



INVESTIGATION OF ROOTZONE SALINITY WITH FIELD MONITORING SYSTEM AT TSUNAMI AFFECTED RICE FEILDS IN MIYAGI, JAPAN

Ieyasu Tokumoto^{*1}, Katsumi Chiba², Masaru Mizoguchi³, and Hideki Miyamoto¹

¹Department of Environmental Sciences, Saga University, Saga, Japan

5 ²Department of Environmental Sciences, Miyagi University, Sendai, Japan

³Department of Global Agricultural Sciences, University of Tokyo, Tokyo, Japan

Correspondence to: Ieyasu Tokumoto (yasu@cc.saga-u.ac.jp)

ABSTRACT

10 After the 2011 Tohoku earthquake, thirteen thousand hectares of farmlands
were damaged by massive Tsunami near coastal sites in Miyagi, Japan. Some eighty
percent of the damaged farmlands have been recovered in 2014, but subsidence and
high salinity groundwater make it difficult to completely remove salinity from the soil.
To solve the problem, management of saltwater intrusion plays an important role in
15 rootzone salinity control with the Field Monitoring System (FMS), which is remote
sensing technology of wireless real-time soil data through the internet data sever to
investigate high soil moisture and high salinity in tsunami affected fields. Using the
FMS with the time domain transmission system, we monitored soil moisture, electrical
conductivity (EC), groundwater level, and EC of groundwater at tsunami damaged
20 paddy fields. The field measurements of the FMS were conducted at two sites of
tsunami damaged farmlands in Iwanuma and Higashimatsushima of Miyagi prefecture,
Japan. After the Tohoku disaster, co-seismic subsidence of 17-21 cm and 50-60 cm of
the land was reported at the sites, respectively. Our findings were high EC of
groundwater ($> 35 \text{ dS m}^{-1}$) due to intrusion of sea water into groundwater in 2013.
25 Although the shallow groundwater provided salinity to the soil surface in 2014, the



FEM allowed us to monitor high EC ($< 6 \text{ dS m}^{-1}$) even in saturated soil condition. Rainfall facilitated desalination process, but the saline groundwater level reached the soil surface after heavy rainfall, suggesting that coastal zone aquifer management is essential to prevent saltwater intrusion into groundwater.

30

Key words: Field Monitoring System, TDT sensor, Tsunami affected soil

1. INTRODUCTION

The 11 March 2011 M9.0 megathrust earthquake off the East Coast of Japan (Fig. 1a) (e.g. Ozawa et al., 2011; Sato et al., 2011) generated a devastating tsunami that inundated over 1300 km of the Pacific Coast, and reached more than 5 km inland in some areas of the Sendai Plain in Miyagi, Japan (Chagué-Goff et al., 2012). The tsunami caused extensive damage to thirteen thousand hectares of farmlands, which contained collapsed houses, buildings and many types of infrastructure (Earthquake and Reconstruction Division of Miyagi Prefecture, 2014). Sendai Plain, which Sendai airport is located, was the place to recover the infrastructure after the disaster. In April 2011, some surveys reported the situation of paddy fields to assess the environmental impacts of tsunami inundation at the areas of Sendai Plain (Fig. 1a and 1b) (JSIDRE, 2011). In May 2011, ponded water was still recorded in many rice paddy fields and in 45 depressions up to 2.6 km inland north of Sendai Plain, and salt crusts were also observed on many paddy fields, where water had evaporated and/or leached into the soil (between ~1.2 km and ~3.5 km inland) (Chagué-Goff et al., 2012).

With the guideline of desalination process proposed by MAFF (2011), the first comprehensive attempt to recover the devastated paddy fields was carried out (Fig. 2).



50 Some eighty percent of the damaged farmlands have been recovered in the whole
damaged areas of Miyagi (Earthquake and Reconstruction Division of Miyagi
Prefecture, 2014) (Fig. 2a and 2b), although underdrains, which can remove salinity
under saturated soil condition, have been installed at a part of recovered paddy fields
(Fig. 2c and 2d). Chiba et al. (2012) investigated the effect of underdrains on
55 desalination process due to rainfall in paddy fields in Sendai Plain with/without
underdrains, suggesting that underdrains facilitated the desalination during rainy season
between June and September. However, subsidence and high salinity groundwater,
making it difficult to completely remove salinity from the soil near the coastal side all
over the Miyagi (Chiba et al., 2015).

60 Field Monitoring System (FMS) to measure soil moisture and salinity
developed by Mizoguchi et al. (2012) can facilitate recovery of agricultural production
on damaged lands (Fig. 3). The FMS contains three main components: data loggers
(Decagon Device and/or Campbell Sci.), soil/meteorological sensors, and a field router
(FR)(X-ability), allowing us to collect the in-situ data through Bluetooth and send it to
65 the data server over the Internet. The FR mainly consists of a micro-PC, 3G/GSM USB
modem, webcam, and battery in a waterproof dust-tight box. The FR consumes little
power (six-watt solar panel), is easy to set up, and transmits data inexpensively over a
cellular mobile line. With the FMS, Chiba et al. (2012) monitored electric conductivity
(EC) of groundwater and groundwater level successfully. However, monitoring high
70 soil water content (θ) and high bulk EC caused by salt leaching and saltwater intrusion
was limited. To monitor high bulk EC in soil, transmission line, electromagnetic
measurement methods such as time domain reflectometry (TDR) and time domain
transmission (TDT) would be widely accepted. Especially, TDT sensor (Acclima) is
more affordable than TDR sensor due to low cost, high precision of θ estimation, and



75 less user-ability requirement of TDT waveform analysis (Blonquist Jr. et al., 2005).
Miyamoto et al. (2013) examined bulk EC affecting permittivity with TDT devices
through the obtained TDT waveform analysis in sand, loam, and clay. Their results
showed a threshold of 5 dS m^{-1} when maximum slope of TDT waveform for bulk EC
estimation was too low to detect.

80 Understanding the desalinization process and the management of saltwater
intrusion in coastal aquifers is a critical challenge in the tsunami damaged farmlands.
There have been hydrological studies regarding saltwater intrusion under natural
conditions for more than 100 years (Barlow, 2003), but the degree of saltwater intrusion
varies widely among localities and hydrogeologic conditions. For the management of
85 saltwater intrusion after subsidence, a new approach is required in the Tohoku
earthquake damaged land (Sasaki, 2014; Miyauchi, 2015).

The aim of this study was thus to investigate temporal change in rootzone
salinity of the tsunami damaged farmlands in Miyagi using the FEM with TDT sensor
system to compare θ and high bulk EC with the saline groundwater level. This was
90 achieved at two farmlands, completed clearance of disaster debris due to the MAFF
guideline of desalinization process. In addition, this paper presents the current status on
a construction method for the saltwater intrusion management along the Pacific coast.

95 2. METHODOLOGY

2.1 Study site

The field measurements of the FMS were conducted at two sites of tsunami
damaged farmlands: Iwanuma ($38^{\circ}03'17.8''\text{N}$ $140^{\circ}54'50.3''\text{E}$) and Higashimatsushima



(38°25'38.6"N 141°14'46.4"E) in Miyagi, Japan (Fig. 4). The paddy fields in Iwanuma
100 are located at a costal side, 0.7 km and 0.25 km away from the Pacific Ocean and
Abukuma River estuary, respectively (Fig. 4a). After the disaster, co-seismic subsidence
of 17-21 cm of the land was reported by Ozawa et al. (2011), and the area was covered
by the top of 10 cm thick sediment layer consisting of sand and/or mud (Chiba et al.,
2012). The geomorphology of the low-lying coastal land prevented much of the
105 seawater from draining away, resulting in water ponding for 20 days. In 2013, drainage
trench and canals in the area were recovered, and deposition of debris such as woods
and rock fragments was stripped from the soil surface. However, much of the area near
Iwanuma has high EC of groundwater due to the low sea level (approximately 0 m). In
Higashimatsushima, the tsunami damaged area (3600 ha) consisted of 40% farmlands,
110 in combination with subsidence of 60 cm and deposit of 50-cm sea sand layer, resulting
in 10-cm lower land prior to the disaster (Ota et al., 2013). In 2014, debris was removed,
but underdrain for desalination process was not constructed in the areas.

The regions are characterized by a warm humid temperate climate (mean
monthly temperatures ranged from 1.6 °C to 24.2 °C from 1981 to 2010), and average
115 of annual rainfall is approximately 1100 mm (Japan Meteorological Agency, 2015).
Monthly rainfall over 150 mm was recorded between July and September, but typhoons
are rare in the regions. Light snow (maximum snow accumulation < 10 cm) occurs
between December and February. For seasonally rainfall frequency, summer time is the
best season to reduce soil salinity. In general, EC of rainfall near the costal side ranges
120 from 1.7 to 8.58 mS m⁻¹ (Environment Policy Division of Miyagi Prefecture, 2005),
suggesting that chloride deposition from sea spray is low.

2.2 TDT sensor calibration



Calibration of TDT sensor (Acclima) was conducted in a walk-in controlled-temperature laboratory to perform at the standard temperature of 25°C. A
125 9.8-cm i.d. × 20-cm long cylindrical column was filled with sieved and air-dried soils (dominated by organic-rich and muddy sediments) of Iwanuma and Higashimatsushima above 2-cm sand layer that was at the bottom of the column, and was packed to a dry bulk density of 1.50 g cm⁻³. A TDT sensor was inserted vertically in the center of the column. EC_{1:5} (1:5 soil to water extract EC) of tsunami affected soil from Iwanuma and
130 Higashimatsushima was 0.75 dS m⁻¹ and 2.33 dS m⁻¹, respectively. For the reference, we used the desalinized soil (EC_{1:5} = 0.24 dS m⁻¹) of Higashimatsushima that was washed with distilled water. Water was allowed to infiltrate in a stepwise manner from the bottom at a rate of 0.5 to 2 cm d⁻¹ over a 3-day period to create a range of water contents, which is known as the rapid upward infiltration method proposed by Young et
135 al. (1997). The weight of the soil column was monitored with a digital balance to calculate the average of water content in the influence area of TDT sensors. We confirmed that there was no influence of the sand layer on TDT measurements. After the experiment was completed, average volumetric water content in the entire soil column, θ_{ave} and bulk density, ρ_b were obtained gravimetrically.

140 Permittivity and EC data of the TDT sensor were determined with SDI-12 (digital signal processing algorithms) of CR800 (Campbell Sci.), showing travel time and maximum slope of the TDT waveform. The resulting digitized waveform can be analyzed by taking the first and second derivatives and extracting maximum inflection points and maximum slope points in the waveform (Blonquist Jr. et al., 2005). While
145 the entire TDT waveforms were not received by CR800, permittivity and EC were calculated from the readings of maximum inflection points and maximum slope. Before the experiment, bulk EC of TDT sensor was calibrated with salt water.



2.3 FMS with TDT sensors

In the summer of 2014, we began a study at the sites (Iwanuma and
150 Higashimatsushima) to monitor soil moisture and bulk EC using FMS with TDT
sensors (Acclima) (Fig. 4b and 4c). Three TDT probes were installed at depths of 10, 20,
and 40 cm. TDT measurements were recorded every 1 h by a model CR800 datalogger
(Campbell Scientific, Logan, UT) and uploaded at the data server at noon through the
FR (X-ability). Groundwater level (G.W.L.) and EC of groundwater were measured
155 with a CTD sensor (Decagon Devices), hooked up with a Em50 datalogger (Decagon
Devices). The CTD sensor was placed in a well at a depth of 50 cm from the soil
surface.

RESULTS AND DISCUSSION

TDT Sensor Calibration

160 The relationship between ε and θ , obtained with salinity ($EC_{1.5} = 2.33 \text{ dS m}^{-1}$)
and desalinized soils ($EC_{1.5} = 0.24 \text{ dS m}^{-1}$) from Higashimatsushima, was very close,
although θ ($\varepsilon > 21$) of the salinity soil was slightly higher than the desalinized soil (Fig.
5). When saturated θ for the soil was $0.55 \text{ m}^3 \text{ m}^{-3}$, bulk EC of the desalinized soil was 6
 dS m^{-1} , which caused a considerable measurement error (ε was equal to zero). However,
165 we did not find such errors in the desalinized soil of Higashimatsushima at saturated
condition. Likewise, no error readings occurred in the salinized soil of Iwanuma ($EC_{1.5}$
 $= 2.33 \text{ dS m}^{-1}$), resulting in a threshold of 6 dS m^{-1} for those tsunami affected soils.

Measured ε - θ relationship was nearly identical to Topp Eq. (Topp et al., 1980),
but Topp Eq. slightly underestimated θ (Fig. 5). For more accurate θ estimation, we
170 applied a multiplier of -1.15, obtained by a regression analysis to Topp Eq., yielding the
equation



$$\theta = 1.15 \times (-5.3 \times 10^{-2} + 2.9 \times 10^{-2}\varepsilon - 5.5 \times 10^{-4}\varepsilon^2 + 4.3 \times 10^{-6}\varepsilon^3) \quad [1]$$

with an r^2 of 0.98 for a value of ε in the range from 3.6 to 31.5. On the other hand, the ε - θ relationship for the soil of Iwanuma was fitted well with Topp Eq. ($r^2 = 0.97$) (data is not shown).

175 **Soil Moisture and EC Monitoring by FMS at Iwanuma**

In October 2014, the Iwanuma region was hit by two typhoons, caused rainfall events over 112 mm, while typhoons are rare (Fig. 6a). Soil water content drastically increased at depths of 10, 20, and 40 cm on 5 October and θ below 20 cm depth was saturated for 20 days (Fig. 6b). Saturated hydraulic conductivity was 0.35 and 9.76 cm
180 d^{-1} at depths of 15 and 25 cm, respectively. Bulk EC increased with increasing θ , and the highest bulk EC was 3.7 dS m^{-1} at a depth of 40 cm (Fig. 6c). Shallow groundwater level also increased up to 20 cm and 40 cm above the soil surface on 5 October and 13 October, respectively (Fig. 6d). An example of webcam photos showed the ponding condition after the heavy rainfall on 5 October (Fig. 7), suggesting that EC of
185 groundwater decreased from 22 dS m^{-1} to 5 dS m^{-1} due to a direct inflow into a well. For this reason, increase in EC of groundwater was found after 5 October (Fig. 6d). This indicated the intrusion of salt wedge into the groundwater, which has a seasonal cycle of salinity variation due to the strongly seasonal rainfall.

EC of the ocean near the experimental site was 45 dS m^{-1} . In 2012, EC of
190 groundwater was 25 dS m^{-1} at a depth of 70 cm where the intrusion of salt wedge into the groundwater occurred, while the average of groundwater level was approximately 25 cm depth (Chiba et al., 2015). To decrease the groundwater level, a pumping station was recovered in 2012. The pumping station was used to sustain rotational upland fields



195 from rice farming to wheat or soybean and maintain the groundwater level (45 cm to 50
cm below surface), which was pumped into water drainage channels that finally drained
into the sea. Rice farming was confirmed to remove salt concentration out of the
agricultural fields in the region (Chiba et al., 2015), but the high salt concentration (EC
> 0.9 dS m⁻¹) was resulted in dead soybean (Hoshi and Yusa, 2012). At the end of
October 2014, the groundwater level was controlled by the pumping station, resulting in
200 daily variation of the groundwater level from soil surface to 50 cm depth (Fig. 6d). In
spring 2015, the pumping station operated simultaneously to maintain the groundwater
below a depth of 50 cm (data not shown).

An important question for the Iwanuma site is whether the land subsidence
due to the earthquake causes the saltwater intrusion into the groundwater, which is
205 characterized as “transition zone” between freshwater and seawater, containing
concentrations of chloride ranging from about 250 to 19,000 mg L⁻¹. Based on
Miyauchi (2015), who simulated the saltwater movement from Abukuma River
estuary with -1 m of sea level of Tokyo Bay, possible contamination of the saltwater
(concentrations of chloride = 500 mg L⁻¹) occurred even at approximately 200 m away
210 from the sea shore. Our bulk EC data were consistent with the chloride concentration
using relationship between chloride concentration and EC proposed by Kaneko et al.
(2002):

$$\text{Chloride concentration (mg L}^{-1}\text{)} = 270.86 \times \text{EC (dS m}^{-1}\text{)} \quad \text{Eq. [2]}$$

Soil Moisture and EC Monitoring by FMS at Higashimatsushima

215 During October 2014, total rainfall was 211 mm (Fig. 8a), and θ was
completely saturated at a depth of 40 cm (Fig. 8b). Bulk EC at a depth of 20 cm
exceeded 6 dS m⁻¹, which was the maximum detectable value of EC with TDT sensors
(Fig. 8c), resulting in error of θ measurements at the same depth. This suggests that



coated TDT probes would be required to monitor θ in such high salt concentration. To
220 decrease salt concentration near soil surface, daytime pumping was operated (Fig. 8d).
A mismatch of daily variations between groundwater level and unsaturated θ condition
may be explained by low saturated conductivity of the soil ($K_s = 1 \text{ cm d}^{-1}$). Without
exceptions of indirect inflows after typhoons, however, EC of groundwater was about
10 dS m^{-1} at a depth of 50 cm.

225 Locally, we confirmed the trend of bulk EC decline from 9.4 dS m^{-1} to 2.44 dS
 m^{-1} near the soil surface, indicating the effect of rainfall leaching through 2 yr-period,
but we found that the subsidence of 60 cm in Higashimatsushima made it difficult to
remove salt movement from salty groundwater in freshwater-saltwater environments of
the Pacific Coast. Comparison of groundwater level in the Higashimatsushima with
230 Iwanuma sites showed that Higashimatsushima site was flooded more frequently, even
though the site was covered with tsunami deposit of 50 cm. The profile of EC of
groundwater increased linearly as soil depth increased (Fig. 9). As we mentioned,
rainfall could maintain the freshwater zone to decline soil salinity near the soil surface.
However, it seemed that increase in salty groundwater level caused salination below the
235 soil surface. This explained why the shallow groundwater could be salinity source to the
soil surface after the subsidence. To solve the salinity problem, raising the ground level
of the agricultural fields would be needed (Chiba et al., 2012); nevertheless it represents
a costly soil construction method which can also lead to issues of a soil stock from
mountain side (Sasaki, 2014).

240 Instead of removal of tsunami sediments and underlying soil, Ota et al. (2013)
suggested the use of tsunami sediments for agricultural soil because their results showed
that tsunami sediments were not contaminated by high concentration of heavy metals
such as copper, lead, and arsenic. If the underlying soil is turn over on tsunami



sediments, it would be feasible and sustainable options to maintain fertile soil in the root
245 zone. However, Ota et al. (2013) also insisted on the need of a construction method to
prevent ongoing saltwater intrusion.

Control of salinity movement from the costal side

For control of saltwater intrusion, the surface water canals and levee system
was proposed to convey freshwater from inland water conservation (storage) areas to
250 coastal areas, where the water is recharged through the canals to the underlying aquifer
to slow saltwater intrusion in the aquifer (Barlow and Reichard, 2010). In addition to the
conventional method, an innovative approach is being proposed to manage saltwater
intrusion along the Pacific coast (Ota et al., 2013; Sasaki, 2014), which is the technique
to maintain freshwater zone under the tsunami affected agricultural fields. Figure 10
255 shows the schematic figure of the surface water canal to show the amount of surface-
water canal, Q ($\text{m}^3 \text{h}^{-1}$) (Sasaki, 2014):

$$Q = \frac{N \cdot H^2 \cdot L}{2d} \quad [3]$$

where N is hydraulic conductivity (m h^{-1}), H is water level difference between the
Ocean and canal, L is length of the canal, and d is distance between the ocean and canal.

260 Two dimensional saltwater intrusions with the surface water canal, simulated
by Ota et al. (2013), showed that saltwater contamination (concentration of 500 mg L^{-1}
chloride) can be avoided in root zone at $d = 40 \text{ m}$. Without the canal scenario, their
simulation result was similar to our observed EC data shown in in Figs. 8c and 9,
although our survey was only conducted at a small area of 200-m away from the costal
265 side. This suggests that the recovery of agriculture needs to recharge for the freshwater
zone due to water supply near the costal side. To date, no surface water canal has been
constructed in the severe subsidence region where the possibility of contributing to
control of salt-water intrusion would be a very exciting proposition.



As mentioned in the Introduction, so far some eighty percent of the damaged
270 farmlands have been recovered in terms of removal of tsunami sediments and
underlying soil through the guideline by MAFF (2011). However, our results show that
local variability of subsidence and high salinity groundwater were affected to remove
salinity from the farmlands. As the surface water canal is constructed, it would be
necessary to investigate salt concentration with the FMS in terms of assessment of
275 salinity movement from the costal side. The FMS with TDT sensor system was easy to
setup and retrieve in-situ data through the Internet.

CONCLUSIONS

Our study shows that investigation of rootzone salinity with the FMS at tsunami
affected rice fields in Miyagi, Japan. The FEM performed adequately to monitor high
280 bulk EC ($\approx 5 \text{ dS m}^{-1}$) even at high θ ($\approx 0.54 \text{ dS m}^{-1}$) for the effect of rainfall leaching
through 3 yr-period after the 2011 disaster. Our finding was decline in bulk EC due
to the rainfall leaching, but the shallow saline groundwater made it difficult to
remove salinity from the tsunami damaged field in Higashimatsushima where
severe subsidence occurred. The EC of groundwater seemed to increase because of
285 saltwater intrusion in groundwater. For the recovery of the damaged fields, the
management of saltwater intrusion is also the key components of the recovery plan
to maintain the large-scale aquifer storage along the coastal side.

This paper summarized a new approach to manage saltwater intrusion along
the Pacific coast with the surface water canal system, proposed by (Ota et al., 2013;
290 Sasaki, 2014). Based on temporal changes in bulk EC profiles and groundwater level,
the surface water canal system is required. To continue monitoring and scientific
analysis of the entire hydrologic system, therefore, the utilization of FMS is expected
to provide positive feedback for the recovery of agricultural production.



295 **ACKNOWLEDGEMENTS**

The research was supported by a grant from the Japan Society for the Promotion of Science (Research Project Number: 26511009).

REFERENCES

- 300 Association of Japanese Geographers: Map of tsunami inundation reported by
Tsunami Damage Team 2011, available at:
<http://danso.env.nagoya-u.ac.jp/20110311/map/574017Sendaikukou.jpg> (in Japanese),
2011.
- Barlow, P.M.: Ground water in freshwater-saltwater environments of the Atlantic
305 coast, U.S. Geological Survey, Reston, Virginia, available at:
<http://pubs.usgs.gov/circ/2003/circ1262/pdf/circ1262.pdf>, 2003.
- Barlow, P.M., and Reichard, E.G.: Saltwater intrusion in coastal regions of North
America, *Hydrogeology Journal*, 18, 247–260, 2010.
- Blonquist Jr., J.M., Jones, S.B., and Robinson, D.A.: A time domain transmission
310 sensor with TDR performance characteristics, *Journal of Hydrology*, 314, 235-245,
2005.
- Chagué-Goff, C., Niedzielski, P. Wong, H.K.Y., Szczuciński, W., Sugawara, D., and
Goff, J.: Environmental impact assessment of the 2011 Tohoku-oki tsunami on
the Sendai Plain, *Sedimentary Geology*, 282, 175-187, 2011.
- 315 Chiba, K., Kanmuri, H., and Kato, T.: Desalinization technique for tsunami-hit
farmland by infiltration of rain and discharge from underdrain, (in Japanese), *J.
Japanese Soc. Soil Physics*, 121, 29-34, 2012.



- Chiba, K., Kanmuri, H., and Kato, T.: Recovery of farmlands from the tsunami damage using the agricultural engineering technology, (in Japanese), J. Japanese Soc. Soil Physics, 129, 13-18, 2015.
- 320
- Earthquake and Reconstruction Division of Miyagi Prefecture: Situation of recovery of agricultural fields in Miyagi Prefecture, available at: <http://www.pref.miyagi.jp/site/ej-earthquake/list441-510.html> (in Japanese), 2014.
- 325
- Environment Policy Division of Miyagi Prefecture: Result of general and simultaneous investigation of acid rains in Miyagi Prefecture, available at: <http://www.pref.miyagi.jp/uploaded/attachment/2925.pdf> (in Japanese), 2005.
- Hoshi, N. and Yusa, T.: Desalinization of a Salt Affected Paddy Field by Tsunami in Miyagi Pref., (in Japanese), Bulletin of the Soc. Sea Water Sci., Japan, 66, 74-78,
- 330
- 2012.
- Japan Meteorological Agency: Weather, Climate & Earthquake Information, available at: http://www.jma-net.go.jp/sendai/kansoku-toukei/heinen/sfc_m_monthly.html, 2015.
- 335
- JSIDRE (Japanese Society of Irrigation, Drainage, and Rural Engineering): Results of field survey in Miyagi, available at: <http://www.jsidre.or.jp/saigai/taiou/> (in Japanese), 2011.
- Kaneko, T., Murakawa, M., Kozai, N., and Mitsugi, K.: Desalting technique for illuviated salts soil at paddy field by using underdrainage, (in Japanese), J. Agri.
- 340
- Engineering Soc., Japan, 70(7), 611-614, 2002.



- MAFF (Ministry of Agriculture, Forestry and Fisheries): Manual for salt leaching.
available at: <http://www.maff.go.jp/i/press/nousin/sekkei/pdf/110624-01.pdf> (in
Japanese), 2011.
- Matsumoto, H.: Beach ridge ranges and the Holocene sea-level fluctuations on
345 alluvial coastal plains, northeast Japan, Science Report Tohoku University, 7th
series (Geography), 35, 15-46, 1985.
- Miyamoto, H., Ito, N., Mase, A., Tokumoto, I., and Chikushi, J.: Application of time
domain transmissiometry (TDT) to coupled measurements of soil moisture and
electrical conductivity. (in Japanese with English abstract), JSIDRE, 288,
350 513-519, 2013.
- Miyauchi, T.: Salinity problems in Miyagi prefecture, (in Japanese), J. Japanese Soc.
Soil Physics, 129, 19-21, 2015.
- Mizoguchi, M., Ito, T., and Kobayashi, D.: Environmental monitoring of village
contaminated by radionuclides, Proceedings of AFITA/WCCA 2012, available at:
355 [http://www.iai.ga.a.u-tokyo.ac.jp/mizo/edrp/fukushima/fsoil/Seminar%20\(19\)-03.pdf](http://www.iai.ga.a.u-tokyo.ac.jp/mizo/edrp/fukushima/fsoil/Seminar%20(19)-03.pdf),
2012.
- Ota, K., Okamura, M., Kume, K., and Kato, S.: Report on recovery of agriculture
in Omagari, Higashimatsushima. (in Japanese). Proceeding of JSIDRE, Tohoku
Branch, 56, 120-121, 2013.
- 360 Ozawa, S., Nishimura, T., Suito, H., Kobayashi, T., Tobita, M., Imakiir. T.:
Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake,
Nature, 475, 373-377, 2011.
- Sasaki, K.: Agricultural recovery plan after the 2011 Tohoku-Oki earthquake. (in
Japanese). <http://www.pref.miyagi.jp/uploaded/attachment/305520.pdf>, 2014.



365 Sato, M., Ishikawa, T., Ujihara, N., Yoshida, S., Fujita, M., Mochizuki, M., Asada.
A.: Displacement above the hypocenter of the 2011 Tohoku-oki earthquake,
Science, 332, 1395, 2011.

Topp, G.C., Davis, J.L., and Annan. A.P.: Electromagnetic Determination of
Soil-water content- measurements in coaxial transmission-lines, Water Resour.
370 Res., 16(3), 574-582, 1980.

Young, M.H., Fleming, J.B., Wierenga, P.J., and Warrick, A.W.: Rapid laboratory
calibration of time domain reflectometry using upward infiltration, Soil Sci. Soc.
Ame. J., 61(3), 707-712, 1997.

375

380

385



390 Figure Captions

Fig. 1 Photograph of the damaged farmlands in Natori, Miyagi on 26 April 2011: (a) Tsunami inundated areas and (b) massive amount of debris (JSIDRE, 2011).

Fig. 2 Schematic figures of recovery process of agricultural fields after the disaster (MAFF, 2011).

395 Fig. 3 Diagram of the FMS for remote sensing technique to measure environmental factors (soil moisture, bulk EC, etc.) at the Tsunami affected agricultural fields.

Fig. 4 Experimental sites near the costal side in Miyagi, Japan. The map showing inundated areas of the Tohoku earthquake and massive tsunami (Geospatial Information Authority of Japan).

400 Fig. 5 TDT sensor calibration using a Tsunami affected soil and desalinated soil.

Fig. 6 Temporal changes in rainfall (a), water content (b), bulk EC (c), and EC of groundwater (d) at the tsunami affected agricultural field in Iwanuma, Miyagi, Japan.

Fig. 7 Webcam pictures of the Iwanuma site on the day before-and-after Typhoon in 2014.

405 Fig. 8 Temporal changes in rainfall (a), water content (b), bulk EC (c), and EC of groundwater (d) at the tsunami affected agricultural field in Higashimatsushima, Miyagi, Japan.

Fig. 9 Profile of EC of groundwater on 9 September 2013 when groundwater level was 5 cm depth.



410 Fig. 10 The surface water canal and levee system to control saltwater intrusion from the costal side.



Fig. 1

415



420



425

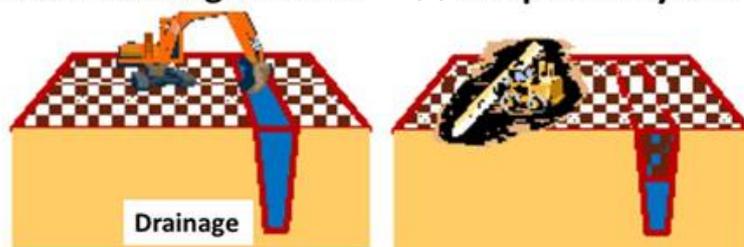


430

Fig. 2

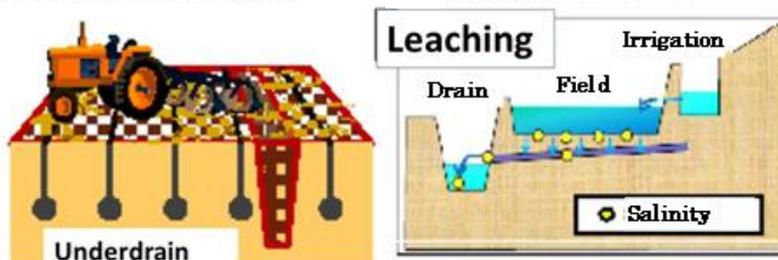
435

(a) Recover drainage trench (b) Strip salinity soil



440

(c) Create underdrain (d) Desalinization



445



Fig. 3

450

455

460

465

470

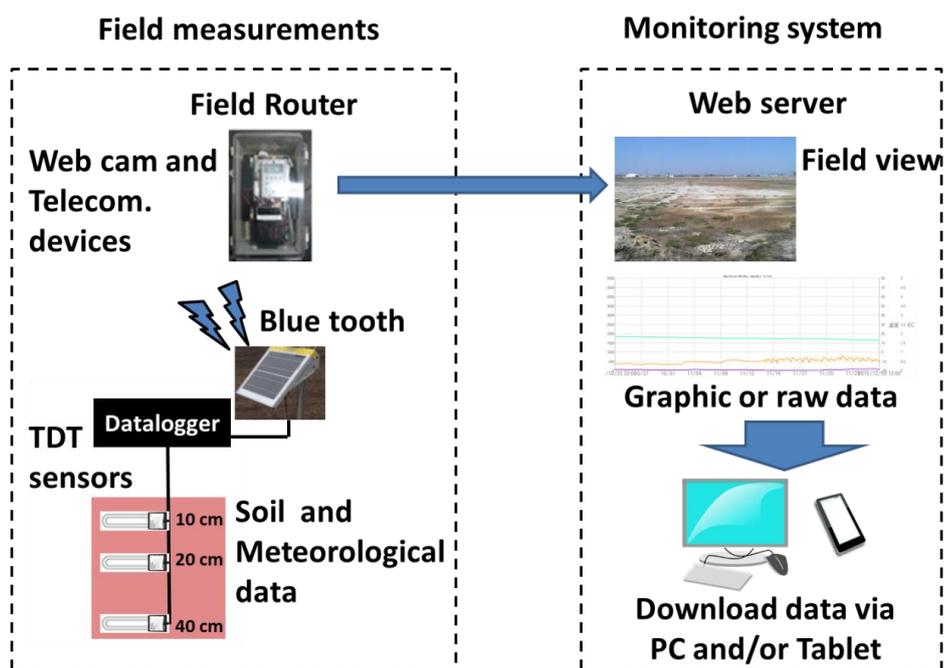




Fig. 4

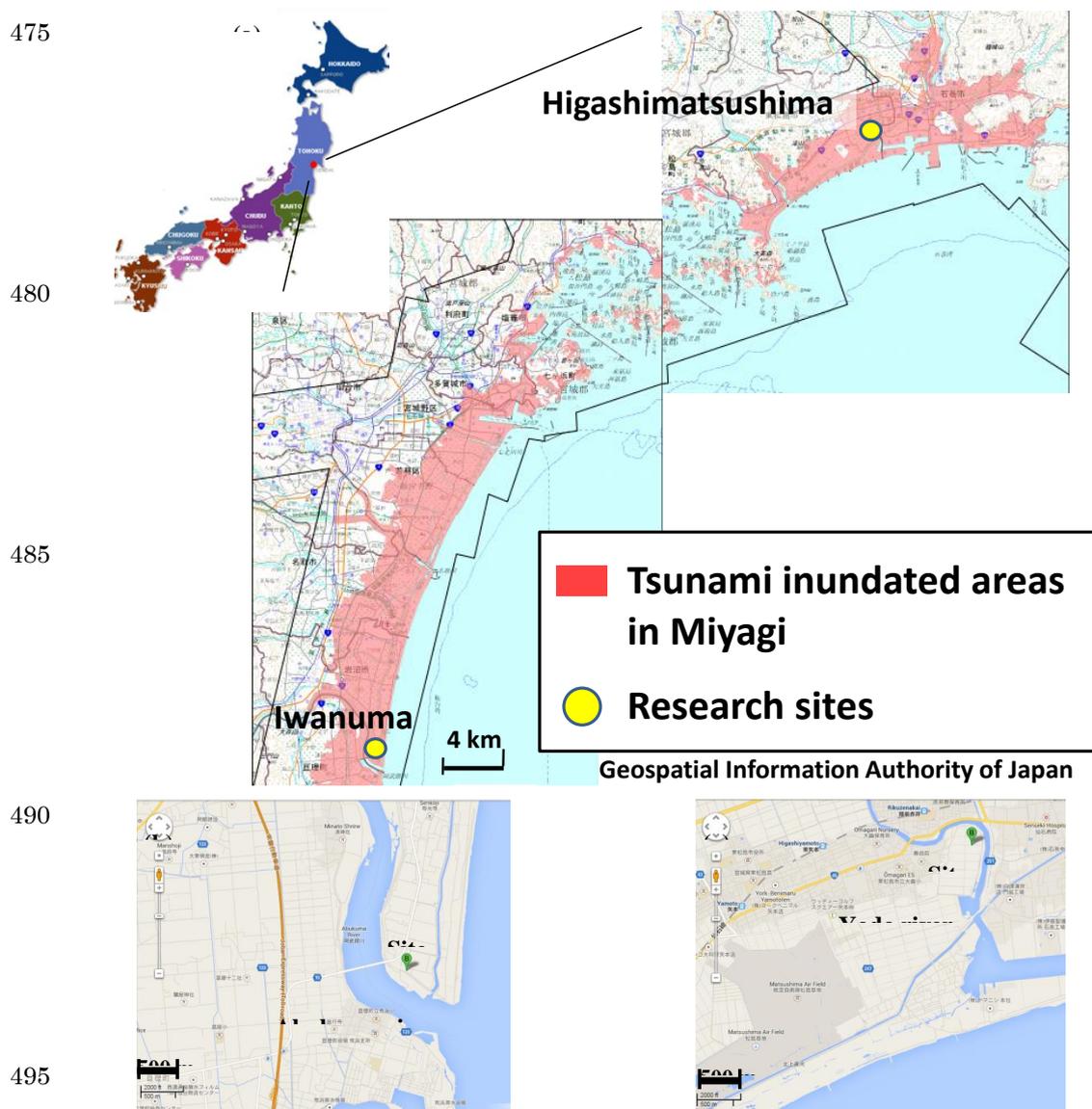
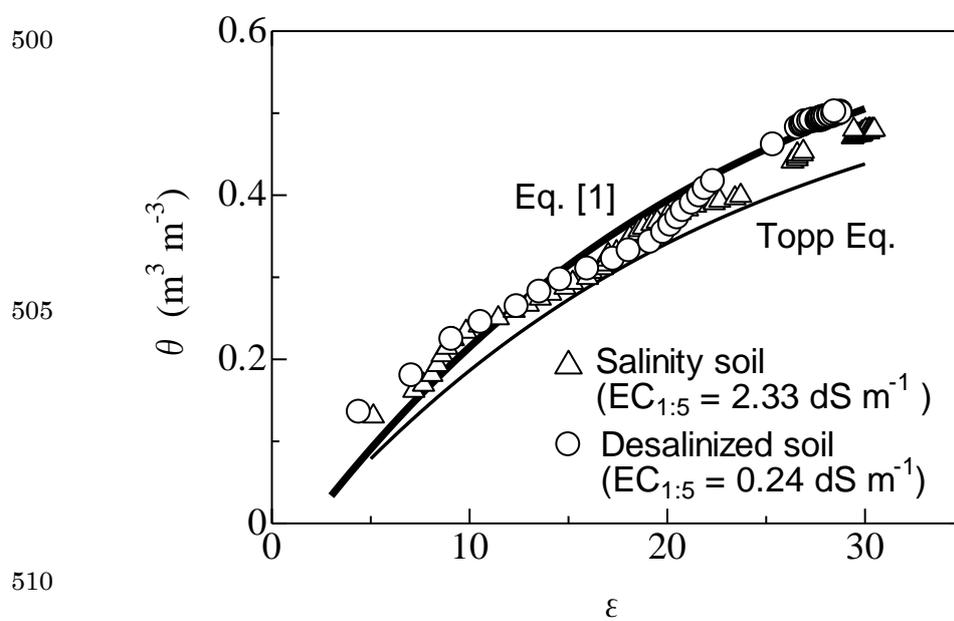




Fig. 5



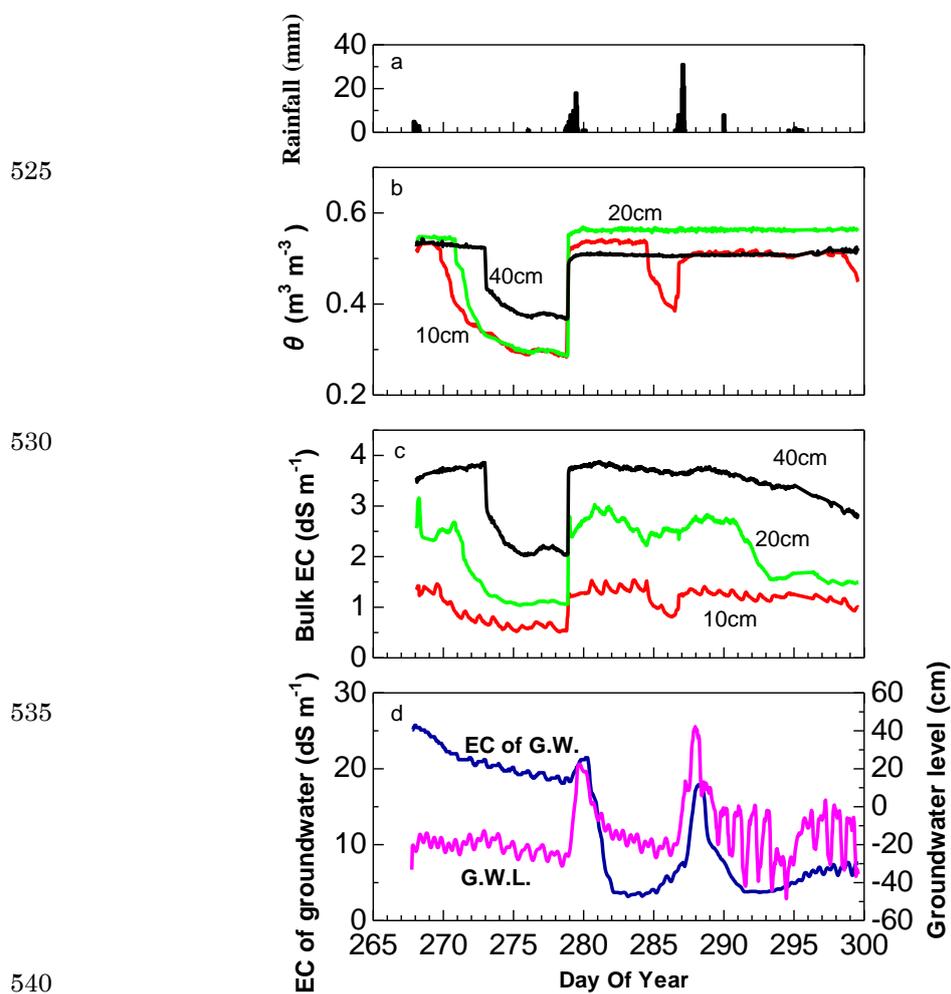
510

515

520



Fig. 6



525

530

535

540

545



Fig. 7

550



555

560

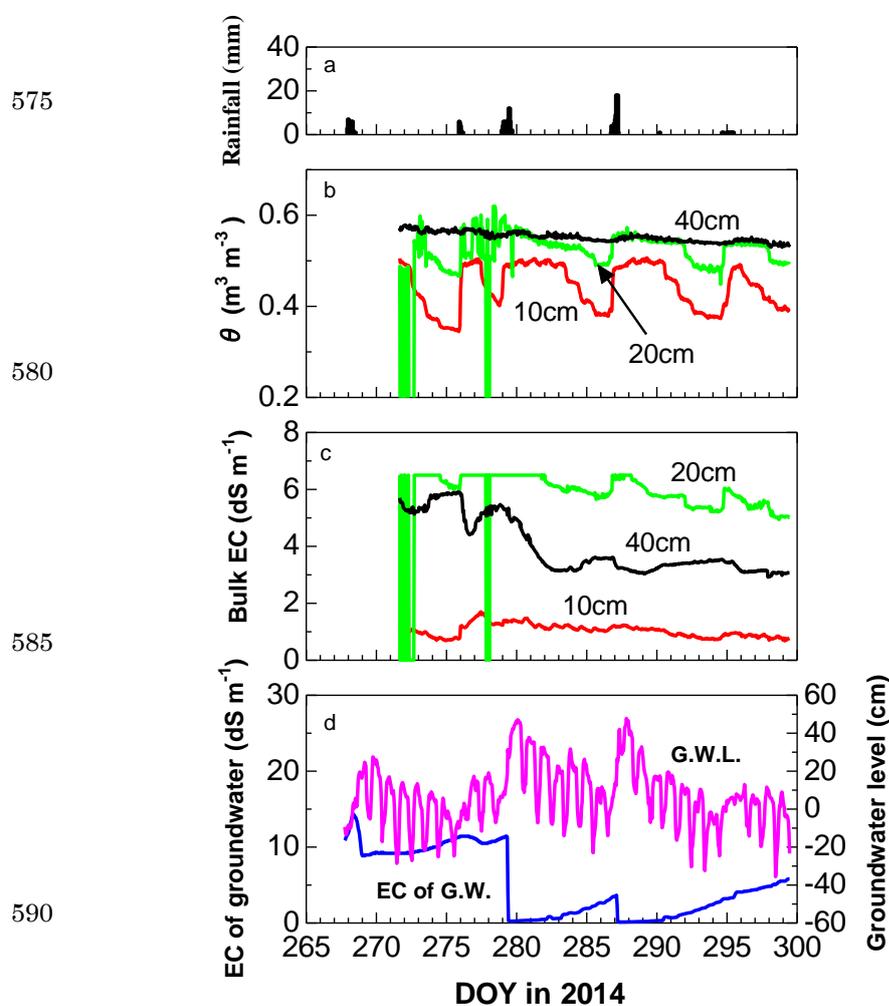


565

570



Fig. 8



575

580

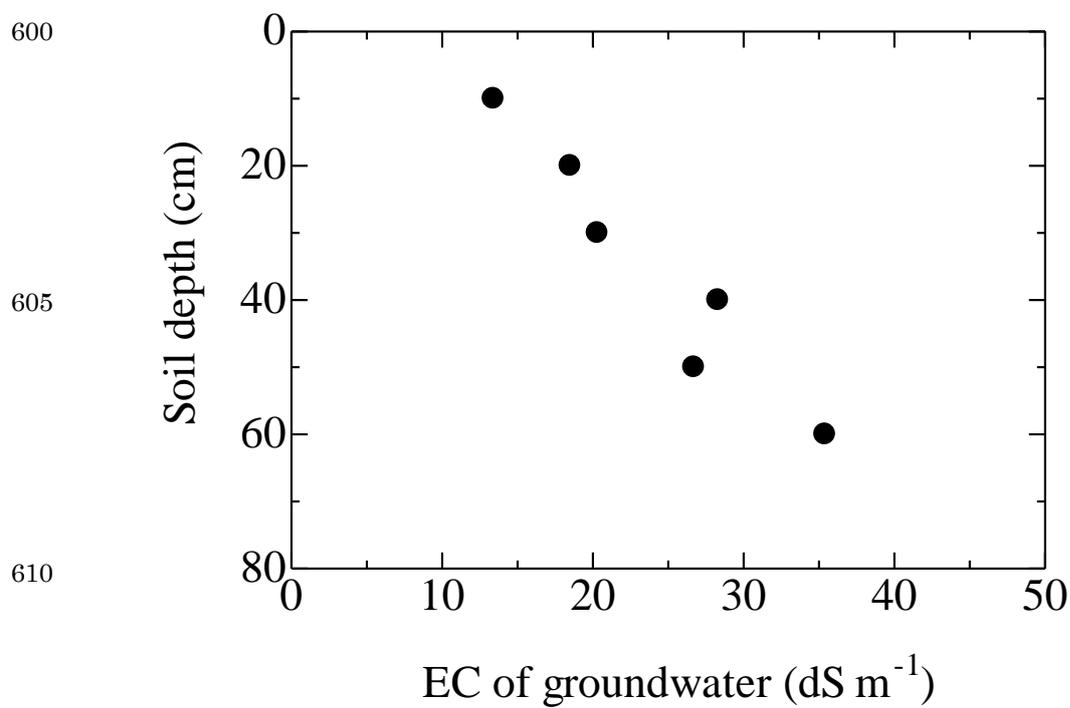
585

590

595



Fig. 9



615

620



Fig. 10

