

COASTAL AQUIFER DEVELOPMENT

Jinno K.

Kyushu University, Fukuoka, Japan

Keywords: desalination, filtered seawater, Ghyben-Herzberg's law, land subsidence, saltwater–freshwater mixing, subsurface dam

Contents

1. Land Subsidence
 2. Seawater Intrusion
 - 2.1. Nature of the Problem
 - 2.2. Geochemical Analysis of Saline Water in an Aquifer
 3. Quantitative Evaluation of Saltwater Behavior
 - 3.1. Experimental Observation of Saltwater Movement
 - 3.2. Ghyben-Herzberg's Law
 - 3.3. Mathematical Tools for Predicting Seawater Intrusion
 4. Groundwater Development in Coastal Aquifers
 - 4.1. Subsurface Dams and an Extraction Well with Radial Collecting Pipes to Increase the Use of Coastal Groundwater
 - 4.2. A Desalination Plant for Salt-Contaminated Groundwater
 5. Utilization of Saline Water in Coastal Aquifers
 - 5.1. Desalination of Saline Water Taken From Coastal Aquifers
 - 5.2. Fish Breeding
 6. Conclusions
- Appendices
Acknowledgments
Glossary
Bibliography
Biographical Sketch

Summary

Industrial and agricultural development and urbanization in coastal regions will lead to an increase in demand for water from groundwater reserves. However, it should be remembered that groundwater in coastal aquifers is more vulnerable to ill-effects arising from excessive exploitation than that in aquifers with a natural freshwater hydrological recharge. These adverse effects include land subsidence and seawater intrusion into freshwater aquifers; these problems, when established, are almost irreversible and may result in disasters and in deterioration of the hydrological environment. Even though the cost of groundwater exploitation is often low compared with that of developing other water resources, all exploitation of groundwater from coastal aquifers must be carefully planned. This article explains the vulnerability of groundwater in coastal aquifers and the fundamental characteristics of saline water movement. Several related technological elements of managed coastal groundwater abstraction, such as subsurface dams and desalination plants, are also considered.

1. Land Subsidence

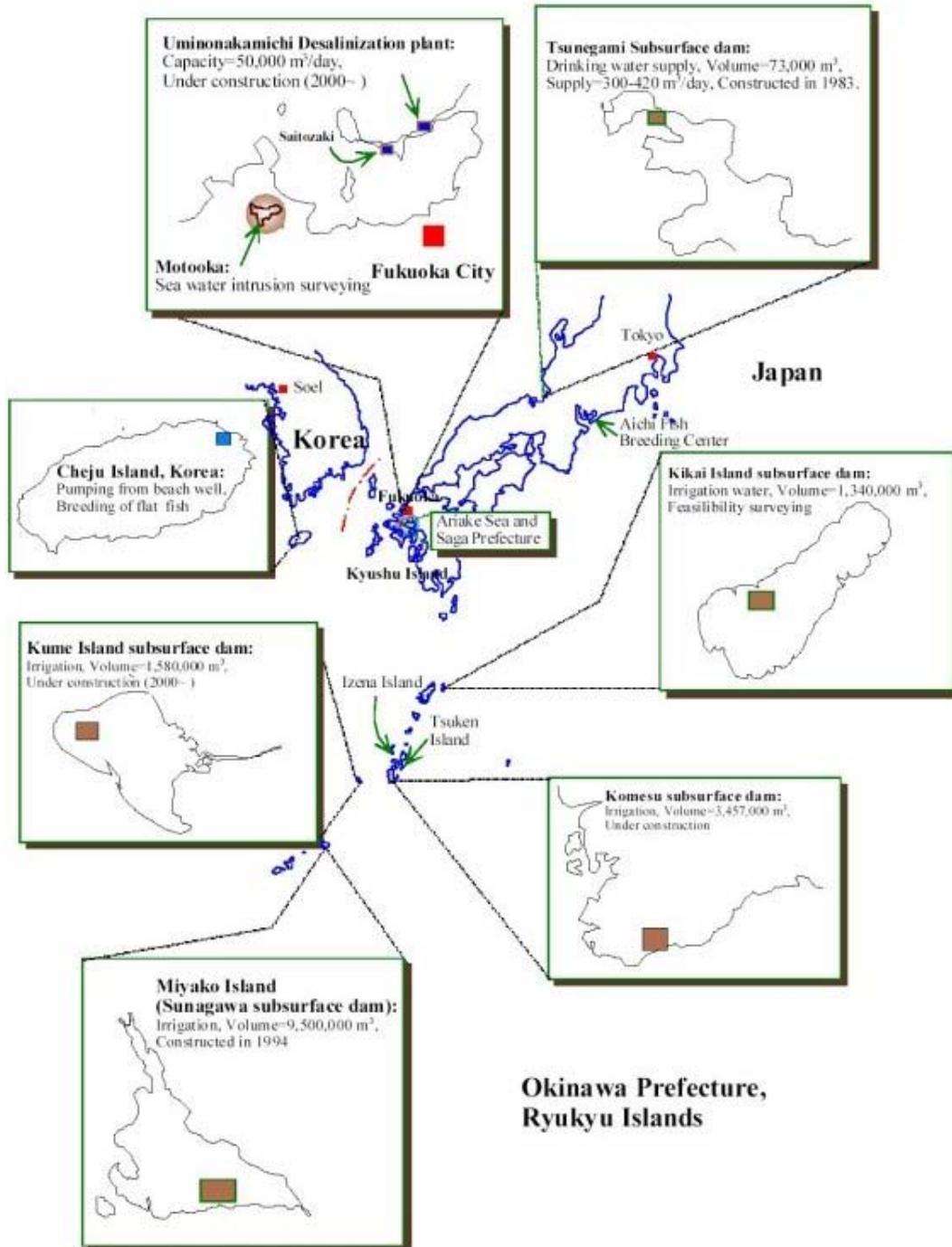


Figure 1. Locations of coastal aquifers studied in this article.

One of the typical adverse effects of groundwater exploitation from coastal aquifers is subsidence of the aquiclude, which consists of unconsolidated soils like clay and silt. This subsidence occurs mainly in alluvial plains close to the coast, where the groundwater is utilized by industry and agriculture and for drinking water. A reduction in water pressure in the soft clay or silt of the aquiclude due to excessive groundwater

Exploitation of groundwater started in the 1950s due to an increased demand for irrigation and drinking water. Groundwater and land-level monitoring started when land subsidence was first observed in 1958. Figure 3 illustrates how groundwater extraction has led to land subsidence. The land elevation varies, following (after a time lag) seasonal groundwater drawdown. The lowest level corresponds with peak groundwater extraction during the period of paddy field irrigation. Land subsidence in 1994 was particularly serious as a result of the most severe drought on record. Because of a shortage of the irrigation water usually supplied from rivers and ponds, groundwater was extracted at volumes almost three times larger than for a normal year. Land subsidence reached approximately 16 cm in 1994, almost four times the 3.7 cm yearly average of the previous four years.

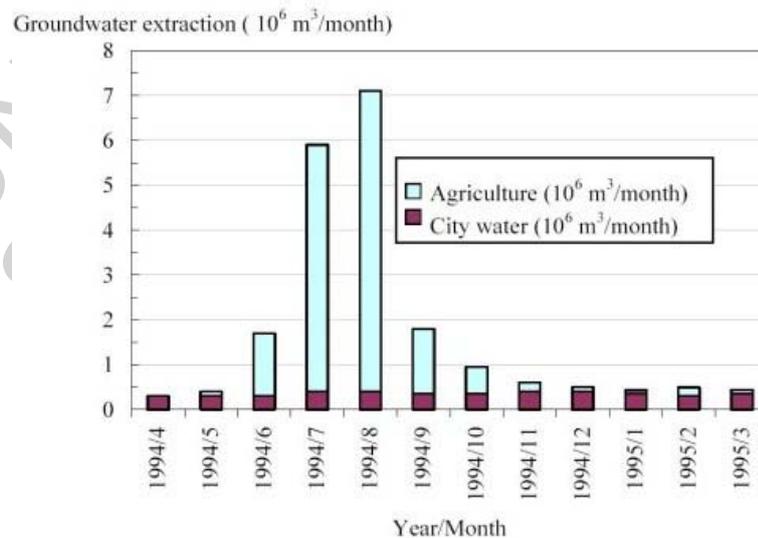
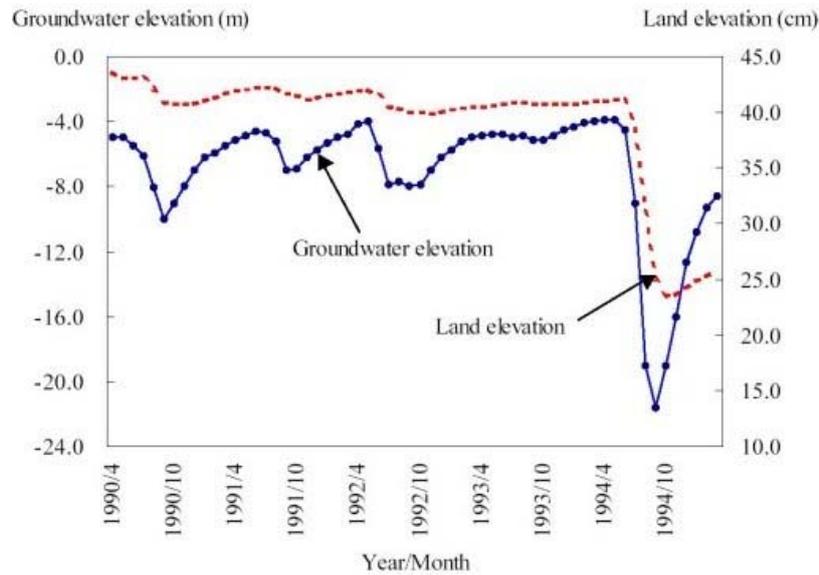


Figure 3. (a) Change in the elevations of groundwater head (m) and land surface (cm) in Saga Prefecture, Japan. (b) Groundwater extraction for the drought year of 1994 in Shiroishi Town.

Excessive exploitation of groundwater, as in this case, may lead to irreversible land subsidence. Flooding can easily take place if a heavy storm affects the areas of subsidence, and the floodwater will persist for a long time within them. Severe damage is unavoidable.

2. Seawater Intrusion

2.1. Nature of the Problem

Another problem affecting coastal aquifers is seawater intrusion. Its major causes include groundwater extraction rates exceeding rates of recharge, groundwater level drawdown caused by construction works in the fresh groundwater zone, or seawater level rise.

According to the US Geological Survey (<<http://ga.water.usgs.gov/edu/saline.html>>), saline water may be classified in terms of its salt content as follows:

- *freshwater*: less than 1000 mg L⁻¹;
- *slightly saline water*: 1000–3000 mg L⁻¹;
- *moderately saline water*: 3000–10 000 mg L⁻¹;
- *highly saline water*: 10 000–35 000 mg L⁻¹;
- *ocean water*: over 35 000 mg L⁻¹.

Since saltwater is harmful to plants, corrodes metal and concrete, and is unpleasant to drink, concentrations of chloride must be controlled. In Table 1, values of admissible chloride ion concentrations for different water uses in the United States are set out. As can be seen from the detailed explanations of the chloride concentrations permitted for drinking water, plants, and industrial uses at <<http://agnews.tamu.edu/drought/DRGHTPAK/SALITAB9.HTM>>, it is clear that management of coastal aquifers to avoid seawater intrusion is important.

Drinking water	Irrigation water (mg L ⁻¹ TDS)		Industrial water (mg L ⁻¹ TDS)
250 mg L ⁻¹ chloride	500–1000 (dependent upon crop sensitivity)	250 mgL ⁻¹ chloride	<u>Brewing</u> : 500~1000 <u>Pulp and paper</u> : 200~500 <u>Boiler feed water</u> : 50~3000 <u>Canning/freezing</u> : 850

Source: <<http://h2osparc.wq.ncsu.edu/info/salinity.html>>

Table 1. Examples of chloride concentration and TDS regulations in the United States

2.2. Geochemical Analysis of Saline Water in an Aquifer

The relationship between electric conductivity (EC) and dissolved ions up to around 2000 $\mu\text{S cm}^{-1}$ for 25°C water may be approximated by:

$$EC(\mu\text{S cm}^{-1})=100\times\sum\text{anions}=100\times\sum\text{cations}(\text{meqL}^{-1}) \quad (1)$$

On the other hand, the total dissolved solid (TDS) can be also correlated to EC, as shown by Eq. (2) (<http://h2osparc.wq.ncsu.edu/info/salinity.html>):

$$EC(\mu S m^{-1}) = TDS(mg L^{-1}) / 64 \quad (2)$$

Here, the unit $\mu S m^{-1}$ represents the magnitude of conductivity of electric current per 1 meter, and “S” refers to “Siemens”. Whichever relation is used, EC increases with ion concentration. Since, as will be demonstrated later, seawater is contaminated by ions, seawater intrusion cannot be discerned by measuring EC. TDS, however, increases with the presence of *any* ions, even those not predominantly dissolved in seawater, so it is insufficient to draw conclusions regarding the cause of seawater intrusion using EC alone. To clarify the nature of the intrusion, a geochemical analysis of water sampled from boreholes is necessary.

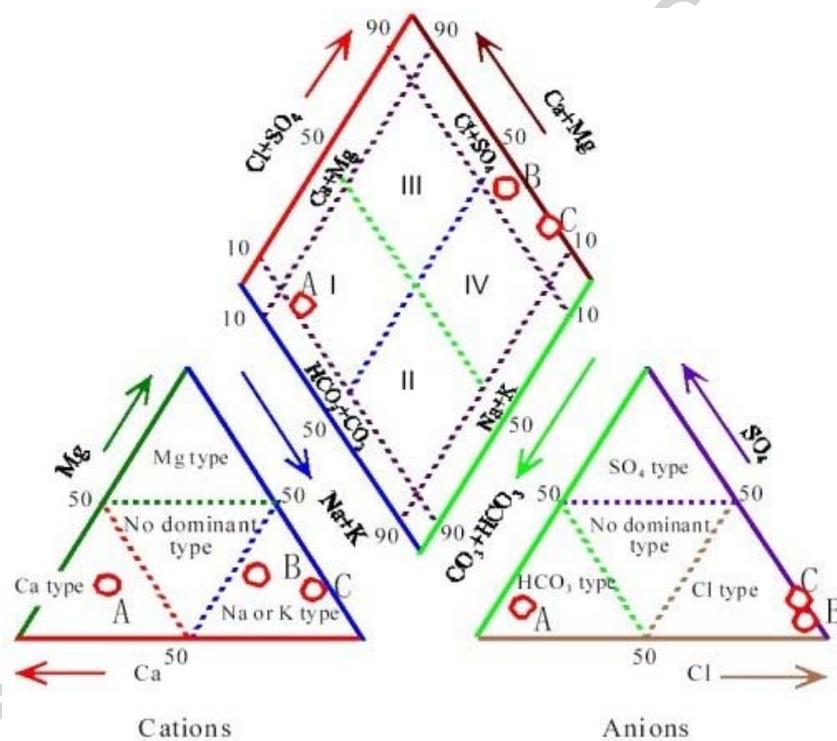


Figure 4. Trilinear classification diagram of groundwater chemistry (after Fetter, 1988; data A, B, and C from Yamamoto, 1983)

A trilinear diagram is often used as one method to distinguish seawater intrusion from unaffected ordinary groundwater. A trilinear diagram, as shown in Figure 4, is made by plotting the major cations and anions which are dissolved in the fresh and saline waters. The symbols I, II, III, and IV represent distinct regions that characterize the groundwater quality. Generally, region I is dominated by calcium as cation and bicarbonate as anion. This type of groundwater is typically found in unconfined aquifers. The dominant anion in this region, bicarbonate, originates from the dissolution of carbon dioxide in the air. In region II, sodium is more dominant than calcium. This type of groundwater is found in confined aquifers. Region III represents a situation in which bicarbonate is replaced by sulfate ions.

Component	A. Spring water in Shougawa Fan				B. Groundwater in the coastal aquifer of Imizu Plain				C. Sea water of Toyama Bay			
	mg L ⁻¹	meq L ⁻¹	%		mg L ⁻¹	meq L ⁻¹	%		mg L ⁻¹	meq L ⁻¹	%	
Na	4.7	0.20	18.02	19.82	3090	134.0	54.32	55.78	10560	470.0	77.37	79.02
K	0.7	0.02	1.80		139	3.6	1.46		380	10.0	1.65	
Ca	13.7	0.68	61.26	80.18	922	46.1	18.69	44.22	400	20.5	3.37	20.98
Mg	2.6	0.21	18.92		769	63.0	25.54		1270	107.0	17.61	
Total of cations	21.7	1.11	100		4920	246.7	100		12610	607.5	100	
HCO ₃	57.3	0.94	81.03	81.03	116	1.9	0.76	0.76	130	2.34	0.39	0.39
Cl	3.4	0.10	8.62	18.97	813	229.0	91.53	99.24	18980	548.00	90.30	99.61
SO ₄	6.0	0.12	10.34		928	19.3	7.73		2650	56.50	9.31	
Total of anions	66.7	1.16	100		1157	250.2	100		21760	606.84	100	

Note: The unit meq L⁻¹ is often used to calculate the ion balance. “meq” refers to milliequivalent, 1/1000 of equivalent.

Table 2. Groundwater quality (from Yamamoto, 1983)

Finally, region IV is affected by saline water typical of the coastal aquifers where seawater intrusion is in progress. Fossil groundwater, hot springwater, and water drained from mines also show similar characteristics, however. Figure 4 shows the data set A, B and C presented in Table 2 on the trilinear diagram. The groundwater sampled at point **B** is similar to seawater, although it is slightly mixed with freshwater as seen from the trace presence of calcium and increased magnesium. Another simple way to assess the presence of seawater is by comparing the ratio of chloride ions with the sum of carbon dioxide and bicarbonate ions $Cl^- / (CO_3^{2-} + HCO_3^-)$.

The chemical properties of groundwater in reclaimed or lowland coastal aquifers are influenced by several factors, including the aquifer materials in contact with the water, the origin of water, contact time, and regional geological history. Careful investigation is therefore necessary. Many detailed analyses of how groundwater is affected by seawater intrusion can be found in the literature.

-
-
-

TO ACCESS ALL THE 25 PAGES OF THIS CHAPTER,
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

Bibliography

Many publications and numerous reports on coastal aquifer development are available. As an example of the enthusiastic pursuit of these issues, regular SWIM (Salt Water Intrusion Meeting) meetings have been held in Europe for more than thirty years. The first fully international meeting took place in Morocco in 2001. These meetings will be important forums for hydrogeologists, engineers, and planners. As well as the conventional literature, there are also Internet sources with plentiful information on groundwater exploitation.

Abdel-Jawad M. and Ebrahim S. (1994). Beachwell sea water intake as feed for an RO desalting system. *Desalination* **99**, 57–71. [Discusses the availability of sand-filtrated seawater from beach wells for desalination plants: an important issue due to the low silica density index of reverse osmosis membranes.]

Bear J., Cheng A.H.-D., Sorek S., Ouazar D., and Herrera I. (1999). *Seawater Intrusion in Coastal Aquifers: Concept, Methods and Practices*. Kluwer. [This textbook deals specifically with problems of seawater intrusion, including general aspects and mathematical descriptions.]

Fetter C.W. (1988). *Applied Hydrogeology*, Merrill. [This textbook covers general topics of groundwater hydrogeology. See pages 354–366 for geochemistry.]

Grube A., Schmalz B., Nachtigall B.K., and Wichmann K. (1999). Provisional results of investigations on groundwater salinization with emphasis on the region of Lübeck, Northern Germany. In: Breuck, W. D. and L. Walschot (eds.) *Proceedings of the 15th Salt Water Intrusion Meeting (SWIM)*, Ghent, May 1998. *Flemish Journal of Natural Science*, Volume 79, 164–171. [This paper discusses the geochemical structure of saline groundwater in Northern Germany.]

Huisman L. and Olsthoorn T.N. (1983). *Artificial Groundwater Recharge*. Pitman. [This book is useful concerning enhancement of groundwater by artificial recharge, and seawater intrusion in coastal aquifers.]

Jinno K., Momii K., and Hosokawa T. (1990). Estimation of transverse dispersivity in the mixing zone of fresh-salt groundwater. *International Association of Hydrological Society Publication* **195**, 149–157. [Gives an approximate solution to identifying transverse dispersion length using borehole data.]

Kishi S., Hamatani N., Nagata J., Hara I., and Kusumoto T. (1998). Groundwater development from the freshwater lens with a radial well in Tsuken Island, Okinawa Prefecture. *Journal of Japan Society Engineering Geology* **39**(3), 298–305. [In Japanese. This paper summarizes various ways of developing groundwater resources using subsurface dams and wells that are useful on small islands.]

Nielsen D.M. (1991). *Ground-Water Monitoring*. Lewis. [Covers general topics in groundwater hydrology, with explanations of technical terms.]

Saga Prefecture Office (1999). *Land Subsidence Observed in the Saga Plain*. Annual Report of Land Subsidence, Saga Prefecture, Japan. [In Japanese. This is an annual report on land subsidence in the Saga area.]

Segol G. (1993). *Classic Groundwater Simulations*. Prentice-Hall. [Demonstrates mathematical approaches used in numerical analyses.]

Tohno I. (1994). Land subsidence problems in Japan. *Lowlands* (eds. N. Miura, M.R. Madhav, and K. Koga), pp. 413–437. Balkema. [This considers common geotechnical and hydrological problems in lowland areas.]

van Dam J.C. (1994). Groundwater hydrology in lowland. *Lowlands* (eds. N. Miura, M.R. Madhav and K. Koga), pp. 219–246. Balkema. [Covers special topics related to geotechnics and hydrology in lowland areas of the world.]

van Dam J.C. (1999). Exploitation, restoration, and management. Chapter 4, *Seawater Intrusion in Coastal Aquifers—Concept, Methods and Practices* (eds. J. Bear, A.H.-D. Cheng, S. Sorek, D. Ouazar, and I. Herrera). Kluwer, pp.73–125 [This article gives special attention to coastal aquifer management. Besides the problem of seawater intrusion into aquifers, the behavior of freshwater lenses above the salt water is explained mathematically.]

Yamamoto S. (1983). *Method of Groundwater Survey*. Kokon Shoin. [In Japanese. This textbook offers broad coverage of field survey methods used in groundwater hydrology.]

Biographical Sketch

Kenji Jinno was born in Japan in 1947. His main fields of research are groundwater hydrology, groundwater chemistry and pollution, modeling of multiple-component transport in groundwater, water resources engineering, and hydrologic and chaotic time-series analysis.