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An Integrated Management Plan for Groundwater Resources in the Coastal areas of Korea (I)

Jeongho Lee | Jeong-ho Yoon | Yuri Mun | Hun-Mi Kim | Sang Il Hwang
Research Staff

Leading Researcher:
Jeongho Lee (Korea Environment Institute)

Participating Researcher:
Jeong-ho Yoon (Korea Environment Institute)
Yuri Mun (Korea Environment Institute)
Hun-Mi Kim (Korea Environment Institute)
Sang-il Hwang (Korea Environment Institute)

Project Advisory Committee:
Byoung-Hwa Lee, Gang-Joo Kim, Hyoung-Soo Kim, Ji-Young Kim,
Hyun-Joo Moon, Gayoung Yoo

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Chapter I. Introduction

As the growth of industry and population has concentrated in coastal areas that have good access to ports, groundwater development has been accelerated in order to meet the increased demand for water. Because of this, the groundwater level has declined and the intrusion of saltwater has expanded which poses a threat to the public water supply and deteriorates the quality of groundwater. Consequently, public concern has risen regarding saltwater intrusion and proper management has been requested.

In the southwestern coastal areas of Korea, public complaints have accelerated as their water supply system has been contaminated and closed due to seawater intrusion. In addition, a variety of development projects such as Enterprise Cities, Saemangeum Tideland Reclamation, and National Industrial Estates, further threaten the areas groundwater.

This study aimed (1) to comprehend the current situation of groundwater development and its management in the southwestern coastal areas of Korea, (2) to investigate state-of-the-art techniques and case studies from the U.S. and Europe and (3) to suggest policy recommendations.
Chapter II. Characterization of Groundwater Flow Patterns in the Coastal Areas of Korea

1. Theoretical Background

When freshwater is withdrawn at a faster rate than it can be replenished, a draw down of the water table occurs with a resulting decrease in the overall hydrostatic pressure. When this happens near an ocean coastal area, salt water from the ocean intrudes into the freshwater aquifer as shown in Figure 2-1. The result is that freshwater supplies become contaminated with salt water as is happening to communities along the southwestern coastal areas of Korea.

1.1. Ghyben-Herzberg (G-H) Relation

Along a coastline, freshwater floats atop a denser seawater wedge that dips landward beneath the coastline due to differences in the density of seawater and freshwater. This principal was discovered by two scientists; Baden-Ghyben and Herzberg.

Freshwater ($\rho_f$) is lighter than seawater ($\rho_s$). Freshwater has a density of 1.0g/cm$^3$ while seawater is slightly denser: 1.025g/cm$^3$. It is the density difference between the fresh and seawaters that causes the freshwater to float above the transition zone (the interface where freshwater naturally mixes with seawater as it is discharged to the sea) at and below sea level and is integral to understanding why seawater intrusion occurs. This freshwater-seawater balancing act is governed by the Gyben-Herzberg Relation. It is a physical relation based on the difference in densities of seawater and freshwater. Due to this difference, small changes in freshwater level or head can effect large changes in the transition zone.
Chapter II. Characterization of Groundwater Flow Patterns in the Coastal areas of Korea

Figure 2-1. Interface between freshwater and saline water

The Baden Ghyben-Herzberg relation states that for every foot \((h_i)\) of groundwater above sea level there is forty feet of freshwater below sea level \((z)\)

Thus:

\[
z = \frac{\rho_f}{\rho_s - \rho_f} h_f = 40 \ h_f
\]

1.2. Upconing of interface

According to G-H Relation, the decline of the groundwater table by pumping in coastal areas causes the upconing of interface between the freshwater and seawater.

The following discussions are based mostly on the studies of Schmorak and Mercado (1969).

\[
z = \frac{Q \rho_f}{2\pi d K (\rho_s - \rho_f)}
\]
Where, 
\( z \) = rise of interface above its initial position
\( Q \) = pumping rate of the well (L\(^3\)/T)
\( d \) = distance between the well’s bottom and the interface (L)
\( K \) = hydraulic permeability (L/T)

According to Dagan and Bear (1968), when \( z \) is less than \( 1/3 \) of \( d \), it becomes steady. And if \( z = 0.3d \), the maximum permitted pumping rate should meet the following equation.

\[
Q_{\text{max}} \leq 0.6\pi d^2 K \frac{(\rho_s - \rho_f)}{\rho_f}
\]

Figure 2-2. Schematic model of upcoming interface
1.3. Type of Seawater intrusion in Korea

In coastal areas of Korea, public concerns have accelerated as groundwater has been contaminated by seawater intrusion. For this reason, a seawater intrusion monitoring network system has been operated by the Ministry of Agriculture and Forestry since 1996. The data, including groundwater level, temperature, and electrical conductivity are monitored from the seawater intrusion monitoring network. The data is used to analyze types of seawater intrusion through coastal aquifers.

Even though it is difficult to assure the typical types of seawater intrusion in Korea, it is still possible to analogize the following types of seawater intrusion:

1. Seawater intrusion due to reclamation work.
2. Seawater intrusion due to natural disasters such as flooding and tidal waves.
3. Seawater intrusion due to excessive groundwater pumping
2. The Assessment Method of Groundwater flow discharges in Coastal areas

The discharge of groundwater flow can be estimated using Darcy’s method along the coastal areas.

\[ Q = -K \frac{dh}{dl} A \]

Where, \( Q \) = flow rate (L^3/T), \( K \) = hydraulic conductivity (L/T)
\( A \) = flow area (L^2), \( dh/dl \) = hydraulic gradient

Figure 2-3. Conceptual model of groundwater flow discharge
2.1. Average thickness of freshwater

We can get the value of average thickness of freshwater by applying the Badon Ghyben-Herzberg equation.

\[ \rho_s = \rho_f (Z + h_f)g \leftrightarrow \rho_s z = \rho_f z + \rho_f h \]

\[ h_f = \frac{\rho_s - \rho_f}{\rho_f} z \leftrightarrow h_f = \alpha z \]

The density of Freshwater (\( \rho_f \)) is 1.0 g/cm\(^3\) and the density of seawater (\( \rho_s \)) is 1.025 g/cm\(^3\). Therefore, the value of \( \alpha \) becomes 0.025.

\[ \therefore \alpha = 0.025 \]

\[ z = 40h_f \]

For the case of groundwater head at the well > D/41, the average thickness of freshwater becomes;

\[ \overline{D} = \left( \frac{\alpha}{h} \times \frac{D}{2} + \frac{h_f - \alpha}{h_f} \times D \right) = D \left( 1 - \frac{\alpha}{2h_f} \right) \]

On the other hand, for the case of groundwater head at the well < D/41, the average thickness of freshwater becomes;

\[ \overline{D} = \frac{4h_f}{2} \]

Where, \( \alpha = D / 41 \)
2.2. Optimal pumping rate of Groundwater in Coastal areas

The Simulation-Optimization Model was developed for identifying the best locations and operation rates for pumping and injecting wells in coastal areas (Park and Hong, 2003).

The following factors are considered:

- Discharges of groundwater flow in the coastal area (q)
- Hydraulic conductivity (K)
- Depth from mean sea level to aquifer base (D)
- Coastline which assumes K, D and q are constant (B)
- Distance from the coast to the pumping well (L_w)
- Distance of seawater intrusion before installation of pumping well (L_{toe,1})
- Maximum available distance of seawater intrusion after installation of pumping well (L_{toe,2})

Assume that there is an interface between the freshwater and saline water. Then, the values of L_w and L_{toe,2} should be larger than L_{toe,1} (Figure 2-4). The maximum available distance of seawater intrusion can be decided by considering the position of the pumping well. Once the pumping is started at L_w, the groundwater level and hydraulic gradient become lower. Therefore, seawater intrusion occurs and the pumping rate (Q) at L_{toe,2} become the maximum available pumping amount from a single well.

The number of pumping wells determines the total available pumping amount of groundwater. However, the additional pumping wells cause a decline of groundwater level and more intrusion of seawater due to the interaction between the wells. To avoid this interaction, the distance between the well should be at least twice longer than the radius of influence (R).

Then, the number of well (N_w), which can be installed in the coastal area, is as below:

\[ N_w = \frac{B}{2R} \]
And, the optimal pumping rate \( W \) of groundwater, which does not cause seawater intrusion, is as below;

\[
W = N_w Q
\]

Figure 2-4. Conceptual model of optimal pumping rate of groundwater
Chapter III. Current Situation of Groundwater Management in the Coastal areas of Korea

1. Groundwater monitoring network management system

The main purpose of the groundwater monitoring network management system in Korea is to collect information about groundwater variables such as heads, temperature, hydrogeochemical components, and quality.

There are four kinds of groundwater monitoring stations in Korea. The first one is the National Groundwater Monitoring Network (NGMN) managed by the Ministry of Construction and Transportation (MOCT). NGMN was first constructed in 1995. There were 320 national groundwater-monitoring stations nationwide as of 2007. Each station consists of one or two monitoring wells and corrects data such as groundwater level, electric conductivity, and temperature.

The second type is the Groundwater Quality Monitoring Network (GQMN) managed by the Ministry of Environment (MOE). There were 2,021 monitoring well sites nationwide as of 2007. Groundwater quality monitoring stations are generally located in regions with high possibility of pollution such as waste dump regions, urban regions, agricultural regions, industrial complexes, storage tanks, golf courses, and mine regions. Groundwater quality tests are implemented two times per year and include at least 15 items such as pH, COD, Coliform group, Chloride, Nitrate-Nitrogen, Cyan, Cadmium, Arsenic, Lead, Chromium, Mercury, Phenol, Trichloroethylene, Tetrachloroethylene, and Organophosphorus.

The third type is the Subsidiary Groundwater Monitoring Network (SGMN) managed by the local government. There were 611 subsidiary groundwater monitoring stations nationwide as of 2007. The purpose of SGMN is to assist national groundwater monitoring stations and groundwater quality monitoring stations. This monitoring system measures basic water level at least two times a month and groundwater quality two times a year.
The last type is the Seawater Intrusion Monitoring Network (SIMN) managed by the Ministry of Agriculture and Forestry (MAF). There were 131 monitoring wells in the coastal areas of Korea as of 2007. The purpose of SIMN is to ensure stable water supply in the coastal areas and to prevent groundwater contamination by seawater intrusion. This monitoring system measures groundwater level, temperature, and electrical conductivity automatically every hour.

<table>
<thead>
<tr>
<th>Category</th>
<th>Based on</th>
<th>Function</th>
<th>Managed by</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGMN</td>
<td>Article 17 Groundwater act</td>
<td>Primary network</td>
<td>MOCT</td>
</tr>
<tr>
<td>GQMN</td>
<td>Article 18 Groundwater act</td>
<td>Primary network</td>
<td>MOE</td>
</tr>
<tr>
<td>SGMN</td>
<td>Article 17 Groundwater act</td>
<td>Secondary network</td>
<td>Local government</td>
</tr>
<tr>
<td>SIMN</td>
<td>Rural area consolidation act</td>
<td>Secondary network</td>
<td>MAF</td>
</tr>
</tbody>
</table>
2. Seawater intrusion monitoring network system

2.1. Seawater intrusion monitoring system

For the groundwater management of coastal areas, there are diverse efforts by government agencies being carried out. The Ministry of Agriculture and Forestry (MAF) established a ‘Seawater Intrusion Monitoring System (SIMNS)’ in 1998.

The main purpose of SIMS is to ensure stable water supply and to prevent groundwater contamination by seawater intrusion. This monitoring system measures groundwater level, temperature, and electrical conductivity automatically every hour.

2.2. Measurement Results

With groundwater data from the seawater intrusion monitoring network, we analyzed the effect of seawater intrusion on coastal areas of Korea.

The data, including groundwater level, temperature, electrical conductivity, and Cl/HCO₃ mole fraction obtained from 65 monitoring wells was evaluated.

Based on statistical analysis, correlation analysis, and variation type analysis, groundwater levels were mainly affected by rainfall and artificial pumping.

Relatively consistent influence from seawater is observed at 15 seawater monitoring wells as results of electrical conductivity analysis and Cl/HCO₃ mole fraction analysis. Weak influence from seawater, which still needs to be cautioned, is also present at another 13 seawater monitoring wells.

Therefore, water supplies from alternative water resource are required at a total of 28 seawater monitoring wells which show the apparent increase on the values of electrical conductivity and mole fraction.
Figure 3-1. Seawater intrusion monitoring network system in Korea
3. Groundwater use in coastal areas

Annual groundwater use data is available from the Ministry of Construction and Transportation (MOCT).

As a result of the data analysis from the year 2000 to 2005, we can see that groundwater use has increased from approximately 3.1 thousand million tons to 3.7 thousand million tons. Also, the number of groundwater wells has increased from 1,079 to 1,270.

![Figure 3-2. Estimated groundwater use (year 2000 - 2005)](chart)

Analysis of groundwater use in the coastal areas from the year 2000 to 2005 was also implemented. The results showed that groundwater use in the coastal areas increased from approximately 5 hundred million tons to 5.5 hundred million tons. Groundwater use in the coastal areas represents 15% of total groundwater use in Korea.

However, it is expected that groundwater use in the southwestern coastal areas of Korea will increase sharply, due to a variety of development projects such as Enterprise Cities, Saemangeum Tideland Reclamation, and National Industrial Estates that are planned in this area.
Figure 3-3. Groundwater use in the coastal area (year 2000 - 2005)
Chapter IV. Case Studies: The U.S., Europe and Numerical Modeling

1. Case study area selection

The southwestern coastal areas of Korea have a relatively flat seashore and high tidal range. These coastal environments generate an extensive tidal flat. Tidal flats in the southwestern coastal areas of Korea make up 2.5% of Korea’s territory. The western seacoast has approximately 83% of the tidal flats in Korea. Therefore, this study is mainly focused on the west coast of Korea.

There are world five tidal flat areas; Western tidal flat in Korea, East coast in Canada, The north sea coast in Europe, River basin in Amazon and East Georgia coastal area in the United State. Among these world five tidal flat areas, the North Sea coast in Europe and Georgia coastal area in the U.S. have relatively high population as similar as western tidal flat in Korea. Therefore, these two areas are selected as case study areas.

Figure 4-1. World Five tidal flat areas (www.tidalflat.go.kr)
2. Groundwater Management plans in Coastal areas

Groundwater is managed by both the federal and state governments in the United States. There are no specified standards for groundwater at the federal level. Groundwater quality standards basically follow the drinking water standards under the Safe Drinking Water Act (SDWA).

2.1. Coastal areas in Florida and Georgia

a. Florida

Florida State, which is located to the south of Georgia, relies on groundwater as their main water resource more than surface water (see table 4-1). According to data collected between 1965 and 2005, groundwater use has sharply increased while surface water use has remained steady (see Figure 4-2). Therefore, effective groundwater management policies are required to maintain sustainable water supplies in this area.

Water resources are managed primarily through the cooperation of the federal government and the U.S. Geological Survey. The government of Florida divided the state into five water management districts (Figure 4-3). Each district is responsible for collecting data and managing its own water resources.

<table>
<thead>
<tr>
<th>Water Use</th>
<th>Groundwater</th>
<th>Surface water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public supply</td>
<td>2,199.36 (26.8%)</td>
<td>237.43 (2.9%)</td>
</tr>
<tr>
<td>Domestic use</td>
<td>198.68 (2.4%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Industrial use and mining</td>
<td>430.70 (5.3%)</td>
<td>132.60 (1.6%)</td>
</tr>
<tr>
<td>Agricultural use</td>
<td>1,989.95 (24.3%)</td>
<td>1,933.06 (23.6%)</td>
</tr>
<tr>
<td>Leisure</td>
<td>230.45 (2.8%)</td>
<td>181.28 (2.2%)</td>
</tr>
<tr>
<td>Electric power</td>
<td>29.53 (0.4%)</td>
<td>628.73 (7.7%)</td>
</tr>
<tr>
<td>Total</td>
<td>5,078.67 (62%)</td>
<td>3,113.10 (38%)</td>
</tr>
</tbody>
</table>
Figure 4-2. Water use in Florida (Marella, 2004)

Figure 4-3. Water management District in Florida (FDEP, 2007)
The government of Florida manages the groundwater resources used for drinking purposes under nine groundwater acts (see Table 4-2).

### Table 4-2. Groundwater Acts in Florida (FDEP, 2007)

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Effective Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>62-4</td>
<td>Permits</td>
<td>2007. 10. 1</td>
</tr>
<tr>
<td>62-40</td>
<td>Water Resource Implementation Rule</td>
<td>2006. 5. 7</td>
</tr>
<tr>
<td>62-520</td>
<td>underground water Classes, Standards, and Exemptions</td>
<td>1996. 12. 9</td>
</tr>
<tr>
<td>62-521</td>
<td>Wellhead Protection</td>
<td>1995. 7. 13</td>
</tr>
<tr>
<td>62-522</td>
<td>underground water Permitting and Monitoring Requirements</td>
<td>2001. 8. 27</td>
</tr>
<tr>
<td>62-524</td>
<td>New Portable Water Well Permitting in Delineated Areas</td>
<td>2000. 6. 27</td>
</tr>
<tr>
<td>62-528</td>
<td>Underground Injection Control</td>
<td>2005. 12. 27</td>
</tr>
<tr>
<td>62-531</td>
<td>Water Well Contractors</td>
<td>2003. 7. 17</td>
</tr>
<tr>
<td>62-532</td>
<td>Water Well Permitting and Construction Requirements</td>
<td>2002. 3. 28</td>
</tr>
</tbody>
</table>

Groundwater in Florida is classified according to designated uses as follows:

1. **Class F-I (Potable water use)**
   Groundwater in a single source aquifer described in Rule 62-520.460, F.A.C., which has a total dissolved solids content of less than 3,000 mg/l and was specifically reclassified as Class F-I by the Commission.

2. **Class G-I (Potable water use)**
   Groundwater in single source aquifers which has a total dissolved solids content of less than 3,000 mg/L.

3. **Class G-II (Potable water use)**
   Groundwater in aquifers which has a total dissolved solids content of less than 10,000 mg/L, unless otherwise classified by the Commission.

4. **Class G-III (Non-potable water use)**
   Groundwater in unconfined aquifers which has a total dissolved solids content of 10,000 mg/L or greater; or which has total dissolved solids of 3,000-10,000 mg/L and either has been reclassified by the Commission as having no
reasonable potential as a future source of drinking water, or has been designated by the Department as an exempted aquifer pursuant to subsection 62:528.300(3), F.A.C.

(5) Class G-IV (Non-potable water use)
Non-potable water use, ground water in confined aquifers which has a total dissolved solid content of 10,000 mg/L or greater

b. Georgia

Prior to the industrial development and population growth of the first half of the 20th century in the coastal region of Georgia (and Florida and South Carolina), groundwater in Georgia’s aquifers flowed from recharge areas in an east-southeastward direction, extending in a broad arc from Valdosta to Waynesboro, eventually discharging offshore. After World War II, as the region developed, centers of groundwater pumpage formed in Georgia around Savannah/Chatham County, Brunswick, Jesup, Riceboro, St. Marys; Hilton Head, South Carolina, and the Jacksonville-Fernandina Beach area of Florida. The bulk of the groundwater pumped is from what is now known as the Upper Floridan aquifer, which is a porous limestone geologic formation having extremely high productivity. At these pumping centers, cones of depression formed in the potentiometric surface and flow directions changed. Groundwater containing salt began to flow toward, or into, the Savannah-Hilton Head, Brunswick, and Jacksonville-Fernandina Beach pumping centers.

Salt is a naturally occurring mineral. At high concentrations, salt makes water unpalatable to drink. The United States Environmental Protection Agency (EPA) has established a secondary drinking water standard of 500 mg/L for total dissolved solids and of 250 mg/L for chloride ion. Since chlorides are relatively simple to measure, studies of seawater intrusion often use chlorides as a surrogate for measurements of salinity. Water having chloride levels of less than 250 mg/L is considered palatable to drink (assuming there are no other deleterious constituents exceeding other drinking water standards).
Since the early 1960’s, the problem of seawater intrusion into coastal Georgia aquifers has been recognized. While the problem was first recognized in the Savannah-Hilton Head area, groundwater monitoring by the United States Geological Survey (USGS), on behalf of the precursor agency of the Georgia Environmental Protection Division (EPD), indicated the presence of elevated chloride levels in Upper Florida aquifer wells. Shortly thereafter, some water supply wells on the Brunswick peninsula had to be abandoned due to high chloride concentrations.

In the 1970’s and 1980’s additional hydrogeological studies were performed, well construction was monitored, and water resource alternatives for the Upper Floridian aquifer were identified. As the seawater intrusion problem became more evident, efforts to conserve water and utilize alternative water supply sources followed. Conservation efforts resulted.

Between 1985 and 1995, a series of events demonstrated that Georgia needed to aggressively develop a plan to address the intrusion of salt water in coastal areas.

In 1995, the EPD embarked on a public education program – through a series of public meetings – to inform the residents of coastal Georgia of the salt water problem, and to solicit comments that might aid the development of a plan for managing the problem. Over the course of these meetings, it became apparent that the technical information needed to effectively deal with the problem was inadequate and that a solution to the seawater intrusion problem could not be addressed until additional scientific studies had been designed, funded, and completed.

After evaluating hundreds of verbal and written comments, in 1997 - with the concurrence of a Joint Senate-House subcommittee of the Georgia General Assembly – the EPD embarked on a two stage approach to resolve the seawater intrusion problem. The first stage consisted of the development of an “Interim Strategy for Managing Seawater Intrusion in the Upper Florida Aquifer of Southeast Georgia” – covering a 24-county area of Georgia (refer to Figure 4-4) – that described how the EPD would address groundwater withdrawal during the period 1997-2005. The Interim Strategy instituted a moratorium on groundwater withdrawal permits for the Upper Floridian aquifer for municipal, industrial, and agricultural uses within the 24-county area. The second stage, called the Coastal Sound Science Initiative (CSSI),
included the definition and execution of an array of scientific and engineering investigations intended to generate the data and information required to guide the development of a more well-founded plan for managing salt water intrusion.

The 24-county region mentioned above, did not require a uniform set of permitting strategies to address seawater intrusion. The EPD proposed to subdivide the 24-county area into three sub-regions (see Figure 4-5); namely (1) a bifurcated sub-region consisting of all of Bryan and Liberty counties, and Chatham County and a portion of Effingham County south of Georgia Highway 119; (2) a Glynn County sub-region, and (3) the remaining 19 counties and a portion of Effingham County north of Highway 119.

Figure 4-4. Counties covered under the Coastal Georgia Water & Wastewater Permitting Plan for Managing Seawater Intrusion
Figure 4-5. Sub-regions associated with the Coastal Georgia Water & Wastewater Permitting Plan for Managing Seawater Intrusion (GaEPD, 2006)

The Coastal Georgia Water & Wastewater Permitting Plan for Managing Seawater Intrusion establishes three sub-regions for purposes of implementing region-specific policies and permitting requirements to stop seawater intrusion, manage wastewater, implement water conservation, and reuse practices. The three sub-regions are:

- **Sub-region 1**: Chatham County and that portion of Effingham County south of Highway 119; Bryan and Liberty Counties.
- **Sub-region 2**: Glynn County
- **Sub-region 3**: The remaining 19 counties within the 24 county coastal area, and that portion of Effingham County north of Highway 119.
These sub-regions are defined based on their varying vulnerability for or contribution to seawater intrusion as determined by the CSSI. Sub-region 1 (Chatham, Bryan, Liberty, and part of Effingham Counties) overlaps the cone of depression that extends into South Carolina. The Gulf Trough bisects Effingham County roughly in a line defined by the location of Highway 119. The Gulf Trough is a feature of the aquifer whose low permeability acts as a barrier to the development of the cone of depression toward the northwest. Groundwater pumping on the northern side of the Gulf Trough has insignificant influence on the cone of depression. In Sub-region 2, Glynn County, seawater intrusion is caused by much localized pumping that does not contribute significantly to the development or extent of the cone of depression underlying Sub-region 1. The remaining 19 counties contained in Sub-region 3 do not contribute significantly to the development or extent of seawater intrusion at Savannah-Hilton Head or Brunswick (see Figure 4-5).
2.2. The North Sea Coast of Europe

a. Germany

Around 74% of drinking water comes from groundwater, making it Germany’s most important drinking water resource.

The Federal Republic of Germany is based on a federal system, which is similar to the U.S., i.e. public functions are distributed between the Federal Government and the Federal Lander. The enforcement of water resources management regulations are the sole responsibility of the Federal Lander (local government) and the municipalities.

In Germany, the Federal water act applies to surface water, coastal water, and groundwater. Therefore, the quality of water bodies is managed under the Federal water act. However, most legal guidelines follow the EC Water Framework Directive (WFD) like other European Union countries.

![Diagram](image.png)

Figure 4-6. Water management system in Germany
Around 60% of European tidal flats are located in Germany (Figure 4-7). All the tidal flats were designated as national parks in the mid 1980s and have been managed under the national park rule. This rule prohibits not only developing tidal flat areas but also public access. Because of this strict management policy in the coastal area, there have been no serious problems reported related to seawater intrusion.

Figure 4-7. National Park in tidal flat area, Germany
b. The Netherlands

About 70% of the land in the Netherlands is located below sea level and around 67% of the drinking water comes from groundwater.

Groundwater is managed at three levels; National level, Provincial level and regional and local level (see Figure 4-8). Every year in the Netherlands, 1.674 million m³ of groundwater is pumped. Of that, 563 million m³ is used by households, 525 million m³ by industry, and 450 million m³ for agriculture. Yearly replenishment is 2.615 million m³. The amount that can be extracted is approximately 1.900 million m³. In the lower parts of the Netherlands hardly any freshwater can be extracted because salt or brackish water comes up. Therefore, diverse efforts by government agencies are carried out.

Figure 4-8. Water management system in the Netherlands
Even though diverse efforts have been carried out to protect groundwater from seawater intrusion since the 1900s, many cases of salt water contamination are still reported.

Lying well below sea level, the western part of the Netherlands is constantly being intruded by brackish groundwater. Even in the eastern part, which lies slightly higher, brackish groundwater occurs at shallow depths in many places. Many water wells are seriously threatened by the upconing of fossil seawater. Over 100 pumping stations have already been closed down for that reason, and it is estimated that more than 20% of the existing Dutch well fields will eventually experience salinization.

Therefore, state of the art techniques such as membrane filtration (Figure 4-9) are applied.

Figure 4-9. Application of the membranes
3. Numerical Modeling (Buan, Jeonbuk, Korea)

A series of three-dimensional numerical simulations using a multidimensional hydrodynamic dispersion numerical model (COFAT3D, Kim and Yeh, 2004) was performed to analyze seawater intrusion under groundwater pumping in an unsaturated fractured porous coastal aquifer area (Buangun, Jeonbuk, Korea, see Figure 4-10) which is heterogeneous and true anisotropic.

![Figure 4-10. Modeling area](image)

The numerical simulation results show that such heterogeneity and true anisotropy have significant effects on spatial and temporal distributions of density-dependent groundwater flow and salt transport. Therefore, it may be concluded that both heterogeneity and true anisotropy must be properly considered when more rigorous and reasonable predictions of long-term
density-dependent groundwater flow and salt transport induced by groundwater pumping are to be obtained for the optimal management of coastal groundwater resources (Kim, 2006)

Pumping rate (Q) of (a) 100 m³/day at well O4 (b) 100 m³/day at well OA1 (c) 400 m³/day at well O4 (d) 400 m³/day at well OA1

Figure 4-11. Salt concentration at final steady state
Chapter V. An Integrated Groundwater Management Plan for the Coastal areas of Korea

From case studies of the U.S. and Europe, it was learned that groundwater management systems were developed by integrating available techniques, the current status of seawater intrusion, and socio-economic situations.

This study suggests several solutions in order to build an integrated groundwater management system in the coastal areas of Korea.

Firstly, the attitude current policies take regarding groundwater in the coastal areas should change. Since groundwater was recognized as ‘a subsidiary water resource’, the government has paid more attention to other water resources such as surface water and drinking water. However, once the groundwater is contaminated, it takes much more time to remediate than other water bodies. Because groundwater exists below the unsaturated layer (surface zone and vadose zone), it is difficult to find contamination during the early stages. Therefore more efforts and attention are required to keep the groundwater fresh and to prevent contamination.

Secondly, more monitoring network systems are required. The monitoring network system needs to be managed more systematically to ensure the timely detection of adverse changes in quality and to develop targeted remediation and minimization strategies.

Thirdly, a function distribution between the government and local governments is required. The phenomenon of seawater intrusion occurs in areas such as the southwestern coastal areas of Korea. Therefore locally based policies are required for a more effective management system.

In addition to the above three suggestions, the development of state of the art techniques and research, an integrated plan with superior national plans such as a master plan for groundwater and cooperation between the relevant government ministries are also required.
**Chapter VI. Conclusions**

Since the 1960s, water use in Korea has increased continuously due to the rapid growth of the national economy, and the improvement of living standards. Due to imprudent groundwater development and overdrafts, problems such as excessive groundwater level decline, and groundwater contamination, increasingly occurred in populated areas, especially coastal areas. Because of this, seawater intrusion has expanded and poses a threat to the public water supply and deteriorates the quality of groundwater. Consequently, public concern has risen regarding salt water contamination and proper management has been requested.

In the southwestern coastal areas of Korea, public complaints have accelerated as their water supply system has been contaminated and closed by seawater intrusion. In addition, a variety of development projects such as Enterprise Cities, Saemangeum Tideland Reclamation, and National Industrial Estates, further threaten the areas groundwater.

This study investigated (1) the theoretical background of groundwater flow pattern and the assessment method of groundwater flow discharges in the coastal areas, (2) the current situation of groundwater development and its management in the southwestern coastal areas of Korea, and (3) the state of the art techniques and case studies from the U.S. and Europe.

Throughout the whole study, it can be concluded that while the various research groups have achieved remarkable outcomes, their efforts have resulted in incompatible policies and repeated investments.

On the other hand, the management systems of the U.S. and Europe were developed by integrating the available techniques for prevention and remediation, the current status of seawater intrusion, and socio-economic situations. As each investigation and policy implementation was supervised by an integrated management system, their outcomes contributed to ensuring the supply and quality of groundwater.

Further studies are required regarding similar integrated management systems in order to provide consistent policies, increase the efficiency of collected data and information, and encourage relevant research.
| References |


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