value = 0.000). However, horizontal and vertical grids did not have significant effect on salinity.

Table 1. Regression results between independent variables and groundwater salinity during weeks without freshwater injection.

Independent Variables	Coefficients (β)	t	p-value	Interpretation
Time	-69.523	-13.8	0.0	Highly significant
Horizontal grid	-0.156	-0.76	0.541	Not significant
Vertical grid	-0.658	-1.15	0.894	Not significant
Intercept (a)	2366.854	27.1244	0.001	Highly significant

The model has a coefficient of determination (R^2) of 0.72. The model is:

$$S = 2366.854 - 169.52T \quad (2)$$

Where:
S = predicted groundwater salinity, mg/L
T = time without freshwater injection, weeks ($1 \leq T \leq 8$)

This means that during weeks without freshwater injection, groundwater salinity levels in the whole study area are statistically similar with each other for a given week. However, the salinity levels in the whole study area are significantly different from one week to another.

That is, salinity decreased as time changed from April to August. Note that April and August are the first and last months of salinity data collection, respectively.

Figure 5 also describes the relationship between the observed and the predicted groundwater salinity levels during weeks without freshwater injection.

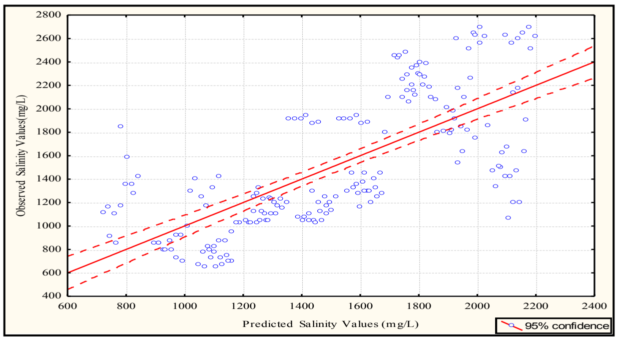

Figure 5. Relationship between the observed and described groundwater salinity values of the study area during weeks without freshwater injection.

The trend could be attributed to the effects of groundwater resources withdrawal to increased groundwater salinity. The higher the amount of groundwater withdrawal, the higher the groundwater salinity level of an area. During intensive groundwater pumping, saltwater tended to migrate inland to fill up the withdrawn freshwater, thereby increasing the salinity.

This scenario can be associated to cropping pattern in the study area which was predominantly rice-peanut. During the months of April to May (weeks 1 to 6), most of the production areas within the study area were planted with peanuts. This was also the growing stage of the crop wherein it demands high amount of groundwater for irrigation to sustain its growth and development. The crop water requirement for peanut is 500-700 mm with 130-140 days growing period (USGS Fact Sheet 103-3).

Farmers would intensively use their existing shallow tubewells to pump out the needed water to irrigate peanuts during this period. The area is rain-fed and no other source of water for irrigation is available, thus ground-water resource is at stake to saltwater contamination.

June to July (weeks 7 to 10) are the months for planting rice wherein groundwater pumping was already lesser compared to April to May. Ground-water pumping was only done during land preparation for rice. During this period, rainy season had not yet started in the study area, but farmers were already preparing their fields through pumping of groundwater resource using existing shallow tube wells.

However, the groundwater pumping might not be as intensive as in April and May. With these, there was an extensive use of groundwater resources in the study area during April to May and lesser during June and July. According to the Groundwater-Depletion across Nations USGS Fact Sheet 103-03, the most severe consequence of excessive ground-water pumping is when the water table is lowered and causes salt-water to migrate inland and upward resulting in saltwater contamination of the water supply.

Salinity as a Function of Time and Spatial Variation during Weeks with Freshwater Injection

Time of freshwater injection and the vertical grids of the study area showed highly significant relationships with groundwater salinity level during weeks with freshwater injection. The equation that relates groundwater salinity, time and relative location is:

$$S_{(i,j)} = 1094.49 - 208.88T + 0.872L_{(i,j)} \qquad (3)$$

Where:

$S_{i,j}$= predicted groundwater salinity at the row and i^{th} and j^{th} column of the study area;

T = time of observation, weeks. That is, a week without freshwater injection serves as an initial week in developing Equation (3); the second week is the week with fresh water injection, and the succeeding weeks are those without fresh-water injection but are showing the effect of freshwater injection, 1≤T≤5;

L = relative location (m) from south to north of the field, 1≤ L≤ 400m on the ith row and jth column of the study area. That is, the ith row is the horizontal distance while the jth row is the vertical distance relative to the 0,0 coordinates where IW1 is found.

The equation has an R^2 value of 0.65. It shows that simultaneous freshwater recharging on the five injection wells was effective in the reduction of saltwater intrusion in the study area as hydraulic barrier that was formed to halt seawater pushing inlands. The injection wells that run parallel to the sea coast and were installed from south to north of the study area were contributory in halting seawater landwards. The trend in the groundwater salinity reduction followed an ideal technique on how the injection wells (IW1 to IW5) were installed for fresh-water injection and hydraulic barrier build up.

The equation also suggests that there was a significant change in salinity concentration with respect to time. That is, the effect of freshwater injection in the five injection wells is still being felt in the next three weeks (weeks 12, 13 and 14) after the week of injection. It must be noted that rainfall had already occurred in the study area after the last week of data gathering (Week 14), the effect of which is expected to further lower the salinity concentration.

Table 2 shows the test of significance of time, T, and the relative location, L. The observed and predicted salinity values during weeks with fresh-water injection were from weeks 11 to 14. The independent variables that were considered were time (T) and the relative location (L), that is, the parallel distance from the seashore.

Table 2. Multiple regression results between groundwater salinity and the independent variables during weeks with freshwater injection

Independent Variables	(β)	t	p-value	Interpretation
Time	-208.88	14.2958	0.001	Highly Significant
Vertical grid	0.872	6.0763	0.001	Highly Significant
Intercept (a)	1094.49	17.9374	0.001	Highly significant

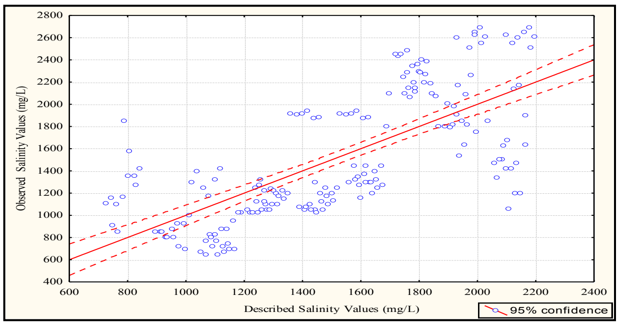

Figure 6. Relationship between the observed and predicted groundwater salinity values of the study area during weeks with freshwater injection

CONCLUSION

Salinity concentration of groundwater in the area is above the 1000 mg/Li threshold limit for freshwater. The higher the groundwater withdrawal, the higher the salinity level. Groundwater table depth is deepest during April to May, and becomes shallower during the months of July to August. Likewise, groundwater table depth is shallower near the coast and is deeper landwards.

The effect of freshwater recharging using a single well would form a hydraulic barrier within the area of injection only. The high pressure produced due to the activity would push salt ions within the edges of the groundwater system, specifically at the toe of the injection site, causing an increase in salinity concentration. A three-well recharging process would have a wider sphere of influence the single well, both having a recharging rate of 50 m^3per day per well. The use of a five-well simultaneous recharging process at a rate of 50 m^3per day well demonstrated the best method of mitigating saltwater intrusion inland. The procedure formed a hydraulic barrier at the widest sphere of influence. The injection wells were spaced 100 m apart.

Groundwater salinity changes with time during weeks without freshwater injection. That is, the salinity increases as time increases. During times with freshwater injection, groundwater salinity was affected by time and vertical grid in the study area.

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