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Estimation of Groundwater Recovery by Recharge in the Agricultural Area

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***Abstract*—**The Kumamoto area, Kyushu, Japan has 1,041km^2 in area and about 1milion in population. This area is a greatest area in Japan which depends on groundwater for all of drinking water. Quantity of this local groundwater use is about 200MCM during the year. It is understood that the main recharging area of groundwater exist in the rice field zone which have high infiltrate height ahead of 100mm/ day of the irrigated water located in the middle area of the Shira-River Basin. However, by decrease of the paddy-rice planting area by urbanization and an acreage reduction policy, the groundwater income and expenditure turned worse. Then Kumamoto city and four companies expended financial support to increase recharging water to underground by ponded water in the field from 2004.

In this paper, the author reported the situation of recovery of groundwater by recharge and estimates the efficiency of recharge by statistical method.

***Keywords*—**Groundwater recharge, groundwater level, spring water, paddy field.

I. Introduction

THE Kumamoto groundwater area, Kyushu, Japan has comprises 11 cities, towns and villages surrounded Kumamoto-city with commanded area of 1,041km^2 and 1 million in population as shown in Fig. 1. It is the largest area of groundwater consumption for drinking water in Japan with the mean annual amount of groundwater withdrawal of 200MCM (Million cubic meters). The demand of groundwater use is decreasing little by little every year. However, the recharge from surface water is greatly limited due to the urbanized area development. Previous study showed that the major existing groundwater recharge was come from paddy field zone located in the western plateau of the Mt. Aso (the Middle Shira-River Area) with high infiltration height of over 100 mm/day as shown in Fig.-1[1]. Since nowadays the number of planting rice area is reduced due to the policy to be controlled by Japanese Government. Therefore the gross of groundwater recharge volume is decreased and might be not sufficiently use in the future. The evidence showed that Kumamoto city incorporated with the 4-companies have played the role and tried to increase groundwater recharging volume using ponded water in farmland since 2004. So that it is necessarily to study groundwater circulation in order to balancing water uses and continuing groundwater development in this area.

The study for estimation of the effect of groundwater recharge by using ponded water in paddy field was carried out. The continuously time-series observation of groundwater levels (GWL) both before and after ponded water in paddy field was done. Furthermore, the quantity of spring water in the Ezu Lake downstream of the groundwater flow in the Middle Shira River Area was also investigated by this study. In this paper, the author shows the evaluation of groundwater recharge using ponded water in used paddy field plots in the Middle Shira-River Area (Fig.-2).

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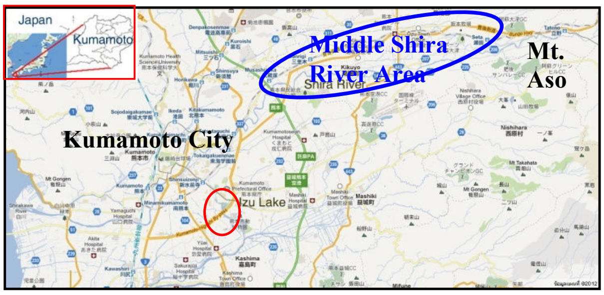


Fig. 1 Map of middle Shira River Area in Kumamoto, Japan

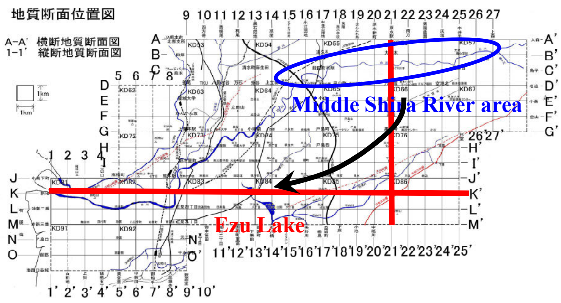


Fig. 2 Location of cross-section profiles surveyed by KFS [2]

II. Geological Survey and Groundwater Observation

The existing cross-sectional geological profiles in Kumamoto groundwater (GW) basin was surveyed by the Kumamoto Foundation Society (KFS) with 1-km interval [2]. These geological features have much information to understand the groundwater flow conditions. Fig.-2 shows the location of cross section with 1-km interval mesh.

As shown in Fig.-2, there are 27 lines in north to south direction and 15 lines in west to east direction respectively. Fig.-3 and Fig.-4 show the cross sectional geological features in line "21-21'" and "K-K'", respectively [2]. In these soil deposits, 2nd to 3^{d} pyroclastic flow sediments, and 2-Lava layers are high permeable layer. Then these layers can be aquifer. Moreover, gravel and sand layer can be aquifer too. Since Kumamoto area

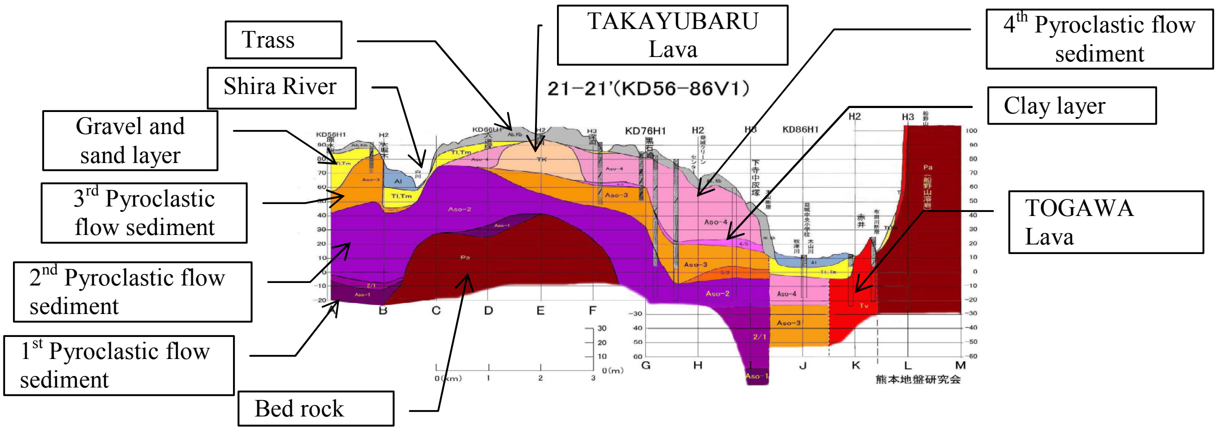


Fig. 3 Cross sectional geological features in line 21-21' [2]

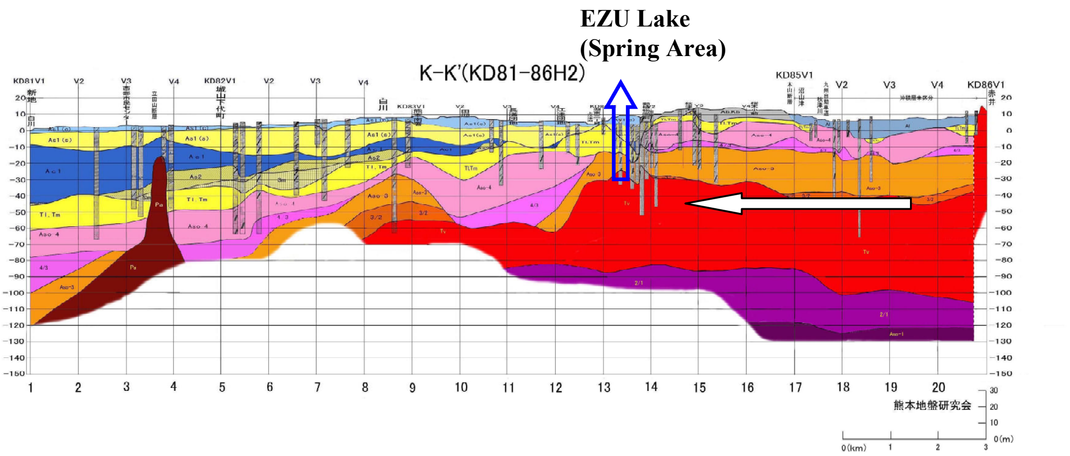


Fig. 4 Cross sectional geological features in line K-K' [2]

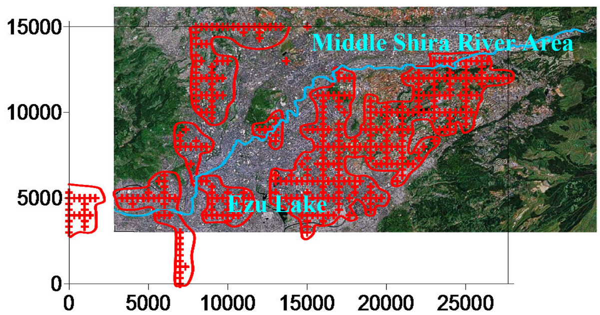


Fig. 5 Distribution of clay layer in Kumamoto GW Basin [2]

has two aquifers divided by the distributed clay layer areas as shown in Fig-5 [2]. The main recharging area of groundwater is around the Middle Shira River Area as shown in Fig.-2 and Fig.-5. There is no clay layer in the recharging area and spring area (Ezu Lake).

Kumamoto Prefecture and Kumamoto city do the quasi-three dimensional groundwater simulation, and reproduce the groundwater flow condition [1]. Fig.-6 shows

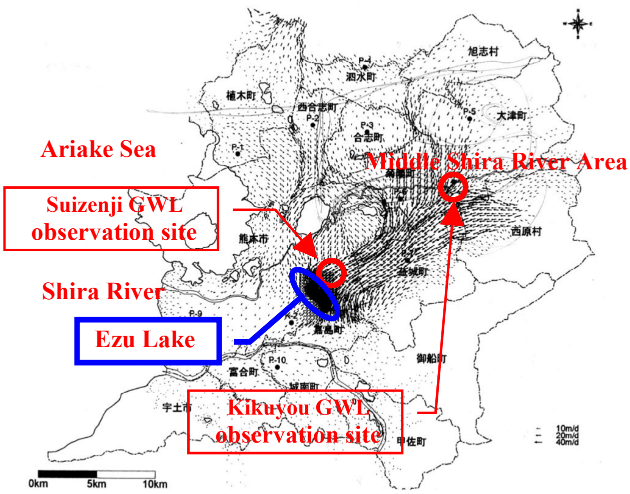


Fig. 6 Groundwater flow in second aquifer in Kumamoto Groundwater Basin (Oct., 2004) [1]

the groundwater flow in second aquifer. From this figure, we can understand that groundwater flow in second aquifer start around the middle Sira-River Area and spring out in the EZU-Lake.

III. Groundwater Level Change and Spring Rate in the Ezu Lake

There are many GWL observation sites which were settled by Ministry of Land, Infrastructure and Transport, Kumamoto prefecture and Kumamoto city. The author chose two GWL observation sites named Kikuyou and Suizenji which Kumamoto prefecture recorded. Those observation sites were located at downstream of the Middle Sira River and closed place to the EZU Lake respectively, as shown in Fig.-6. Those observation well's casing positions were located in the 2nd aquifer of Kumamoto.

Fig.-7 and Fig.-8 show the GWL observation results in the Kikuyou and Suizenji observation sites during 1991 to 2004. Those annual GWL change patterns show the peak level in October and the lowest level in May which GWL had been risen up during planting of paddy season, and fallen after finished season. The decreasing rate of 0.24 (8.87cm/year) and 0.021 (0.77cm/year) mm/day were found in Kikuyou and Suizenji GWL observation sites. The GWL change in the

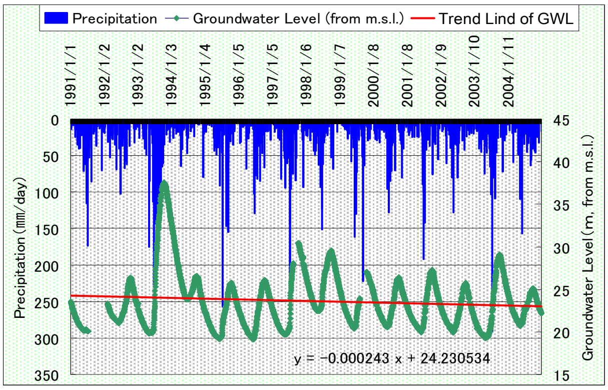


Fig. 7 Daily change of GWL, rainfall and trend line of GWL in Kikuyou observation site

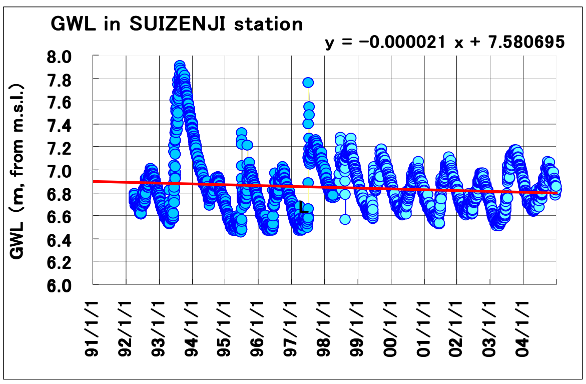


Fig. 8 Daily change of GWL, rainfall and trend line of GWL in Suizenji observation site

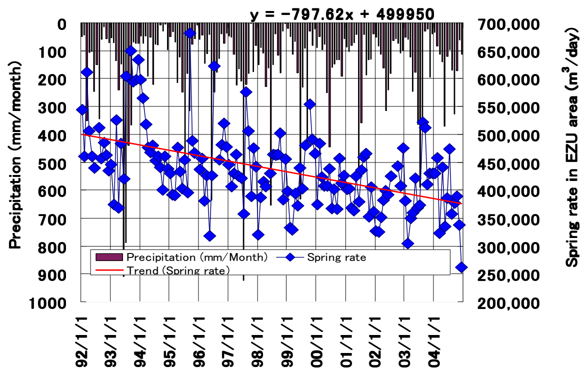


Fig. 9 Monthly change of spring rate, rainfall and trend line of spring rate in the Ezu-Lake

Suizenji site was not high rate because it was much closed to spring area with higher flow out as spring water.

The author observed spring rate in the Ezu Lake in the basis of monthly recorded since 1992 as shown in Fig.-9. The slope of trend line of the spring rate was decreased with the rate of 797.62m^3/day/month (9570m^3/day/year). Therefore, the groundwater storage in the Kumamoto area is decreasing year by year caused by the reduction of the paddy's planting area limited by urbanization and acreage reduction policy.

IV. Development of Ponded Water in Paddy Field

Recently, Japanese government has decided the acreage reduction of growing paddy, because of surplus of rice. Farmers must also reduce paddy area but they can grow other cash crops with less water consuming in their fields. Particularly the ratio of paddy planting adjustment area in the Middle Shira River Area was shown in Fig.-10. Moreover, farmers are getting old age which they stopped cultivation and sold out the land to company as for housing and other uses. Therefore, the recharge rate from ground surface to aquifer is decreasing year by year.

Percentage of paddy field with no making rice is increase year by year as shown in Fig. 10. The policy to pond water on these farmlands (ponded water in the field) was promoted to develop by Kumamoto City incorporated with 4-companies since 2004 with the compensation money to farmer (see Pic. 1). The purpose of this policy is increase of groundwater recharge.

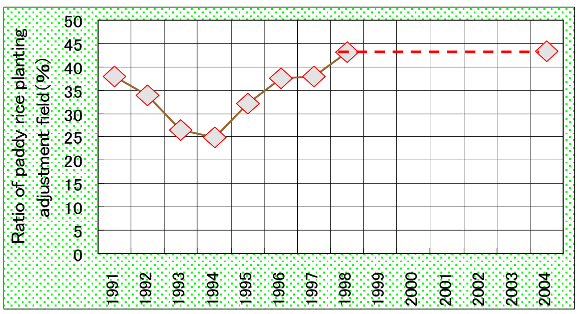


Fig. 10 Percentage of paddy planting area given by the government

Pic. 1 The development of ponded water in paddy field plot

V. Groundwater Recharge Effects and Spring Water

The author observed daily seepage speed within approximately 100 points of ponded water in the field and paddy fields. In paddy field, daily seepage speed was observed 2 times, first observation was before stop of water supply for drying soil, and second observation was after stop water supply to paddy field. The observation of daily seepage speed was carried out using the following steps.

1. Set the measure in the field.
2. stop inflow and out flow in the field
3. time series water levels observation in the field
4. calculate water level drop speed per day
5. daily seepage speed
   = daily water level drop speed – evapo-transpiration

Fig.-11 shows the distribution map of daily seepage speed in ponded field in the Middle Shira River Area. While Fig.-12, 13 are the distribution maps of daily seepage speed before and after stopping supply water to paddy field.

Using Fig.-11, 12 and 13, daily seepage speed in each farm of ponded water in the fields and paddy fields could be calculated. The daily recharge rate and cumulated recharge rate by ponded water in the field since May 2011 was shown in Fig.-11. And the details of recharge rate and ponded days and average seepage speed in each area are shown in Table I.

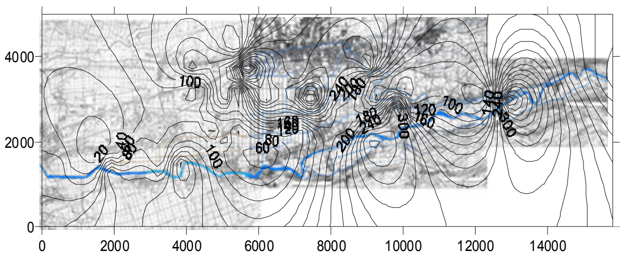


Fig. 11 Distribution map of daily seepage speed in ponded water in the field

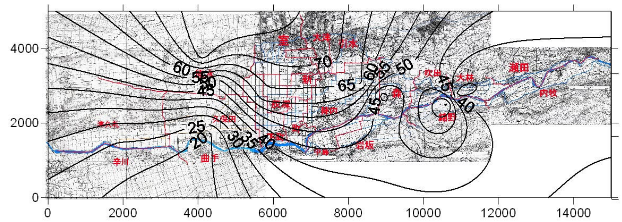


Fig. 12 Distribution map of daily seepage speed before stop water supply to paddy field

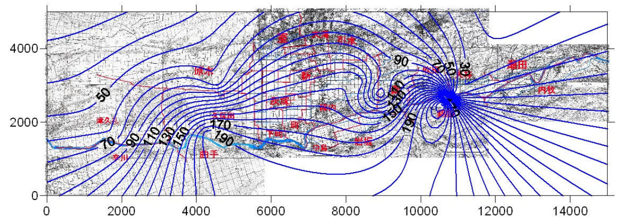


Fig. 13 Distribution map of daily seepage speed after stop water supply to paddy field

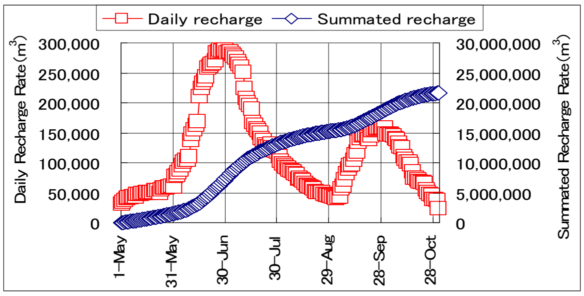


Fig. 14 Daily & cumulated recharge volume from ponded plots

TABLE I
Calculation of Recharge Rate, Water Set Days and Average Daily Seepage Speed in Ponded Water in the Field (2011)

Orner	Area	Area of ponded water (m^2)	No. of Farmer	Recharge rate (m^3)	Water set days	Daily Seepage speed (mm/day)
Kumamoto	Ohtsu	1,895,256	245	10,336,796	43.6	125.0
	Kikuyou	1,396,933	174	7,109,478	56.8	89.6
	Total	3,292,189	419	17,446,274	49.2	107.6
Comp.A	Ohtsu	341,801	43	1,915,850	38.3	145.7
Comp.B	Ohtsu	97,385	14	609,540	34.8	179.6
Comp.C	Ohtsu	96,474	9	502,376	29.2	178.2
Comp.D	Ohtsu	26,694	6	120,414	55.6	81.2
Company Total		563,354	72	3,148,181	37.0	151.1
Total		3,855,543	491	20,594,455	47.4	112.6

The ponded water area in the field of 3.86km^2 during 47.4days with the recharge volume of 2.06MCM and average seepage speed of 112.6mm/day were summarized in Table I.

Fig.-15 and Fig.-16 show the change of paddy area and recharge rate in each plot during 2004-2011, respectively. It was cleared that during 8 years of 1km^2 of paddy field was changed to the compacted soil as the impermeable layer (i.e. housing, load). Moreover, paddy area is reduced year by year with less than 50% of all paddy area. Therefore, the recharge rate through paddy field is reduced. Since the recharge rate during 2004-2008 by ponded water in the field was increased from 0.92 to 21 MCM. The constant recharge rate was 20 MCM/year after 2008.

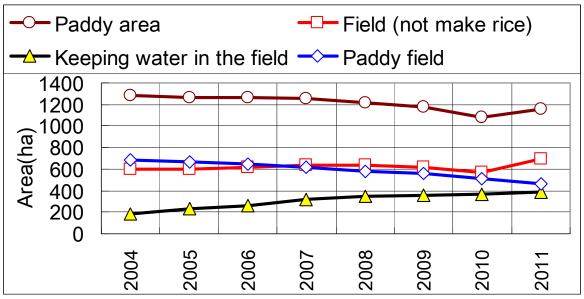


Fig. 15 Change of paddy area

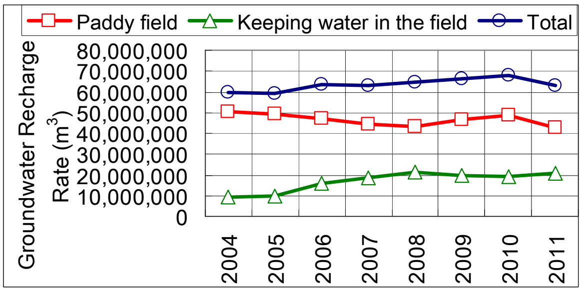


Fig. 16 Change of recharge rate in paddy field and ponded water volume in the field

TABLE II
TOTAL SEEPAGE HEIGHT IN EACH YEAR

Year	Paddy Field (mm)	Ponded Water in the field (mm)
2004	7,406	4,941
2005	7,366	4,409
2006	7,374	6,117
2007	7,397	5,939
2008	7,513	6,229
2009	8,096	5,773
2010	7,885	5,727
2011	7,085	5,297

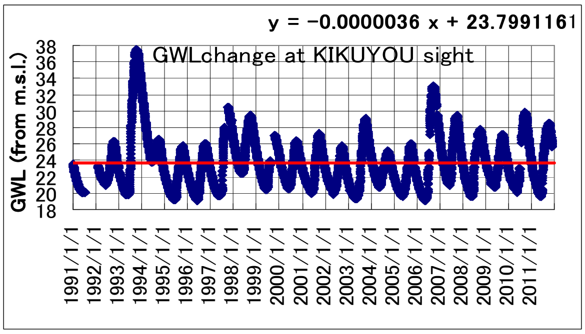


Fig. 17 GWL change at Kikuyou observation site

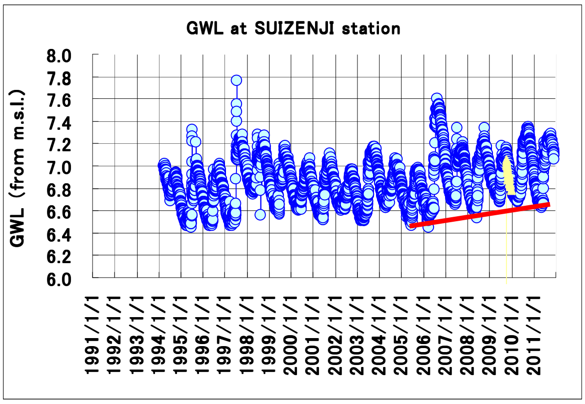


Fig. 18 GWL change at Suizenji observation site

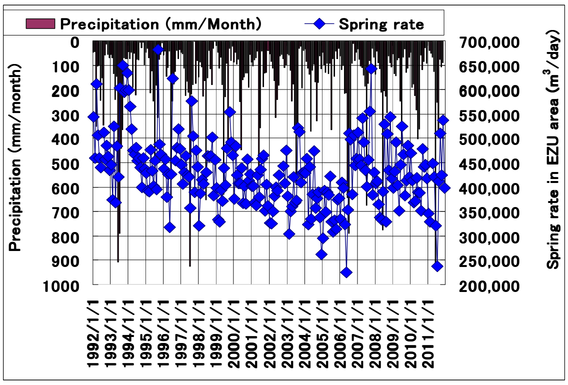


Fig. 19 Change of spring rates around the Ezu Lake

Table II shows the total annual seepage height in paddy field and ponded water in the field since 2004. And the total seepage height in paddy field was 7,000-7,500mm with higher than 5,000-6,000mm of ponded water in the field. This means that if all of paddy areas (12 km^2) make rice every year, the total recharge rate from the Middle Shira River Area will be 84-90 MCM/year.

After the development of ponded water into the field was started since 2004, GWLs in Kikuyou and Suizebji, and spring rate in the Ezu Lake were changed as shown in Fig.-17, 18, and 19, respectively. Those rate values were increased after the development of ponded water into the field. However, GWL and spring rate were not raised much and tried to be felled since 2008. So it can be said that the effect of the development of ponded water into the field to recover the groundwater storage became a limit.

VI. Statistical Analysis and Effect of Ponded Water in the Field Development

The evaluation of the effect of ponded water in the field development was observed by using Kikuyou GWL data observed in the Middle Sira River Area. The GWL data of Kikuyou was shown in Fig.-6 and 17. In usual, GWL rises and drops by recharge condition. If there was no recharge water through ground surface, then GWL dropped continuously and

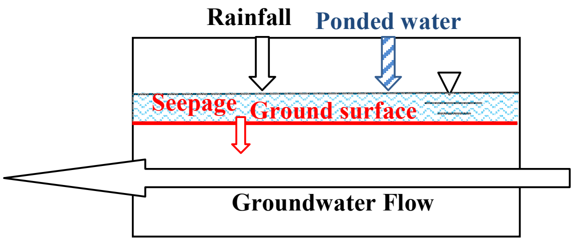


Fig. 20 Controlled boundary of studying GW recharge

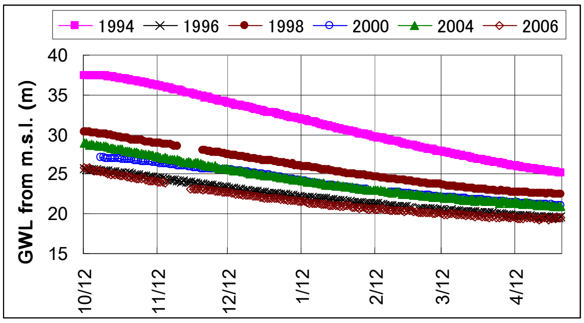


Fig. 21 GWL change in dry season

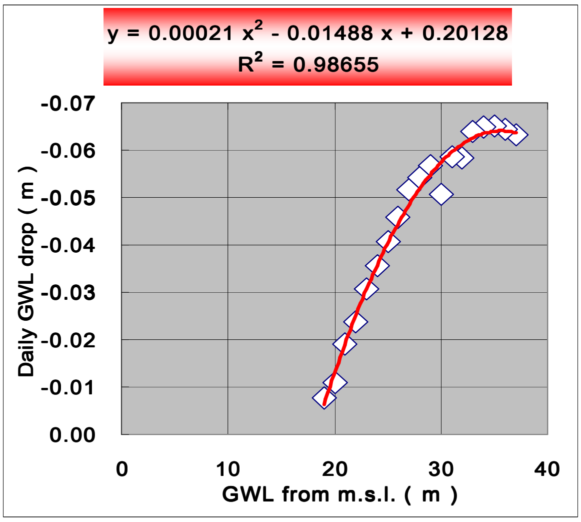


Fig. 22 Parabola equation of regression between daily GWL drop and GWL

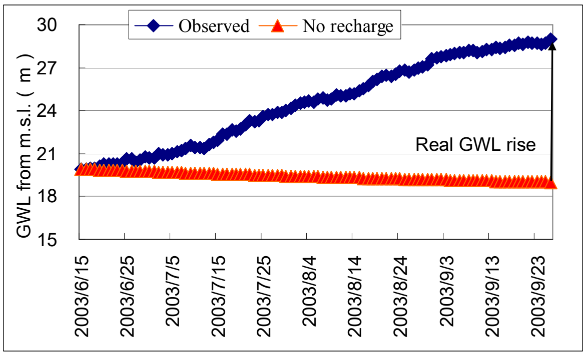


Fig. 23 GWL rise by recharge

Fig. 24 Cropping pattern and water supply in paddy field

Pic. 2 Big cracks in bottom of paddy field after stop water

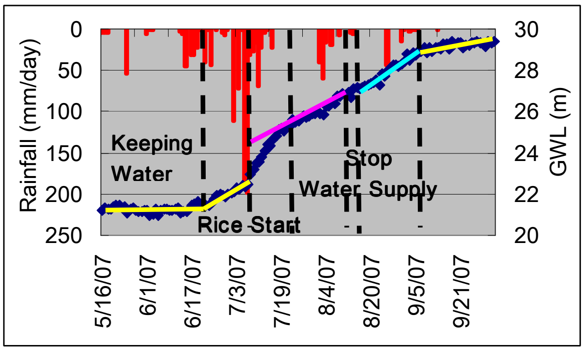


Fig. 25 Pattern of GWL rise and farming event

flowed out from the boundary to others as shown in Fig.-20. GWL drops continuously caused by groundwater flow in dry season (from November to May), but, rises caused by recharge through ground surface in rainy season and paddy crop period (from June to September) as shown in Fig.-18. Groundwater flow exists in rainy season and paddy crop period, too. Then, GWL changes in rainy season include GWL dropped by GW flow. Therefore, the estimation of height of GWL drops by GW flow was done using GWL data of dry season as shown in Fig.-21. In Japan, rainfall in dry season is only a little. But, a few rainfall influences to daily GWL drops. Then the calculation of average GWL drops with a few or no rain days was done by using the regression analysis with a parabolic equation between GWL drop and GWL as shown in Fig. 22. From this Fig. 22, the author calculated the GWL rise in rain, paddy and ponded water period as shown in Fig. 23.

Moreover, the estimation of groundwater recharge by rainfall and ponded water in the field during the period of ponded water from May to October, and paddy crop period during June to September were done with two overlap periods of GWL rises.

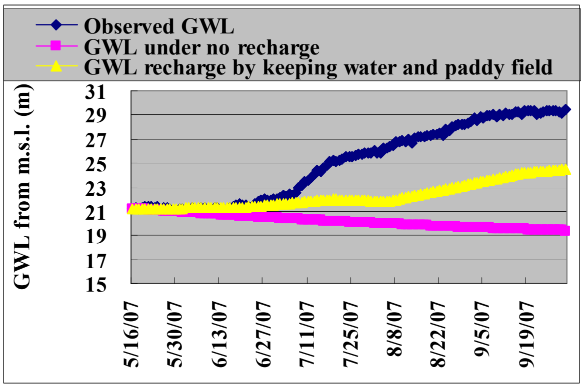


Fig. 26 GWL change in three cases

GWL is raised up followed by recharging rainfall, paddy field and ponded water in the field. Due to the water supply pattern in paddy field as shown in Fig.-24, farmer stop water supply for several days after rice growth period. The ground surface cracking in the bed of paddy field as shown in Pic.-2 cause easily water flow to underground with over 30 cm depth in the paddy field and lead GWL risen up as shown in Fig.-25 based on farming events. In this case, the value of GWL raise could not be decided during rain because GWL change by rain was larger than paddy field and ponded water in field. By using GWL's slope in case of no rain from Fig. 25, daily GWL raise by paddy field and ponded water in field could be estimated. The application of those 3 cases of GWL changes, those are observed GWL (largest GWL), GWL with no recharge (lowest GWL), and GWL with recharge by both paddy field and ponded water in the field (middle GWL) are shown in Fig. 26. The difference between largest GWL and middle GWL was GWL rise by rain. The difference between middle GWL and lowest GWL was GWL rise by paddy field and ponded water in field. The calculations of GWL and recharge in 1992-2011 were studied. With it, GWL rise from recharge rate by paddy field and ponded water in the field are calculated as shown in Table III and Table IV, respectively.

Fig. 27 shows the GWL rise in each factor. From this figure, if rainfall during period of ponded water in the field and paddy field was less than 500mm, GWL rise by rain became zero.

TABLE III
GW RECHARGE IN EACH FACTOR AND PERCENTAGE

Year	GW Recharge (MCM)			% of Paddy 9.4field
	Paddy Field	Ponded in the Field	Total	
2004	50.3	9.2	59.5	84.5
2005	49.4	10.0	59.4	83.2
2006	47.4	16.0	63.4	74.8
2007	44.1	18.8	62.9	70.1
2008	43.4	21.6	64.9	66.8
2009	46.7	19.6	66.4	70.4
2010	48.9	19.1	68.0	71.9
2011	42.7	20.6	63.3	67.4

TABLE IV
GWL RISE BY PADDY FIELD AND PONDED WATER IN THE FIELD

Year	Paddy Field (m)	Ponded in the Field (m)	Total (m)
2004	3.84	0.70	4.54
2005	4.07	0.83	4.90
2006	3.85	1.30	5.15
2007	3.79	1.62	5.41
2008	3.79	1.89	5.68
2009	3.91	1.64	5.55
2010	3.87	1.52	5.39
2011	3.14	1.52	4.66

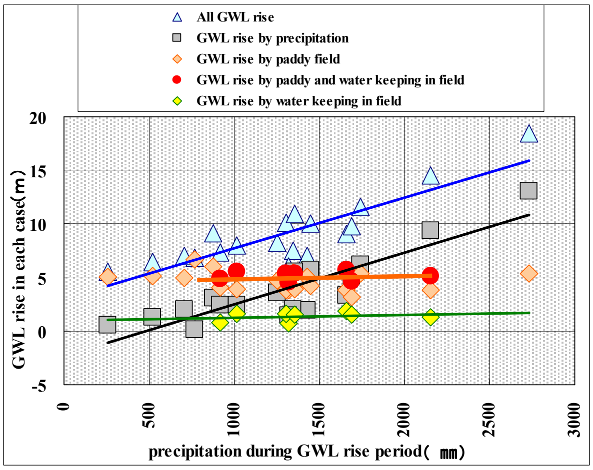


Fig. 27 GWL rise by each factor

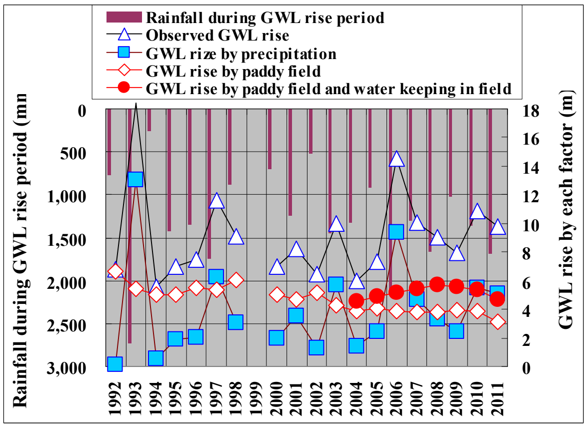
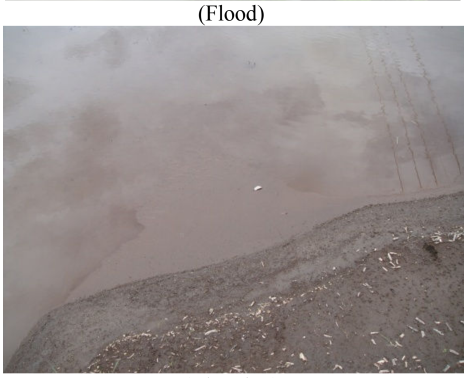


Fig. 28 GWL rise by each factor during 1992-2011

Fig. 28 shows GWL rise by each factors during 1992-2011. From this figure, GWL rise by paddy field decreased year by year during 1992-2003. Moreover, GWL rise increased by ponded water in the field since 2004, but major influence factor is rainfall.

GWL rise by paddy field and ponded water in the field were decreasing in 2011 caused by clogging by muddy water in flooding period as shown in Pic. 3.

(Flood)



(Clogging)

Pic. 3 Flood in the Shira River and clogging in the field

VII. Conclusion

The Kumamoto area, Kyushu, Japan is largest groundwater use area. More than one million of population living in this area and using groundwater for drinking purpose were reported. Areal GWL observation in this region was done by the government over 30 years. Moreover, the author observe spring rate in the Ezu Lake which located in the downstream end of groundwater basin in the Kumamoto Area. These observed data showed that groundwater storage in this area was continuously decreasing. It was cleared that groundwater shortage caused by the reduction of recharge rate in reduced paddy area. Therefore government decided to recover groundwater storage using ponded water in the field that left growing rice (farmland).

The estimation of GW recharge by ponded water in the field in the Middle Shira River area using statistical method was done and summarized as the following conclusions.

1. Groundwater recharge rate by ponded water in the field in the Middle Shira River Area was 9.2-2.1 MCM/year during 2004-2011. The groundwater recharge rate increased within four years of the first half, but fell down for four years of the latter half. The spring rate in the Ezu Lake was raised once but decreased afterwards.
2. The evaluation of GWL rise by ponded water in the field and estimation of GWL rise by rainfall, paddy field and ponded water in the field were studied. As the results, it was clear that if rainfall during period of ponded water in the field and paddy field is less than 500mm, GWL change is no rise by rain. It is seems that GWL rise by paddy field decreased year by year during 1992-2003, and GWL rise increased by ponded water in the field from 2004. But total GWL rise is influenced by rainfall.
3. GWL rise during paddy field growing season was almost same value (3.8-4 m rise) except in 2011. But GWL rise by ponded water in the field is 0.7-1.89 m, and decrease recent 4 years (2008-2011). GWL rise by paddy field and ponded water in the field was decreased in 2011 caused by clogging of muddy water by flood.
4. The technique of GW recharge using ponded water in the field is not enough for Kumamoto Area in the future. Therefore, the other recharge methods should be continuing research.

Acknowledgment

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