Evaluation and Prediction of Risks Associated with Groundwater Salinization and Dilution: examples from coastal plains around the city of Tosa, Shikoku Island, Japan

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Abstract

This paper uses a series of case studies to evaluate and predict the risks associated with the salinization and dilution of groundwater around the city of Tosa, Japan. These case studies focus on the topographic, hydrogeological, and weather conditions that may affect groundwater risk assessments. Salinization risks were considered by examining: (1) the progressive salinization of well water caused by a rising saltwater cone induced by groundwater drawdown during the construction and repair of levees, and (2) the intensity of groundwater salinization in groundwater-rich versus groundwater-poor areas. The evaluation of groundwater salinization is critical for predicting trends in groundwater availability. Dilution risks were considered by examining cultured flatfish mortality caused by the dilution of saline groundwater. Estimates are made of the effects of cumulative precipitation on the viability of cultured flatfish populations. These estimates are used, alongside previously determined relationships between cumulative precipitation and chloride ion concentrations in groundwater, to develop an index that predicts the effects of cumulative precipitation on the health of cultured flatfish populations. By applying the index to groundwater conditions during a record rainfall event that occurred in August 2014, it is suggested that intense precipitation events are associated with the dilution of saline groundwater.

Keywords: coastal plain, groundwater, salinization, dilution of seawater

1. Introduction

In coastal plain areas around the city of Tosa, Kochi Prefecture, Shikoku Island, alluvial groundwater is used for human consumption, agriculture, fisheries processing, and aquaculture. The salinity of coastal groundwater is strongly affected by dilution caused by intense rainfall, saltwater intrusion, and construction and repair of river and coastal levees. Salinity variations may severely impact groundwater sources and availability, as highly saline waters are unsuitable for consumption, and cause decreased agricultural yields and fish culture populations.

This paper presents case studies that evaluate and predict the risks associated with groundwater salinization and dilution. Salinization risks are illustrated using a case study in which groundwater salinization was caused by a rising salt-water cone. This cone was associated with groundwater drawdown during the construction and repair of levees. Dilution (desalinization) risks are illustrated using a case study in which groundwater salinity decreased after an extreme precipitation event and affected cultured flatfish populations. In both cases, the analysis performed was relatively simple and based on topography, hydrogeology, water quality, and hydrological data such as precipitation, groundwater levels, and tidal changes.

2. A case study illustrating salinization risks

Flood damage has occurred frequently on the coastal plains in the Usa district, Tosa. The discharge capacity of the Hagitani River is regularly exceeded following intense frontal rainfall and typhoon storm surges. Plans to repair levees along the river; i.e., enlarge the cross-sectional area to increase discharge capacity, prompted concerns that groundwater salinization may occur because of the subsequent intrusion of salt water from the coast. A groundwater survey was therefore conducted in April 2004, one year prior to the planned construction. The salinization area was predicted by analyzing groundwater levels, precipitation, and electrical conductivity data, in addition to the topographical and hydrogeological characteristics of the region.

2.1 Geomorphology and hydrogeology of the study

The coastal terrain in the study area comprises the dune range on the seaward (east) side of the Hagitani River, whereas the landward (west) side lies within the floodplain (Kochi Prefecture, 1979). A delta-related lowland lies in the southern portion of the study region (Fig. 1). The floodplain elevation is about 2–6 m above sea level, and the surface elevation decreases gradually towards the coast. The south area, the mountains behind the Usa Elementary School, is 0.3 km^2 (Area A in Fig. 1), whereas the area north of the school is 1.3 km^2 (Area B in Fig. 1), or 4.3 times the size of Area A. Given the difference in spatial extent, we expect that there will be a clear difference in groundwater supply between the two areas.

The study area consists of a clayey layer at 15–20 m below sea level, an overlying sandy layer and aquifer, and a gravel layer near the surface (Fig. 2). The sandy layer was deposited by a coastal current and has a hydraulic conductivity is between about 1.0×10^{-4} and 1.0×10^{-5} m/s. This sand coarsens with decreasing depth and consists of three sub-layers: the As-1 layer mainly composed of medium to coarse sand, the As-2 layer composed of silt mixed with medium to fine sand, and the As-3 layer composed of silt mixed with fine to medium grained sand.

Gravel layers, Ag-1, Ag-2, and Ag-3 are principally fines mixed with sandy gravel and probable debris flow deposits from the mountainous area. Although the hydraulic conductivity is between 1.0×10^{-3} and 1.0×10^{-7} m/s, the layer often exhibits low water permeability.

A widely distributed fresh water - saline water boundary exists on the seaward side of the A - A' cross section in Area A (30 < EC ≦ 4000 mS/m). On the other hand, the B - B' cross section of Area B shows a mostly fresh water area (EC ≦ 30 mS/m), and the fresh - saline boundary was not detected in the observation well on the seaward side.

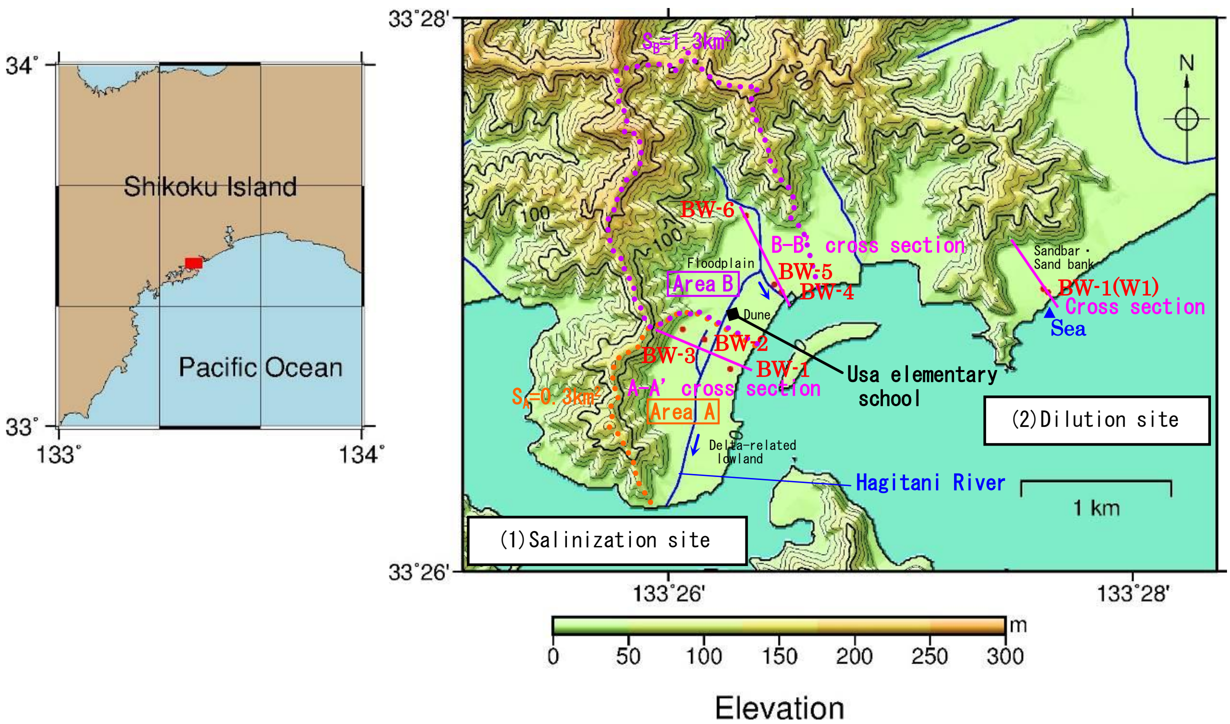

Fig. 1 Geomorphology of the study area and survey location

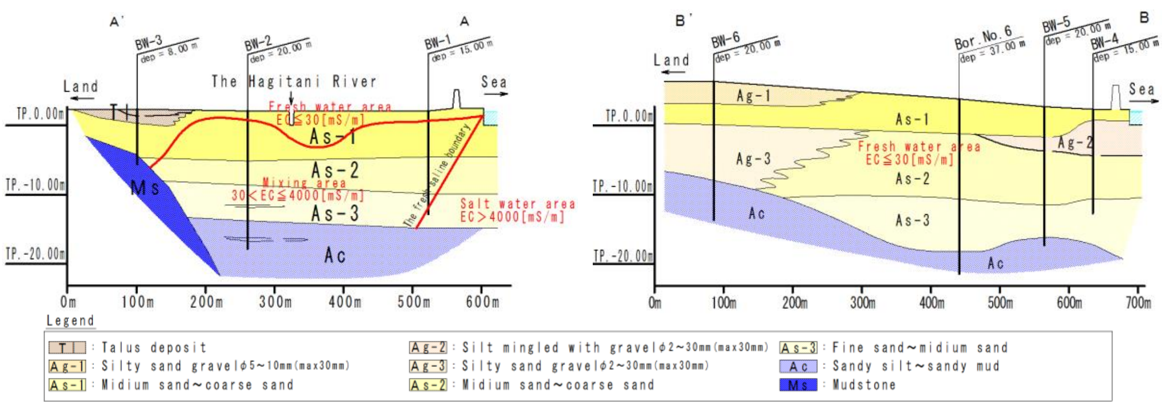

Fig. 2 Hydrogeological model of the study area

2.2 Salinization risk evaluation

(1) Direction and gradient of the water table

In most places, the water table gradient dips from the mountains towards the sea. The seaward gradient in Area A is small in both the dry (–0.03° to 0.09°) and wet seasons (–0.05° to 0.15°). In addition, after a period of low precipitation, the water table gradient tilts inland in the opposite direction in a few months (Fig. 3; cross section A–A'). On the other hand, the water table gradient in Area B is stable and inclined seaward. In Area B, this trend does not change through the year, with dry season gradients of 0.32° to 0.44° and wet season gradients of 0.36° to 0.47° (Fig. 3; cross section B–B').

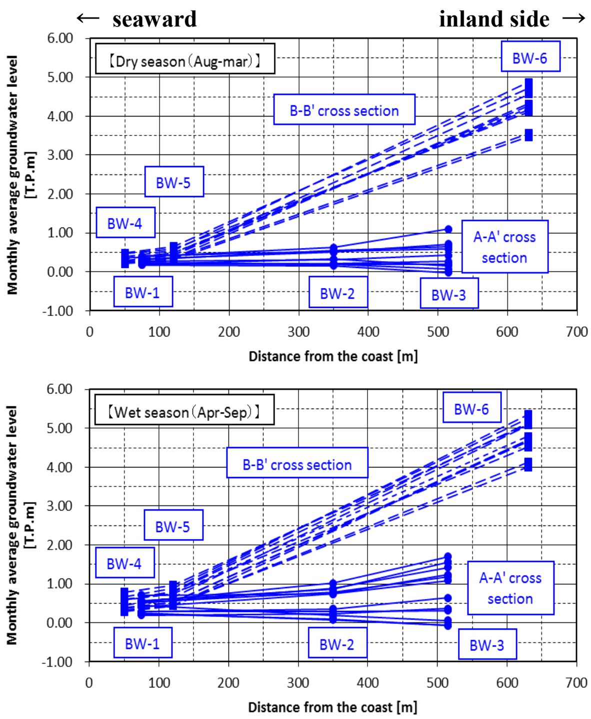

Fig. 3 Seasonal comparison of water table gradients in the study area (December 2004 to September 2006)

(2) Relationship between precipitation and groundwater level

The relationship between the monthly average water level in observation wells and two-month cumulative precipitation in Area A (BW-2) and Area B (BW-5) were compared, and there is a difference in the relationship between the precipitation and the groundwater level in Area A and Area B. Although there is a linear relationship between the monthly average water level and two-month cumulative rainfall in both areas, the amount of water level drawdown that occurs after a decrease in precipitation is larger in Area A than in Area B (Fig. 4).

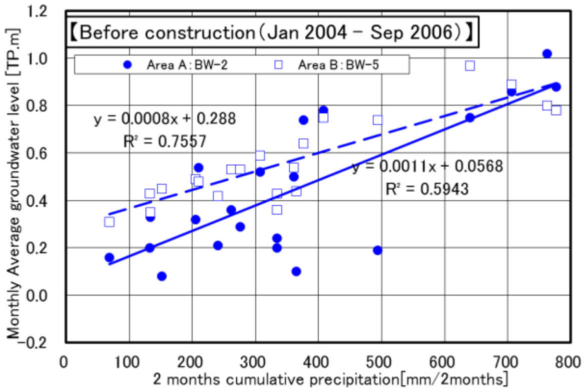

Fig. 4 Relationship of two-month cumulative rainfall and monthly average water level

(3) Evaluation of salinization by the electric conductivity integration method

Salinization at BW-1 (Area A) and BW-4 (Area B) on December 11, 2004 were quantitatively evaluated using the electric conductivity (EC) integration method (Takahashi and Ohtoshi, 2008). This method integrates EC with depth or uses a mean EC value obtained by dividing the integrated EC by the aquifer thickness. EC in BW-1 begins to increase at about T.P. -5 m, with values close to those of seawater (about 4000 mS/m) from T.P. -12 m. The T.P. means the Tokyo Peil, the mean sea-level of Tokyo Bay. At BW-4, groundwater was fresh (about 30 mS/m) at all depths (Fig. 5). At BW-1, integrated EC values were about 14000 mS/m × m, and the average EC was about 1100 mS/m. At BW-4, the integrated EC was about 400 mS/m × m, and the average EC was about 30 mS/m, or about 3% of values at BW-1 (Table 1).

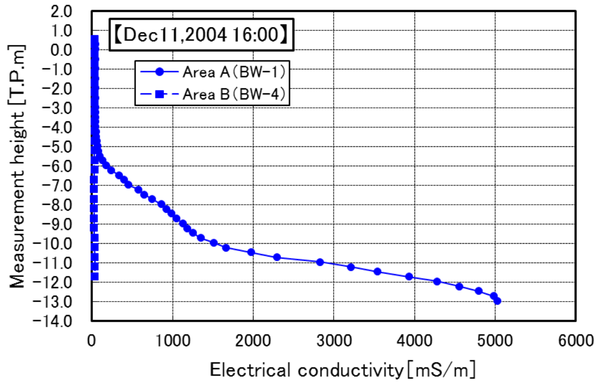

Fig. 5 Vertical EC distribution

Table 1. Comparison of the integrated EC and mean EC

Area	The fresh-saline boundary height※	Integrated *EC*	Mean *EC*
	[T.P.m]	[mS/m*m]	[mS/m]
A(BW-1)	-11.7	14,100	1,050
B(BW-4)	–	400	30

※For convenience boundary height is the height of EC=4000mS/m (—:Without boundary exists).

(4) Estimation of groundwater flow

Groundwater flows in both areas were estimated from the shape of the saline water edge (Fig. 6). Estimations were obtained using the following equations based on the Ghyben-Herzberg relationship and Darcy's law (Domenico and Schwartz, 1990):

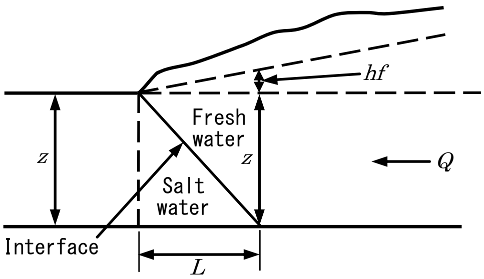

Fig. 6 Groundwater flow calculation method

$$z=\frac{\rho_f}{\rho_s-\rho_f}h_f \tag{1}$$

$$Q'=\frac{Q}{Y}=K\frac{(h_f-0)}{L}z \tag{2}$$

$$Q=Q'Y=\frac{(\rho_s-\rho_f)Kz^2}{\rho_f L}Y \tag{3}$$

Where,

Q = volumetric flow rate of fresh water to the sea
Y = the length of the shoreline (100 m)
Q' = discharge per unit length of the shoreline
K = hydraulic conductivity
(aquifer average = 5.0×10^{-4} [m/s])
L = distance from the shoreline
ρ_f = density of freshwater (1.0)
ρ_s = density of sea water (1.025)
h_f = height from sea level to the water table
z = depth from sea level to the interface (m)

As the fresh–saline water interface was not observed at BW-4, this was assumed to be at the base of the well. As a result, groundwater flows were 10.1 m^3/h/100 m in Area A (BW-1), and 20.8 m^3/h/100 m in Area B (BW-4). Therefore, we inferred that the groundwater supply capability in Area B is at least twice that of Area A (Table 2).

Table 2. Groundwater flow results(Dec11,2004,16:00)

Area (Observation hole)	z※ [m]	L※ [m]	Groundwater flow[m^3/h/100m]
A（BW-1）	15	100	10.1
B（BW-4）	18	70	< 20.8

※z and L was estimated from ground model and interface position

2.3 Prediction and verification of salinization risk

(1) Prediction of salinization risk

Salinization risks in areas A and B were predicted based on the indexes referred to in Section 2.2 (Table 3). The groundwater environment in Area A is susceptible to salinization because the water table is inclined landward with a gradient of 0.03–0.05°, the elevation of the water table is relatively low when precipitation is low, EC values are high, and groundwater flow capability is low. The groundwater environment in Area B is not as susceptible to salinization because the water table is inclined seaward with a gradient of 0.32–0.36°, the elevation of the water table is relatively high, EC values near the coast are low, and groundwater flow capability is high. Therefore Area A is assumed to be an area in which, if the groundwater table falls because of construction, salinization may affect residential and agricultural water supplies.

(2) Evaluation of salinization risk

When construction work started on the river in July 2007, the regional extent of groundwater below T.P. 0 m decreased, and shallow groundwater salinization progressed around the construction zone (Fig. 7). Salinized water is unsuitable for consumption and caused decreased agricultural yields.

In Area B, although groundwater below T.P. 0 m decreased slightly, the extent of EC ≧ 200 mS/m (Cl^- ≒ 200 mg/L) was limited to coastal areas. There was no reported impact on the residents or industry. Therefore, predictions in the previous section of a high risk of salinization in Area A and a low risk in Area B appear to be correct.

Table 3 Comparison of salinization risks

Area	(1) Groundwater table		(2) Precipitation and groundwater level		(3) EC values and salinization in the vertical direction			(4) Groundwater flow
	Minimum value of the dry season (Upper column) Minimum value of the wet season (Lower column)		Groundwater level of two-month cumulative rainfall [T.P.m]		The fresh-saline boundary height [T.P.m]	Integrated EC [mS/m*m]	Mean EC [mS/m]	Freshwater flow [m^3/h/100m]
	Direction of tilt	Gradient[°]	100mm	700mm				
A	Sea→Land	0.03	0.17	0.83	-11.7	14000	1050	10.1
	Sea→Land	0.05						
B	Land→Sea	0.32	0.37	0.85	None	400	30	< 20.8
	Land→Sea	0.36						

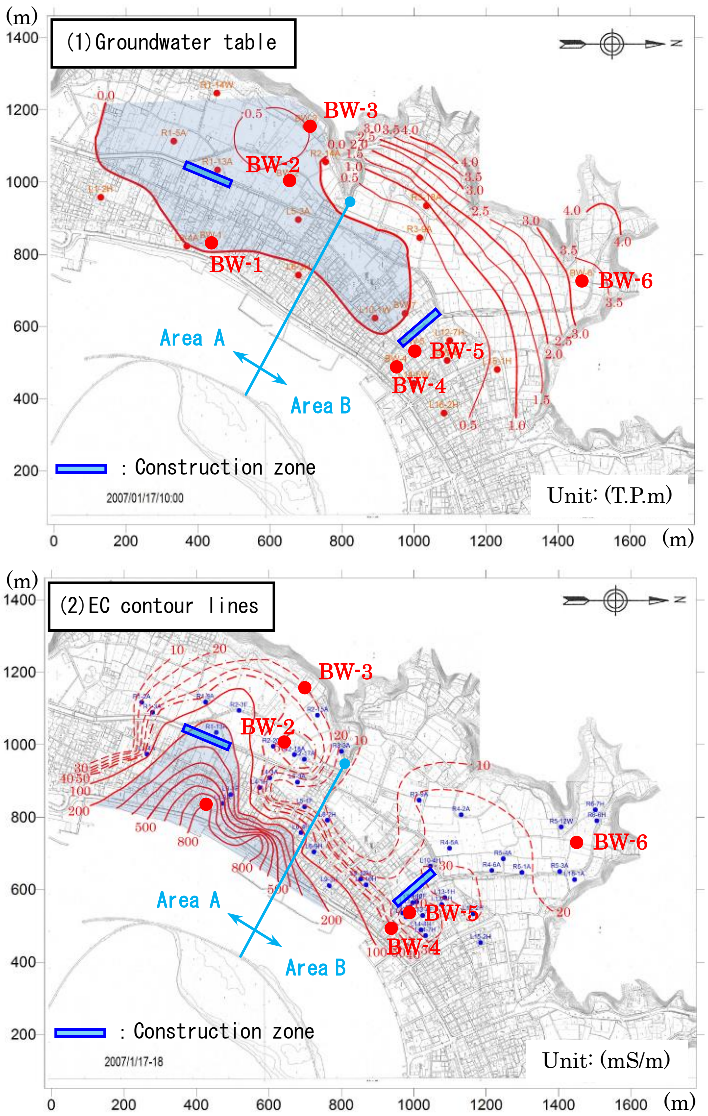

Fig. 7 Groundwater table and EC contour lines after construction (January 2007)

3. A case study of dilution risk prediction

Land farming of flat fish has been carried out by pumping high salinity groundwater from the coastal plains in the Nii district of Tosa. Aquaculture is not adversely affected by the high salinity groundwater that develops during dry periods, as it is similar to seawater. However, groundwater dilution when intense rainfall increases the volume of groundwater may be problematic.

The construction of coastal dikes for earthquake protection in this area consisted of a curtain-like wall of steel pipe. Groundwater observations were carried out because of the possibility of groundwater dilution after construction. An evaluation was made of the dilution of groundwater following a record precipitation event in August 2014. Using the relationship between groundwater salinity and precipitation, the effect of cumulative precipitation on farmed flatfish populations was identified.

3.1 Geomorphology and hydrogeology of the study area

The study area is a narrow plain that lies between the mountains and the coast. It is divided into sandbar and sandbank environments (Fig. 1) (GSI, 2006). The sandbar and sandbank are at an elevation of about 7 m, but decrease gradually in height towards the northwest.

The lithostratigraphy of the study area consists of medium to coarse-grained gravel (As-1) at the surface, which is underlain by sandy gravel (Ag-1) consisting of 2–10 mm rounded gravel and medium to coarse sand, and then a basal silty sand (Fig. 8). The layer boundaries are gently inclined at 2–3° from the mountains towards the sea. The main aquifers are made of two layers of Ag-2 and Ag-3, with a thickness of 3–4 m and about 5 m, respectively. Permeability is generally low, and the hydraulic conductivities (*k*) of Ag-2 and Ag-3 are 1.35×10^{-5} m/s and 4.30×10^{-6} to 7.24×10^{-6} m/s, respectively.

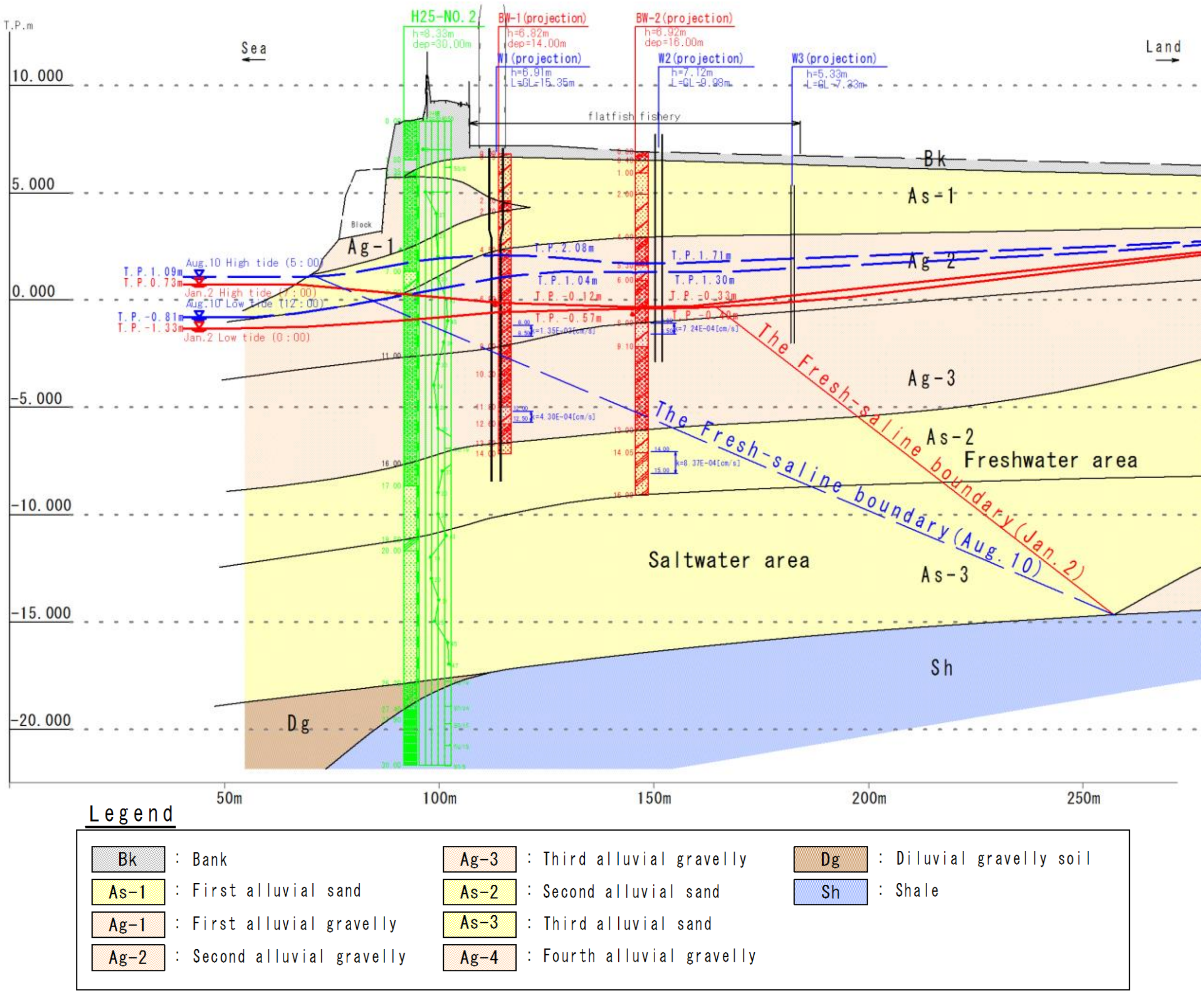

Fig. 8 Hydrogeological model of the study area

3.2 Relationship between groundwater salinity and precipitation

In the study area, the salinity of existing wells (W1) and seawater (Sea) ranges from 3200 to 16000 mg/L, and 9500 to 19000 mg/L, respectively. Thus, salinity at W1 is 34% to 84% of the Sea values. Salinity at W1 tends to decrease with increasing precipitation (Fig. 9). In addition, the salinity of both W1 and Sea was greatly reduced in August 2014, when monthly precipitation was 1164.5 mm, and the recovery of salinity at W1 was gradual.

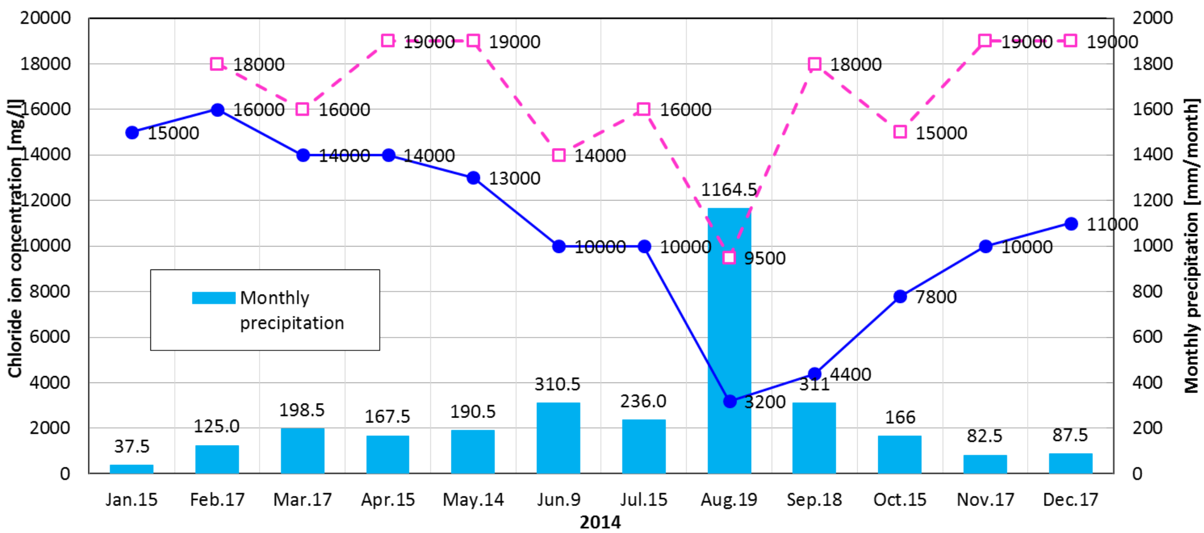

Fig. 9 Changes salinity at W1 and Sea, and monthly precipitation in 2014

3.3 Prediction of dilution risk

(1) Definition of cumulative precipitation

Cumulative precipitation is defined as the sum of any precipitation that occurred before and including the water sampling date. For example, the previous 30 days precipitation (R_{30}) is the cumulative amount of precipitation over the last 30 days, and includes any precipitation falling on the sampling day.

Although data are limited and dispersed, salinity has a strong correlation with R_{30} (Fig. 10). Salinity at W1 decreases rapidly, to about 60% of seawater salinity, when R_{30} reaches 200–300 mm. Salinity then continues to decrease with more precipitation. It is presumed that, when precipitation is low, the ground is able to absorb most of the rainfall. However, in the case of intense precipitation events, residual precipitation that cannot penetrate into the ground flows over the surface directly to the sea or rivers.

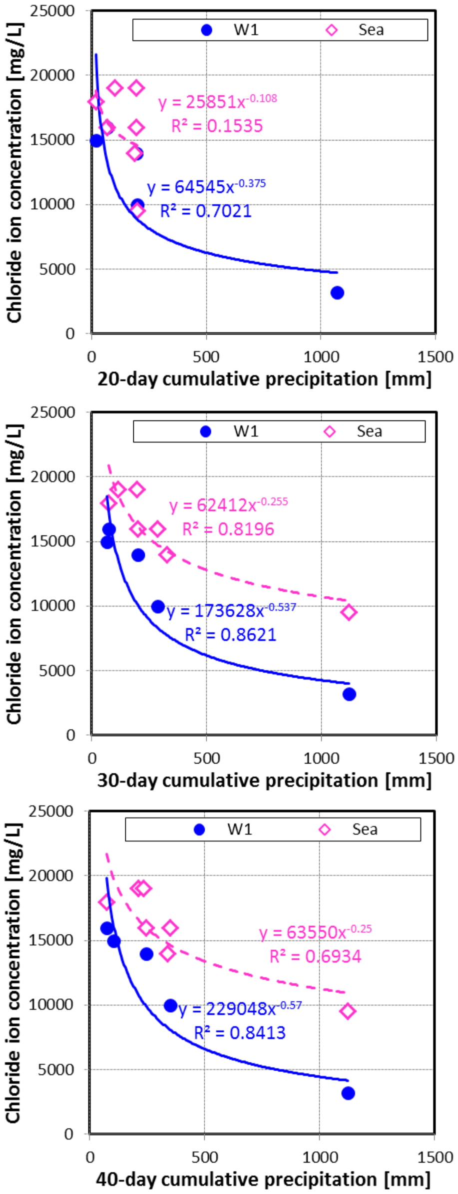

Fig. 10 Relationship between precipitation and salinity (February–August 2014)

(2) The effect of cumulative precipitation on cultured flatfish

As salinity data are limited, salinity was inferred from the EC values. Salinity and R_{30} during the period January–September 2014 without data less than 100 mm, which little affect cultured flatfish, were included in the regression analysis. The regression equation is as follows:

$$W1 = 257296\,R_{30}^{-0.595} \quad (R^2 = 0.8389) \tag{4}$$

If the threshold chloride concentration that affects cultured flatfish us set at 4000mg/L (Ochiai and Tanaka, 1998), then the R_{30} value that affects cultured flatfish is 1100 mm (Fig. 11).

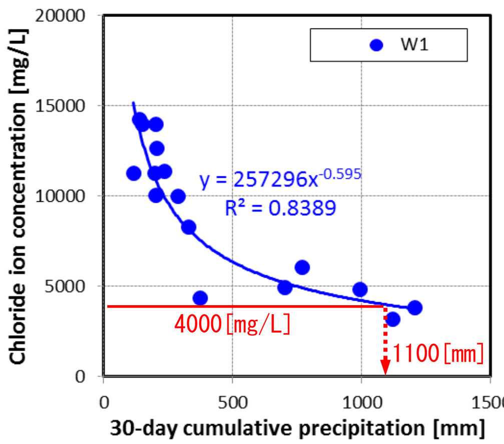

Fig. 11 30-day cumulative precipitation–salinity relationship and threshold for aquaculture

(3) Evaluation of dilution risk

The 14-day period of August 18–31, 2014, was the only time that R_{30} exceeded 1100 mm over the past 10 years (2005–2014; Fig. 12). According to aquaculture records, flatfish mortality was high at this time, and there are few previous records of flatfish mortality as a result of groundwater dilution. Thus, our calculations reflect the observational data, and the R_{30} index appears to be a reasonable method of easily evaluating and predicting flatfish mortality.

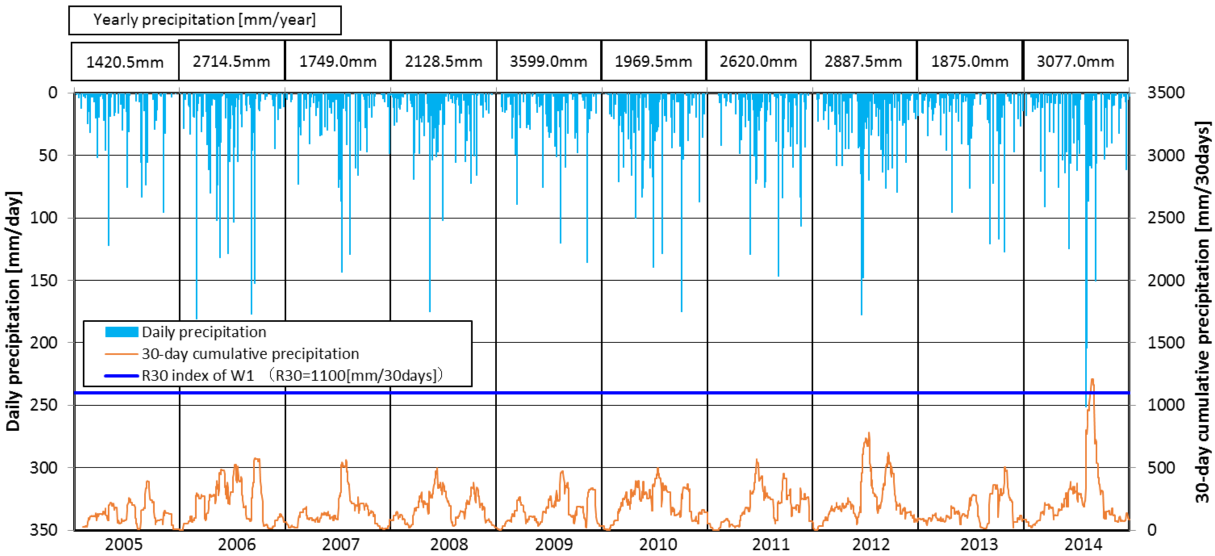

Fig. 12 The impact of accumulated precipitation (R_{30}) on cultured flatfish

4. Summary

To predict the risk of salinization on coastal plains, it is important to evaluate the groundwater recharge capacity using the topographical and hydrogeological characteristics of the area. In the case study presented in this paper, where the groundwater level gradient was gradual in the vicinity of T.P. 0 m, and inclined from the sea to the mountains, salinization progressed quickly, and inhabitants and industry are affected by deteriorating water quality.

The relationship between cumulative precipitation and groundwater salinity offers a simply way to evaluate the groundwater dilution risk.

To date, the evaluation of salinization–dilution risks in this region has been based on a qualitative assessments of topography, hydrogeology, and weather conditions. Future quantitative verification of these risks will require the application of numerical simulation techniques.

Acknowledgements

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