# Impact of Groundwater Level Decrease and Sea Level Fluctuations on Potential Saltwater Intrusion in the Subsurface Coastal Area of West Hokkaido, Japan

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## ABSTRACT

In order to limit possible inland seawater intrusion, important freshwater resources contained in coastal aquifers should be exploited carefully. Salinization of coastal waters is often due to inflow of dense saline water from the sea or deep inland geological layers, during heavy groundwater withdrawals, drought or long-term sea level rise. A continuous trend in the decrease of groundwater level and land subsidence, resulting from freshwater over-pumping, has been noticed in the subsurface of Hokkaido's coastal area facing the Sea of Japan, since the 1960's. This could lead to the decline of groundwater quality. This decline may be further amplified by seawater level increase. Past sea level records along this coast have shown continuous oscillations over various timescales of years and decades. A particularly high rate of sea level increase (3.2 mm/year) compared to the rise of the world ocean level, has been observed towards the northern edge of this coast. To avoid inland saltwater encroachment causing salt contamination of coastal aquifers, it's vital to determine the position of the seawater-freshwater interface and control its movement. For this purpose, water chemical analyses from drilled wells as well as analytical and numerical simulations are often employed to approximate the location of this boundary and understand the relevant processes that cause saltwater intrusion in coastal aquifers. For the present study, two modeling solutions are used to determine the shape and position of the interface between the landward potential seawater intrusion and subsurface freshwater outflow to the coast. Then, investigations are conducted to examine the impact of groundwater level decrease and sea level fluctuations, on the extent of this saltwater interference in the dynamics of the coastal flow system of the area.

**Keywords**: Saltwater intrusion, Groundwater level, Sea level, Modeling solutions, Coastal aquifers

## INTRODUCTION

It's well known that increased level of salt content in aquifers may result from natural phenomena (rock weathering, leaching from unsaturated zones or adjacent aquifers) or anthropogenic effects such as intrusion of seawater, irrigation, disposal of untreated sewage etc. In built-up areas, leaching from road salt, waste sites and sewage systems may result in elevated salinity levels. Another source is corrosion in underground pipes, which, due to the effects on taste, may also limit the usefulness of groundwater for drinking purposes. For efficient planning and management of coastal aquifers, it is essential to delineate and predict the extent of saline water intrusion into the aquifers in response to variations in the

components of the freshwater mass-balance [1]. An accurate estimate of the depth to the theoretical interface between fresh and salt water is critical to estimates of well yields in coastal and island aquifers [2]. The origin of salinity in an aquifer may not always be straightforward; it may be as well from an upper confined source bed, or from its natural salt contents inherited from an ancient marine sedimentation seeping to the lower aquifer, or induced upconing from deep layers to overlying aquifers, as, well-induced seawater intrusion.

In the island of Hokkaido, seawater intrusion has been noticed in shallow and intermediate aquifers of the Pacific coastal area, around Kushiro, east of Hokkaido, from 1983 to 1991. The driving factor of this intrusion was the lowering of groundwater level due to excessive groundwater pumping by the fishing industry. The abundance of boreholes near the shoreline facilitated the monitoring and detection of this freshwater contamination by seawater. Chloride concentrations exceeded 12,000 mg/l in the most saline aquifer [3]. On the opposite sea side, i.e. the Sea of Japan coastal area, there is so far no clear chemical evidence of seawater intrusion from the few existing observation boreholes of the area. The land aquifers' extension several kilometers offshore could probably be a limiting factor to the inland salt-water intrusion. Nevertheless, the continuous trend of groundwater level decrease and land subsidence in and around this coastal area, due to over-pumping since the 1960's, could cause a rapid landward progression of the seawater front. Since surface water resources are relatively abundant in the region, the problem of possible saltwater intrusion in coastal aquifers has been greatly overlooked and minimal attention has been given to the issue. According to Ref. 4, the groundwater level in the deep aquifers has recently reached a maximum depth of about 80 m below the ground surface in the western flank of the Nopporo Hills. This hydraulic level decline added to induced land subsidence are expected to accelerate the degradation of the groundwater quality by increasing its salinity concentration either through self-accumulation or seawater intrusion into the coastal aquifers. This salinity increase may be further amplified by the rising of the global sea level (average rate of 1–2 mm/year during the last century). The present study has a double objective: first, determine the approximate position of the saltwater-freshwater interface then, estimate the effects of groundwater level decrease and sea level fluctuations on the landward seawater movement.

## GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The geology of the coastal area of Hokkaido facing the Sea of Japan shows a wide lateral distribution at shallow depths, of silt, clay, sand, gravel and peat formations on the lowland, and volcanic formations of andesite and volcanic ash on the highland.

The subsurface geology of this area is marked by Quaternary sedimentary units underlain by Tertiary volcano-sedimentary deposits, volcanic or volcano-clastic materials of andesite, volcanic ash, angular fragments of breccia or tuffaceous breccia, shales, siltstones and sandstones. The Quaternary sedimentary units are made of alternating beds of thick layers of fine-grained materials and thin layers of coarse-grained materials, and produce poor aquifers [4]. Detailed geological logs show a vertical distribution of alternating facies of sand, gravel, silt, clay and peat dating from Holocene and, middle to late Pleistocene. These are followed by early Pleistocene layers (gravel, sand and mudstone) named the Zaimokuzawa Formation; and late Miocene Nishino Formation (sandy) and middle Miocene Otarunaigawa Formation made of volcanic conglomerate, tuff breccia, volcanic breccia, pumice tuff, sandstone, mudstone, hard shale, and calcareous nodules [5]. The Lower Pleistocene system consists mainly of marine sediments, while the Late Pleistocene formations result from fluvial deposits; and the volcanic rocks here are mainly a product of submarine volcanism [6].

Figure 1 shows a simplified geological cross-section of the area, along a NW-SE direction that is perpendicular to the shoreline. The land area of this cross-section is reproduced from Oka et al. (in press). Based on the contour depth features of the geological map of the area [7], the land section extension offshore could be derived. The Sea of Japan is connected to the coast of Hokkaido by a continental shelf of around 50 km long. It's well known that continental shelves generally originate from the inundation of flat coastal areas by an increase in the height of sea level. The land-sea transition of this coastal area is marked till 20 km in the sea, by a relatively steep slope with a gradient of 1/100 up to 20 m seafloor depth, then between 20 and 30 m depth, a gentle slope with a gradient of 1/1000, between 30 and 40 m depth, a relatively steep slope with an average gradient of 1/600 and, after 40 m depth, a gentle slope with a gradient of 1/1000 [8]. This flat plain may have been formed about 10,000 years ago when the sea level depth was around 45 m
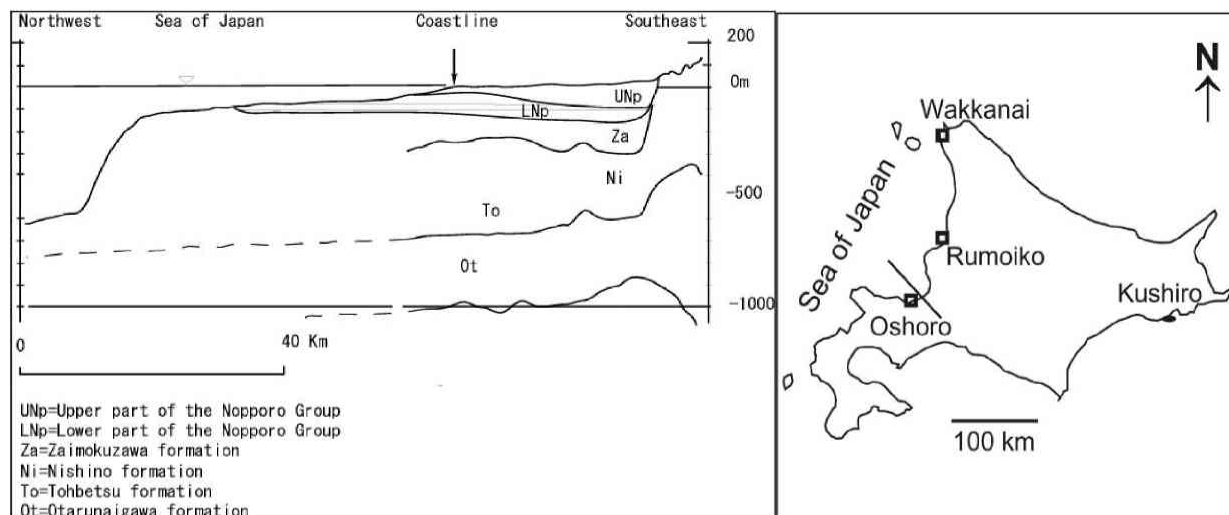
**Fig. 1** Left: Geological cross section along Northwest-Southeast direction (modified from Oka et al., in press). Right: location of the cross section and, the three tidal-gauge stations, which are discussed in section "Response of the interface to sea level changes".

lower than the present level [9]. As in many coastal areas, the shoreline of the area has been affected either by sedimentary erosion or deposition. According to Ref. 10, observed long-range movement of the Ishikari shoreline from 1947 to 1995 indicates a maximum shoreline advance (sedimentary deposition) of around 100 m and a yearly maximum shoreline fluctuation of about 40 m (for 1996–1997).

## HYDRAULIC AND CHEMICAL OBSERVATIONS

The aquifer system of the coastal area of Hokkaido facing the Sea of Japan is generally divided into upper aquifer (less than 30 m below the surface) and middle aquifer (50 to 80 m), both of Quaternary age, and, lower aquifer (more than 120 m depth) of Tertiary Neogene age. The middle and lower aquifers are particularly important for the region as, they are generally exploited for water supply. The chemical sequence of the groundwater in these aquifers, shows an evolution from Ca-Mg-HCO$_3$ type in the highland to Na-K-HCO$_3$ type in the lowland [11]. Since the 1960's, many pumping wells have been constructed for industrial needs, in the area. Some of the most productive aquifers here, could be of limited use due to the presence of saltwater from deep marine layers and possible seawater intrusion. Information about the distribution of saline water in these aquifers and an evaluation of the potential for intrusion or upconing of saline water would contribute to the wise management of the

groundwater resources of this coastal area. The excessive groundwater pumping in the area, led, not only to water level decrease but also to a relatively rapid land subsidence. The groundwater recharge is probably not sufficient to compensate for the losses due to pumping. To evaluate this recharge, we can use the basic water balance concept leading to an approximate groundwater equation:

$$R + G_i - G_0 - G_s - ET_d - Q_w = 0$$

Where $R$ = groundwater recharge
$G_i$ = groundwater inflows through the lateral boundaries and bottom of the aquifer
$G_0$ = groundwater outflows through the lateral boundaries and bottom of the aquifer
$G_s$ = groundwater discharge to streams
$ET_d$ = deep evapotranspiration extracted from the saturated zone
$Q_w$ = well discharge

Due to insufficient data, to accurately obtain the parameters of this equation, we rather adopted a more simple approach i.e. the use of environmental tracers such as chloride. We would assume that the only input of chloride to the groundwater is by rainfall plus dry fallout from the atmosphere. And groundwater recharge may be estimated through the chloride mass balance approach, as follows:

$$P \cdot Cl_p = R \cdot Cl_{gw}$$

Where $R$ = groundwater recharge (mm)
$P$ = mean annual precipitation (mm)

$Cl_p$ = chloride concentration in rainfall (+dry fallout) (mg/l)
$Cl_{gw}$ = chloride concentration in groundwater (mg/l)

The average recharge in the year 2002 evaluated through shallow wells of the area is around 123 mm/year. According to [12], the renewable potential of groundwater resources (volume of groundwater recharge) of Japan is estimated at about 27 km³/year. With a total land area of 376 520 km², the annual groundwater recharge of the country is around 72 mm/year.

The shallow wells of the study area generally show chloride concentrations ranging from 20 to 60 mg/l. Regarding seawater chemical composition, its total salinity estimated by CTD measurements has seafloor value of around 34,000 mg/l along the continental shelf. Assuming that chloride accounts for 55% (generally admitted chloride percentage in seawater) of this amount, we would obtain a chloride concentration of around 19,000 mg/l. This value will be used as initial seawater chloride concentration for the numerical simulation of the solute transport, while the initial amount of chloride in groundwater would be 40 mg/l.

## ANALYSIS OF SALTWATER-FRESHWATER INTERFACE

Various studies have been made to analyze the major factors that determine and influence the location and the thickness of the saltwater-freshwater transition zone near or within coastal aquifers and also to decide an appropriate method of quantitative analysis. Some of these suggest analytical solutions to approximate the saltwater-freshwater interface: the Badon Ghyben relation [13] in the late 1800's, [14] then [15] around the 40's, Henry's solution [16], [17], [18], [19], [20]. A historical review of these works and more, related to quantitative analyses of saltwater-freshwater interface problems can be found in [21]. To determine the quantity of water that can be developed without inducing groundwater quality degradation due to seawater intrusion, several issues must be addressed: the amount of freshwater flow through the system, the quantity of natural freshwater outflow to the sea, the undisturbed position of the interface offshore, the quantity of discharge that must be maintained in order to keep the interface at or near the shore, and the rate at which the interface will move due to onshore development [22]. The zone of mixing will be approximated as a sharp (straight or curved) interface

between fresh and saltwater (both considered as if they were immiscible fluids). The sharp interfacial boundary between fresh and saline water does not occur under field conditions. Instead, a brackish transition zone of finite thickness separates the two fluids. This zone develops from dispersion by flow of the fresh water plus unsteady displacements of the interface by external influences such as tides, recharge, and pumping of wells [23].

The present study aims at determining the approximate position of the saltwater-freshwater interface around the coastal area of Hokkaido facing the Sea of Japan, and the impact of groundwater pumping and sea level fluctuations on this interface. To conduct this investigation, two modeling methods are used: an analytical solution and a numerical model. Chemical data of groundwater of this coastal area do not show any major increase in the salinity, for all the years recorded so far. For example, from 1991 to 2002, the lower aquifer of the observation well nearest to the coastline exhibits electrical conductivity values varying from around 190 to 180 $\mu S/cm$. This supposes that, the relatively accelerated water pumpage of the subsurface of the area has not yet led to noticeable inland saltwater intrusion, at least till the usual pumping depth (less than 200 m below sea level). The lack of deep observation wells near the coastline does not permit clear investigation on the location of the saltwater-freshwater interface. Based on the geological features of the area, the conceptual physical models which will be used for simulations, assume the base of the groundwater flow system at the limit between the late Miocene-Early Pliocene Nishino Formation and relatively impermeable middle to late Miocene Otarunaigawa Formation i.e. around 600 m below sea level. The models' discretization will be made relative to the three geologic units above this boundary. Distinct hydraulic parameters will be attributed accordingly to these units.

## ANALYTICAL MODEL

The coastal groundwater area is considered as a non-homogenous isotropic unconfined porous medium. Three hydraulically connected layers are considered for this study. The mathematical model solution adopted is derived from [24]. The boundary conditions of the model are:

$$\Psi = 0 \quad Y = 0$$
$$\Psi = -1 \quad Y = -\Phi$$

The general solution is:

-For $0 \leq y \leq b_1$

$$Y = \Phi \Psi$$

$$X = \frac{1}{2}(\Phi^2 - \Psi^2)$$

-For $b_1 \leq y \leq b_2$

$$Y = Y_2 + M_1 \Phi \Psi$$

$$X/\kappa_2 = \frac{1}{2}(\Phi^2 - \Psi^2)$$

With $M_1 = (k'_1 b_1)/Q$, $Y_2 = (k'_2 y)/Q$ and $\kappa_2 = k_2/k_1$

-For $b_2 \leq y \leq b_3$

$$Y = Y_2 + M_1 + M_2 = \Phi \Psi$$

$$X = \frac{1}{2}(\Phi^2 - \Psi^2)$$

With $M_2 = (k'_2 b_2)/Q$, $Y_3 = (k'_3 \xi)/Q$

The dimensionless parameters $X$ and $Y$ are defined as:

$$X = \frac{k'_1 x}{Q}, \quad Y = \frac{k'_1 y}{Q}$$

$$\Psi = \frac{\psi}{Q}, \quad \Phi = \frac{\phi}{Q}$$

Where:

$k_1$, $k_2$, $k_3$ horizontal hydraulic conductivity of the first, second and third layers respectively (m/s)

$b_1$, $b_2$, $b_3$ = thickness of the first, second and third layers respectively (m)

$k'_1 = k_1 G$

$G = (\gamma_s - \gamma_f)/\gamma_f$ = excess of the specific gravity of seawater ($\gamma_s$) over fresh water ($\gamma_f$) (dimensionless)

$Q$ = aquifer discharge per unit width of aquifer $(m^3/s/m)$

$Q = RW = 1.44 \times 10^{-4} \ m^3/s/m$

$R$ = groundwater recharge (m/s)

$W$ = width of the coastal aquifer up to the water divide (m) = 37000 $m$

$x$, $y$ = coordinates of physical plane in seepage region (m)

$\xi$ = coordinate variable with origin starting from the layered boundary (m)

$\Phi$ = potential function (dimensionless)

$\Psi$ = stream function (dimensionless)

$\phi$ = potential function or piezometric head function in seepage region

$\psi$ = stream function in seepage plane

Where permeable beds underlie a land area near the sea and extend some distance seaward from the shoreline, the infiltration from rainfall causes continuous flow of fresh water toward the sea [17]. In a dynamic system, usually the case for groundwater flow, it is highly expected that a horizontal seepage face of fresh water will develop across the shoreline. For the present study, the width of the gap through which the freshwater escapes to the sea or outflow seepage face offshore ($x_0$) is estimated as the maximum value of the annual fluctuation of shoreline (refer to the end of section on geology and geomorphology).

The physical model is given in Fig. 2. Initial parameters used for this simulation are:

$k_1 = 7.1 \times 10^{-5} \ m/s$, $k_2 = 1.0 \times 10^{-5} \ m/s$, $k_3 = 7.1 \times 10^{-5} \ m/s$

$b_1 = 100 \ m$, $b_2 = 50 \ m$, $b_3 = 450 \ m$

$G = 0.025$, $Q = 1.44 \times 10^{-4} \ m^3/s/m$

The results obtained are:

$x_0 = -40$ m, $y_0 = 0 \ m$

$x = 20.9 \ m$ at $y = 100 \ m$ (at the lower boundary of layer 1)

$x = 28.9 \ m$ at $y = 150 \ m$ (at the lower boundary of layer 2)

$x = 1868.2 \ m$ at $y = 600 \ m$ (at the lower boundary of layer 3)

## NUMERICAL MODELING

In the study area, the distribution of the freshwater and the position of the freshwater-saltwater interface do not conform to the Badon Ghyben relation.
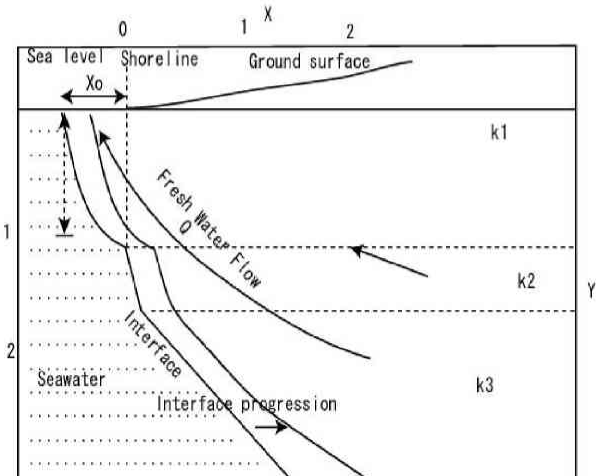


**Fig. 2** Description of the sharp interface model solution. $k_i$: horizontal hydraulic conductivity of the $i^{th}$ layer.

The interface should be much deeper than the one predicted by this relation. This section describes the groundwater pre-development stage simulation of the saltwater-freshwater interface position and the initial conditions for the model runs of groundwater pumping and seawater level changes. The numerical development simulation code used is named Shemat (Simulator for Heat and Mass Transport). This code can simulate two or three-dimensional variable fluid density driven by solute mass and/or temperature on a finite difference mesh; a finite difference method is therefore used to solve the partial differential equation [25]. For the model simulated, hydraulic properties in a distinct hydrogeologic unit are uniform and isotropic, with some extrapolation to the offshore, where little data were available. Three hydrogeologic units corresponding to the main geological layers, identified earlier, are distinguished. The model represents a vertical section of 100,000 m long by 700 m deep and 100 m wide through the coastal aquifer of the area and the continental shelf. The ocean boundary was simulated, by specifying seawater hydrostatic pressure values and constant seawater concentrations. Below are presented the seawater, aquifer and groundwater properties used in the coupled flow-species transport transient simulation model:

Dispersity ($m$): 10
Molecular diffusion coefficient ($10^{-8}\ m^2s^{-1}$): 0.5
Density influence factor ($mol\ kg^{-1}$): 0.08
Reference density ($kg\ m^{-3}$): 998
Solute transport advection scheme: Il'in
Aquifer matrix compressibility ($Pa^{-1}$): $4.5 \times 10^{-10}$
For the upper/middle/lower units:
Porosity (-): 0.22/0.15/0.30
Horizontal permeability ($m^2$): $5 \times 10^{-11}/1 \times 10^{-12}/4 \times 10^{-11}$
Anisotropy factor (-): 1 (for all units)

The interface position and movements are presented in Fig. 3.

## Boundary Conditions

A specified flux is used to represent the groundwater recharge process at the upper boundary. The steady state condition before pumping was assigned a uniform recharge distribution of 0.123 m/year. Hydrostatic-pressure boundaries with saltwater chloride concentration of 19000 mg/l are used in the offshore area. Hydrostatic-pressure boundaries with freshwater chloride concentration of 40 mg/l are applied for the right side of the model domain. A no-

flow boundary condition is used to represent the model bottom domain.

## Model Discretization

The model domain is discretized into 200 columns of 500 m length and 70 layers (distributed across the three main hydrogeologic units distinguished) of 10 m thickness. The model is therefore divided vertically into three permeability domains. The maximum time step discretization of model runs in the simulation of the pre-development stage, the groundwater pumping and the sea-level change is 0.5-year.

## Initial Conditions

The position of the seawater interface in the aquifer of this area may still reflect the lowered sea level of the last glaciation period, about 10,000 years ago. Several runs of the model are made starting with a model domain saturated completely with freshwater and applied time-invariant boundary conditions corresponding to the current sea level to the interface position within a 10,000-year post-glacial period.

## EFFECTS OF GROUNDWATER LEVEL DECREASE

Groundwater level decrease and land subsidence in aquifers of the coastal area, of Hokkaido, facing the Sea of Japan, have been noticed since the 1960's. This continuous trend of groundwater level
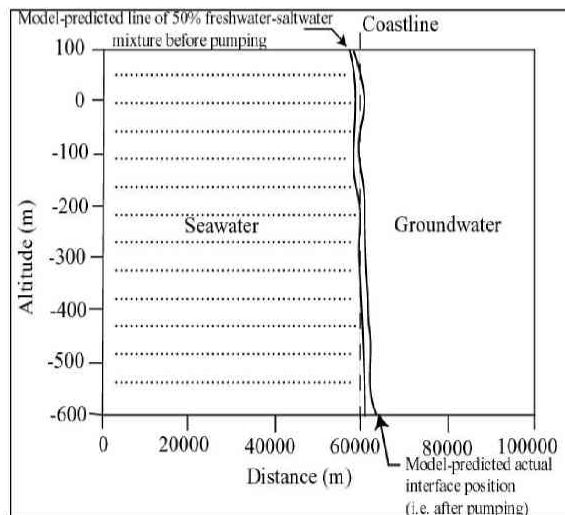
**Fig. 3** The saltwater-freshwater interface position computed by the numerical simulation model and the predicted actual interface reflecting pumping conditions till the year 2002.

decrease and land subsidence is known to be due to over-pumping. This phenomenon could cause a rapid landward progression of the seawater front. Table 1 shows the groundwater level decrease in the main pumping aquifer (the lower aquifer) monitored at existing observation boreholes (Fig. 4). The resulting average yearly decrease in groundwater level is 0.24 m. Considering that this groundwater decrease has been noticed around 1960, we would expect a total average water level decrease of 10.12 m till the year 2002.

For the analytical model, the impact of the observed decrease in groundwater level on the movement of the interface can be evaluated by the amount of flow per hydrogeologic unit. In a layered aquifer with horizontal flow, the total groundwater flow is the sum of the flows per layer, i.e.:

$$Q = Q_1 + Q_2 + Q_3 + \ldots\ldots Q_n$$

Where $n$ is the number of layers.
The flow per layer would be:

$$Q_i = \frac{b_i k_i Q}{\sum_{j=1}^{n} b_j k_j}$$

Where $i$ and $j$ are the layer index numbers and, are numbered beginning from the top.

The pre-development groundwater flow in the mainly exploited aquifer is:
$Q_3 = 1.163 \times 10^{-4}\ m^2/s$
For a decrease of 10.12 m, this flow will be reduced to:
$Q_3 = 1.137 \times 10^{-4}\ m^2/s$
And, this implies a landward interface progression of 35 m in the lower aquifer. In detail:
$x_0 = -39.2\ m,\ y_0 = 0\ m$
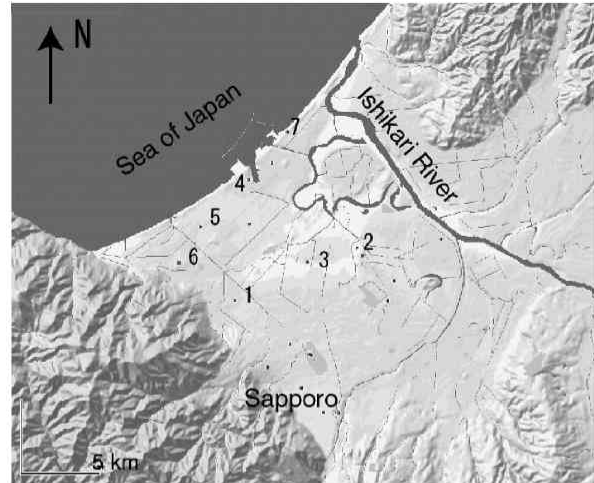$x = 22.6\ m$ at $y = 100\ m$ (at the lower boundary of



**Fig. 4** Boreholes used for the monitoring of groundwater level. The lowland with numbered borehole locations is the Ishikari plain.

layer 1)
$x = 29.7\ m$ at $y = 150\ m$ (at the lower boundary of layer 2)
$x = 1903.4\ m$ at $y = 600\ m$ (at the lower boundary of layer 3)

## RESPONSE OF THE INTERFACE TO SEA LEVEL CHANGES

The position and height of the sea relative to the land (relative sea level) determines the location of the shoreline. Tide gauges are generally used to measure sea level changes relative to the land on which the tide gauge rests. By itself, a tide gauge cannot tell the difference between local crustal motion and sea level changes. The relative sea level rise may alter the position and morphology of coastlines, causing coastal flooding and water logging of soils. They may also create or destroy coastal wetlands and salt marshes, inundate coastal settlements,

**Table 1** Groundwater level decrease in the main exploited aquifer (recorded till the year 2002)

| Borehole Number | Location | Monitoring starting date | Total decrease in water level (annual decrease rate) |
|---|---|---|---|
| 1 | N43°06'43"/E141°16'42" | 1971. 1. 1 | 11.837 m (0.382 m/yr) |
| 2 | N43°08'07"/E141°20'07" | 1972. 9. 1 | 4.166 m (0.139 m/yr) |
| 3 | N43°09'30"/E141°17'22" | 1975. 1. 1 | 7.269 m (0.269 m/yr) |
| 4 | N43°11'08"/E141°17'21" | 1974. 1. 1 | 6.542 m (0.234 m/yr) |
| 5 | N43°09'24"/E141°15'03" | 1973. 7.20 | 8.63  m (0.298 m/yr) |
| 6 | N43°09'04"/E141°14'07" | 1976. 9.21 | 4.704 m (0.181 m/yr) |
| 7 | N43°12'54"/E141°19'10" | 1991. 5.16 | 2.061 m (0.187 m/yr) |

and induce saltwater intrusion into aquifers, leading to salinization of groundwater. Through the estuary floor, saltwater can enter the aquifer by vertical leakage of seawater into the freshwater zone. Due to these backward estuary water movements to the river, the saltwater will mainly affect superficial soil layers. For example, this has been noticed in a borehole located 5 km from the coastline and close to the main stream Ishikari River, with a sudden increase in Chloride concentration from 1984 to 1987 (concentrations exceeded a critical value of 100 mg/l). In the following years, the chloride amount in this well regained its normal value (less than 100 mg/l).

The sea-level rise at the global scale is actually a well-recognized fact. This increase may not only be caused by an actual increase in the volume of water of the world ocean, but also by such factors as tectonics, isostasy, including glacio-isostasy, and subsidence. Therefore, there are difficulties to determine the intensity of absolute sea-level rise with precision. Two main factors contribute to the recent and actual relative sea level rise due to global warming: the partial melting of the ice caps, and small glaciers, then the thermal expansion of seawater. The observed intensities of sea level rise are either local or regional in range. This chapter presents the results of analyses of near coastal sea level changes at the Hokkaido area facing the Sea of Japan and, variations in the intensity of this process along the years 1905–2002 (Fig. 5). Data are from the oldest tidal station of the area (Oshoro) i.e. having the longest data series, then a station with a shorter series (Wakkanai: 1955–2002) near the northern edge and, finally at the mid-coast, a much smaller station (Rumoiko: 1986–2002). The location of these 3 stations is shown on the right side of Fig. 1.

The results are discussed in terms of the rise of the world ocean level as a result of global climate changes. Climate data from 1880 to 1999 show that global monthly sea surface temperatures (SST) and land area temperatures (LAT) have increased respectively by 1.2°C and 0.5°C [26]. It is well acknowledged that the anthropogenic causes of climatic change are indirectly related to the increasing amount of the world energy consumption. A rise by around 10 to 25 centimetres of the general climatic sea level during the last 100 years, with a rate of 1 to 2 millimetres per year has been suggested by various studies such as [27], [28]. The most important results of the analysis of changes of the Sea of Japan level along the coastal area of Hokkaido facing the Sea of Japan are: in the southern part of the coast, the sea level rise over the years 1905–1936 is quite distinct (1.7 mm/year), then a decrease of sea level from 1936 to 1979 (2.3 mm/year) and, an increase from 1979 to 2002 (2.3 mm per year). At the mid-coast there is a slight increase in sea level for the short data series by 1.2 mm/year. The sea level rise is more conspicuous towards the north with a continuous increase of 3.2 mm/year.

Though global fluctuations in sea level may result from the growth and melting of continental glaciers, and large-scale changes in the configuration of continental margins and ocean floors, there are many regional processes that result in rise or fall of the relative sea level, that affect one coastline and not another. These include: thermal expansion of ocean waters, changes in meltwater load, crustal rebound from glaciation, uplift or subsidence in coastal areas related to various tectonic processes (e.g. seismic disturbance and volcanic action), fluid withdrawal, and sediment deposition and compaction. The relative difference in the rate and cycle of evolution between the southern and the northern tidal gauge data (from 1955 to 2002) of this coast could be explained by some of these regional processes.

As noticed earlier, the land transition to the sea of the study area has a steep slope with a gradient of 1/100. Thus for the extreme case of a rapid sea level rise (case of the northern area of the coast) of 0.15 m (total increase from 1955 to 2002), the landward sea movement or shoreline retreat would be 15 m.
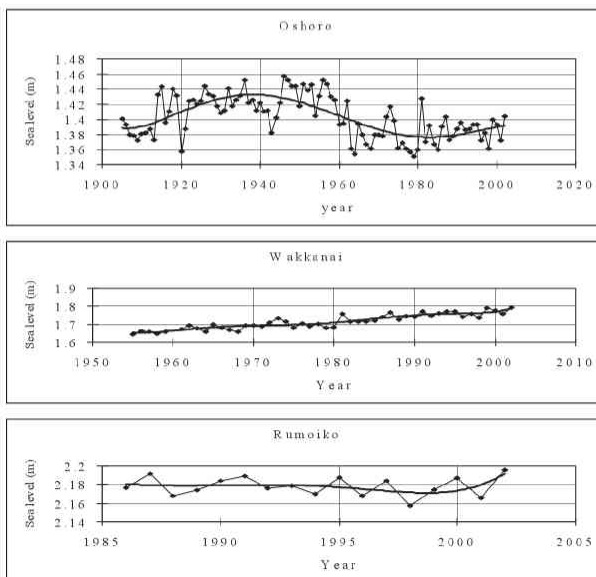


Fig. 5 Sea level trend at the three main tidal gauge stations of the coastal area.

This shoreline retreat will affect coastal aquifers by reducing the extension over which natural groundwater recharge occurs and, therefore the amount of groundwater discharge to the sea. The resulting landward interface movement is less than 1 meter for both the analytical and numerical models. Simulations made in previous coastal studies have shown that the interface response to sea level changes is quite slow and takes place over long time frames. Simulation of the post-Wisconsin glacial maximum sea level rise suggests that the interface of the Soquel-Aptos basin is still responding to long-term Pleistocene sea level fluctuations and has not achieved equilibrium with present day conditions and, the rate of movement of the interface in response to the increased groundwater pumpage that has occurred over the past 50 years is of the same order of magnitude as the longer-term responses [22].

## CONCLUSION

The study developed here used two modeling solutions (analytical and numerical) to determine the shape and position of the interface between the landward seawater intrusion and subsurface freshwater outflow around the coastal area of Hokkaido facing the Sea of Japan. Also, investigations were conducted to examine the impact of groundwater level decrease and sea level fluctuations, on the extent of the saltwater interference in the dynamics of the coastal flow system of the area. For an equivalent time frame, the results suggest that, excessive pumping of groundwater has, much more effect in the seawater contamination of aquifers than the recent sea level rise. The main threat from sea level rise would be the flooding of land areas and surface contamination though the Ishikari River.

## ACKNOWLEDGMENTS

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