

Effect of Substitute Water Projects on Tempo-Spatial Distribution of Groundwater Withdrawals in Chikugo-Saga Plain, Japan

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Abstract Due to large-scale agricultural irrigation and industrial production, groundwater had been excessively employed to benefit the economy development and life improvement in Chikugo-Saga plain since the middle of last century, which led to many environmental problems such as land subsidence, flooding inundation and water shortage. In order to mitigate the impact of environmental hazards, some water supply projects have been performed to substitute surface water for groundwater since 1970s. For the purpose of comprehending the influence of substitute water projects on groundwater withdrawals, a tempo-spatial groundwater withdrawals assessment model with the resolution of one month in time and one kilometer in space was initially established based on various data concerning meteorology, agriculture, land use, soils, surface water consumption and groundwater utilization by using GIS. According to the development of the substitute water projects, a 28-year study period 1979–2006 was then divided into four stages (i.e. 1979–1984, 1985–1995, 1996–2000 and 2001–2006) and the tempo-spatial distribution of groundwater withdrawals for each stage was represented by means of the proposed model. The tempo-spatial variation of groundwater withdrawals for various water use categories under the effect of substitute water projects was finally analyzed by comparing the distributions of groundwater withdrawals at different stages. The results show that with the advance of the substitute water projects studied, the groundwater pumpage for irrigation, industry or waterworks varies geographically and physically in the plain. From the first stage to the last stage, there is a significant decrease by approximately 23 % in mean annual total groundwater withdrawals. During the study period, dramatic declines are found in agriculture-use groundwater pumpage in the downstream land of Chikugo river at the third stage, in industry-use pumpage in eastern Saga area at the second

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stage and found in waterworks-use pumpage in western Saga area at the last stage, while little change in agriculture-use pumpage in western Saga area and in industry-use pumpage in Chikugo area without the corresponding substitution projects. Moreover, it is indicated that the proposed assessment model of groundwater withdrawals is helpful to figure out the regional groundwater exploitation and its impact on the environment, particularly when there is the lack of groundwater pumpage data recorded. It is necessary to develop new substitute water supply plans to reduce the agriculture-use groundwater withdrawals in western Saga area and the industry-use withdrawals in Chikugo area, for more effective management of regional water resources in future.

Keywords Groundwater withdrawals · Substitute water · GIS · Tempo-spatial distribution

1 Introduction

Chikugo-Saga plain, located in Western Japan, is a key rice-growing region in Japan as illustrated in Fig. 1. Owing to the large-scale agricultural irrigation and industrial production, water resource has been playing the prominent role in the development of the region. In the view of the quality and quantity of water resource available, groundwater has been employed to benefit the social production and daily life since the middle period of last century. However, the excessive exploitation of groundwater induced many environmental problems such as land subsidence, flood inundation, seawater intrusion and water shortage. According to the report of Saga prefectural government (2001), the severe land subsidence (covering the area of 328 km²) commenced in the late 1950s and increased greatly during the period 1960–1970s when groundwater served as dominant water resource, and the maximum accumulative settlement was up to 124 cm in 2000. Furthermore, land subsidence which compounds sea level rise increases greatly the coastal flood risk covering the probability and impacts of flooding (Sun et al. 1999; Abidin et al. 2013). Watanabe (1991) studied the state of flood damages and the flood defenses activities in the subsided area of the plain. Hachiya et al. (2002) reported the seawater intrusion into an aquifer in western Sage area (known as “Shiroishi”) of the plain. Hosokawa (1992) carried out the numerical simulation of seawater intrusion and put forward some measures against seawater intrusion. Additionally, records of the severe water shortage in the plain were reported by Saga prefectural government (1995) due to the drought and the groundwater resource lack. The work of Hachiya et al. (1996) indicates that the excessive pumping of groundwater in the drought year contributed to the further subsidence in the area studied. In order to mitigate the impacts of such environmental problems, some substitute water projects were performed in the plain to reduce the groundwater withdrawals and consequently to improve the surface and subsurface hydrological environment.

Since 1970s, seven substitute water projects have successively been performed in the plain, as depicted in Fig. 2. According to the usage of substitute water, the seven projects can be divided into four groups: (1) for industry, Eastern Saga Industrial Water Supply and Kishima Industrial Water Supply started in 1976 and 1978, respectively; (2) for domestic drinking, Eastern Saga Water Works, Southern Fukuoka Water Works and Western Saga Water Works respectively began to supply water in 1980, 1989 and 2001; (3) for agriculture, Agricultural Irrigation Water Transfer Project for low-stream land of Chikugo River commenced in 1996; (4) for multi-purpose use, Chikugo Weir Project was completed in 1985, diverting surface water to Kurume city in Chikugo area. In order to promote an effective implementation of the substitute water projects in future, it is indispensable to understanding the influence of the

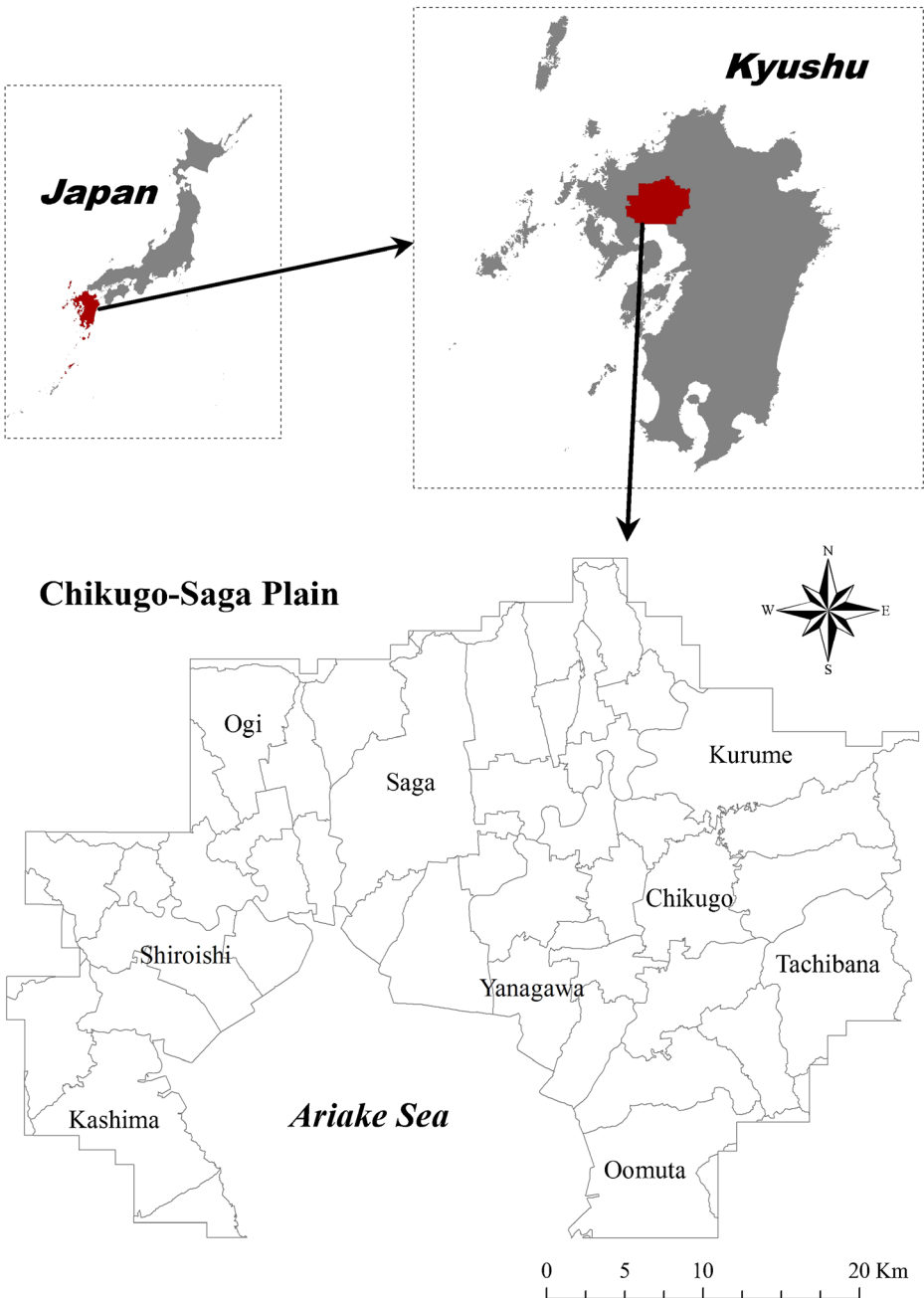


Fig. 1 Location of Chikugo-Saga plain in Japan

substitute water projects available on groundwater utilization. To investigate such influence, it is critically significant to precisely characterize the distribution of the groundwater withdrawals across time and space at a fine scale.

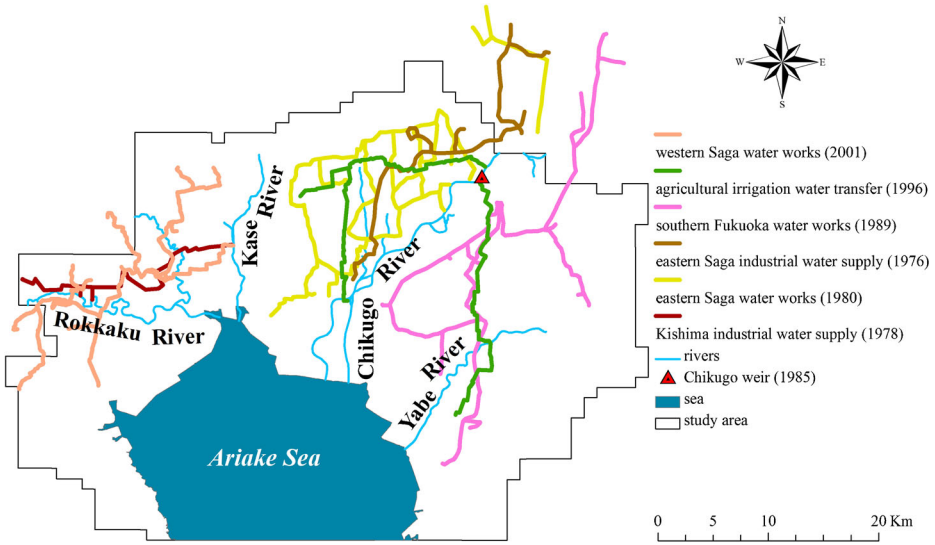


Fig. 2 Location of substitute water projects available in Chikugo-Saga plain until 2006

Generally, the groundwater withdrawals data are from pumping well records for different use categories. Unfortunately, such data is not incomplete in Saga area and not available in Chikugo area. Some methods of deducing the groundwater consumption have been reported in recent studies. Tsanis and Apostolaki (2009) estimated the annual groundwater withdrawal in an agricultural basin based on the fluctuation of the groundwater level, the specific yield, and the annual precipitation. Ahmad et al. (2005) investigated the various water balance components of the unsaturated zone including irrigation rate with canal water, net precipitation rate, actual evapotranspiration rate and change in soil moisture storage and then estimated the net groundwater use as a function of the four components obtained. The methodology can be viewed in Castaño et al. (2010), who deduced the irrigation requirement and the surface for each crop type by using remote sensing techniques and then quantified groundwater withdrawals for irrigation by applying the correction coefficients (obtained from field experiments) for irrigation water consumptive use of each crop type. The sustainable groundwater extraction was assessed by D'haeze et al. (2005) by subtracting the minimum required river baseflow from the annual groundwater recharge. Zoumides et al. (2013) quantified the consumptive green (soil moisture) and blue (irrigation) water use for crop growth based on a soil water balance model and calculated the groundwater withdrawals for irrigation as the difference between the total blue water use and the irrigation water supply from dams and other water treatment plans. Ruud et al. (2004) computed monthly and annual groundwater pumpage in a semi-arid irrigated agricultural basin by comparing the total available surface water with the total applied water demand for crop irrigation.

Notwithstanding the successful application of the methods above-mentioned in some study cases, few of them can be employed to estimate the groundwater withdrawals at a fine time-space scale. Furthermore, various farming patterns (rice paddy, dry farmland and farm green house), diverse water intake modes (from dams, rivers, canals and underground) and high phreatic water level (the impact of upward capillary water in the root zone on crops growth is non-ignorable) contribute to the temporal and spatial complexity in representing the distribution of groundwater withdrawals. In view of the characteristics of the plain, a new

methodology with the consideration of farming patterns, water diversion modes and upward capillary water replenishment was put forward to assess the daily groundwater withdrawals in 1 Km square (1 Km × 1 Km) cells for agriculture, industry and waterworks in the investigation.

With the powerful functions of data management, spatial analysis and visualization, Geographic Information System (GIS) has been widely applied in water resources management for years (Bastiaanssen et al. 2000; Chowdary et al. 2003; Portoghese et al. 2005; Jha et al. 2007; Tilahun and Merkel 2009; Mukherjee et al. 2012). GIS, therefore, was employed in the investigation to establish a fine-scale assessment model of groundwater withdrawals and analyze the variation of the groundwater withdrawals under the effect of the substitute water projects during a 28-year period from 1979 to 2006.

The objective of the investigation is to put forward a GIS-based quantitative method for the assessment of tempo-spatial distribution of the groundwater withdrawals based on the integration of meteorological data, agricultural information, land-use & soil maps, administrative statistic data, surface water diversion data and groundwater pumping data. Furthermore, by overlaying the distributions of groundwater withdrawals estimated in different stages of the study period, the variation of the groundwater withdrawals with space and time was analyzed and the influence of substitute water projects on the distribution of groundwater withdrawals is discussed. The results from investigation is expected to be helpful to comprehensively understand the regional groundwater withdrawals and provide some valuable references for administrative decision making on substitute water projects in future.

2 Methodology

According to the use of groundwater resource in the plain, the methodology consists of the following steps (see Fig. 3). First, daily water requirement of crops in each administrative division is assessed based on crop growth data, soil characteristic parameters and meteorological data. Through the spatial operation of GIS layers including land use, administrative division and data analysis mesh (i.e. 1-Km mesh grid), the daily water requirement estimated

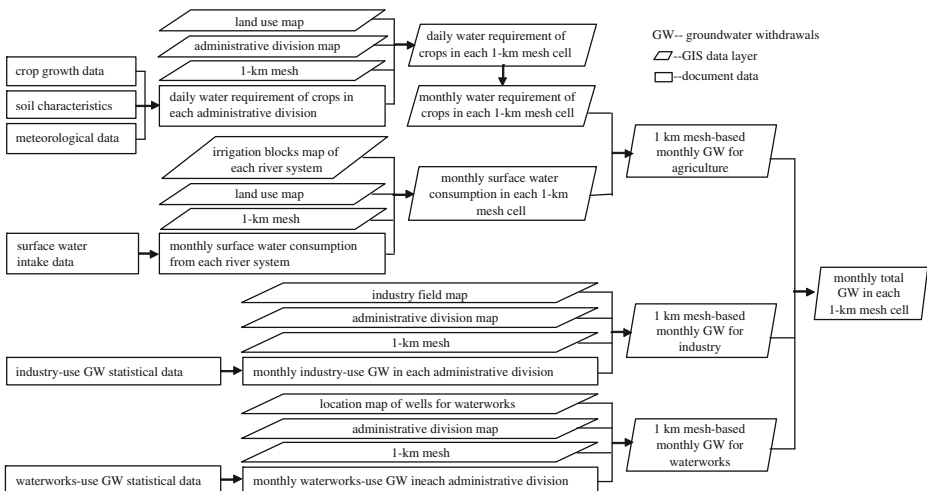


Fig. 3 The flowchart for assessing monthly groundwater withdrawals at a 1-km grid spacing

is allocated into each 1-Km mesh grid cell by using a land use-based method (Baumberger et al. 2007) and subsequently the monthly water requirement is obtained at 1-Km scale. Then, monthly surface water consumption from different river systems is estimated after the collection of surface water intake data. The distribution of surface water consumption at finer time and space scales (monthly and 1-Km) is calculated by intersecting the 1-Km mesh layer with the irrigation block map layer and the land use layer. Afterwards, the monthly groundwater withdrawals for industry (or waterworks) is computed based upon an equal division of the yearly groundwater utilization statistical data and distributed into 1-Km mesh grid cell depending upon the location of urban structures (or waterworks-use wells). Finally, 1 Km mesh-based monthly groundwater withdrawals for agriculture is counted by subtracting the surface water consumption for irrigation from water requirement of crops at the monthly scale and 1-Km resolution. The tempo-spatial distribution of total groundwater withdrawals is depicted by adding together three layers of the groundwater pumpage for agriculture, industry and waterworks.

2.1 Irrigation Requirement Assessment

As far as the plain is concerned, the irrigated crops are mainly comprised of paddy rice, dryland crops and greenhouse crops. Taking into account the different irrigation patterns of the crops, the following three equations were employed to calculate the water requirements of farm crops during the growth periods. In view of the time-scale effect of paddy water demand assessment (Cai et al. 2012), daily precipitation data was used for the irrigation requirement assessment.

The irrigation season for paddy rice growth in the plain lasts 112 days usually from the last 10-day of June to the first 10-day of October and hence no water is required for rice paddy in non-irrigation seasons. Considering the definitions of paddy water demand proposed by Fukuda (2005) and Jang et al. (2007) and a well-developed creek network for paddy irrigation in the plain, the assessment for paddy water demand can be expressed in Eq. 1:

$$WDP_{(i,j)} = (CWU_{(i,j)} - TR_{(i,j)} \times (1 - RCP)) \times Ap_{(i,j)} / (RUR \times 10) \quad (1)$$

where WDP is the irrigation water demand for paddy rice in m^3 ; CWU the consumptive water use (known as “gensuishin” in Japan) in mm; TR the areal rainfall in mm calculated with a Thiessen/Voronoi Polygon method (Lynch and Schulze 1995; Fiedler 2003); RCP the runoff coefficient of paddy fields with the value of 0.7 (RAJ 1997); RUR the reuse ratio of irrigation water and assigned as 1.22 (Kuroda and Cho 1988); Ap the area of paddy rice in ha from the yearly agricultural statistics; i the time scale (daily); and j is the space scale (by administrative division).

For dryland crops in the open fields (e.g. wheat, bean, vegetables and orchard), the crop water use is generally estimated by subtracting the effective precipitation (eFP) from the crop’s evapotranspiration requirement (ETc) which is the product of crop coefficient (Kc) and the reference evapotranspiration value (ETo) (Ko et al. 2009; Farg et al. 2012). ETo values are obtained from the semi-empirical method of Penman-Monteith FAO-56 (Allen et al. 1998). In view of high phreatic water surface in the plain (the depth is about 1–1.5 m), capillary upflow from the water table is non-ignorable for crop water supply (Yang et al. 2007). Moreover, the water in dry soils is strongly bound by capillary and absorptive forces to the soil matrix, and is less available for plant root extraction, which is called as “the effect of soil water stress”. In order to reduce the impact of soil water stress effect on the accuracy of ETc assessment, the water stress coefficient (Ks) was used to modify the ETc assessment equation (Allen et al. 1998; Liu and Luo 2010). Hence, capillary upward moisture supply and soil-water stress

conditions were considered to estimate the irrigation requirement of dryland crops, as described in Eq.2.

$$WDd_{(i,j,k)} = ((ETo_{(i,j)} \times Kc_{(i,j,k)} \times Ks - TR_{(i,j)} \times (1 - RCd)) - CU_{(i,j,k)}) \times Ad_{(j,k)} / 10 \quad (2)$$

where WDd is the water requirement for dryland crops in m^3 ; ETo the FAO Penman-Monteith evapotranspiration in mm; Ks assigned as 0.8 (MAFF 1997); RCd the runoff coefficient of dryland with the value of 0.52 (RAJ 1997); CU the capillary upflow in mm; Ad the area of a given dryland crop in ha from the yearly agricultural statistics; and k is the type of dryland crops.

Due to the relatively closed environment of a greenhouse, there is the difference in meteorological conditions inside and outside it, as presented in Table 1. Since the high humidity makes the root-zone soil water content (at 0–60 cm depth) vary little inside greenhouse (Valdés-Gómez et al. 2009), the capillary upflow for greenhouse crop growth was neglected in the investigation. According to the meteorological and soil-water parameters of greenhouses, the assessment equation of greenhouse crop water demand (Eq. 3) can be represented as a simplified form of Eq.2. Additionally, the irrigation for greenhouse crops is basically dependent on groundwater, owing to the high-quality vegetable and fruit production.

$$WDg_{(i,j,k)} = ETo_{(i,j)} \times Kc_{(i,j,k)} \times Ks \times Ag_{(j,k)} / 10 \quad (3)$$

where WDg is the water requirement for greenhouse crops (e.g. tomato, cucumber and strawberry) in m^3 and Ag the area of a given greenhouse crop in ha from the yearly agricultural statistics.

Kawano et al. (1995) estimated capillary upflow from the water table to the root zone for dryland crops growth under different soil types including andosol, sandy loam, regosol and sandy soil. It is indicated that the capillary upflow has a direct relation to evapotranspiration and the relationship curve varies with the soil type and the ratio of soil surface evaporation to evapotranspiration. Based on the capillary upflow vs evapotranspiration curves reported and the soil type distribution of the plain, the capillary upflow amounts for dryland crops were calculated in the investigation.

2.2 Surface Water Consumption Evaluation

Surface water resources used for agriculture irrigation in the plain mainly comes from four river basins involving Rokkaku, Kase, Chikugo and Yabu. It is shown from Fig. 4 that the

Table 1 Meteorological parameters for greenhouse crops (MAFF 1997; Zabeltitz 2011)

Month	Jan & Feb	Mar & Dec	Apr & Nov	May & Oct	Jun & Sep	Jul & Aug
Temperature	T ^a +15 °C	T+12 °C	T+8 °C	T+5 °C	T+3 °C	T+1 °C
Wind velocity	15 % of that observed outside					
Precipitation	0					
Net radiation	(1- α^b) * shortwave solar radiation * transmittance of solar radiation					
Transmittance of solar radiation	70 %					
Humidity	The saturation deficit inside is equal to that outside					

^a T-Temperature outside greenhouse

^b α -surface albedo (i.e. ratio value of reflected to incoming shortwave radiation: 0.2 for paddy field, 0.17 for dryland, 0.12 for forest, 0.23 for barren land, 0.16 for urban area, 0.06 for water surface)

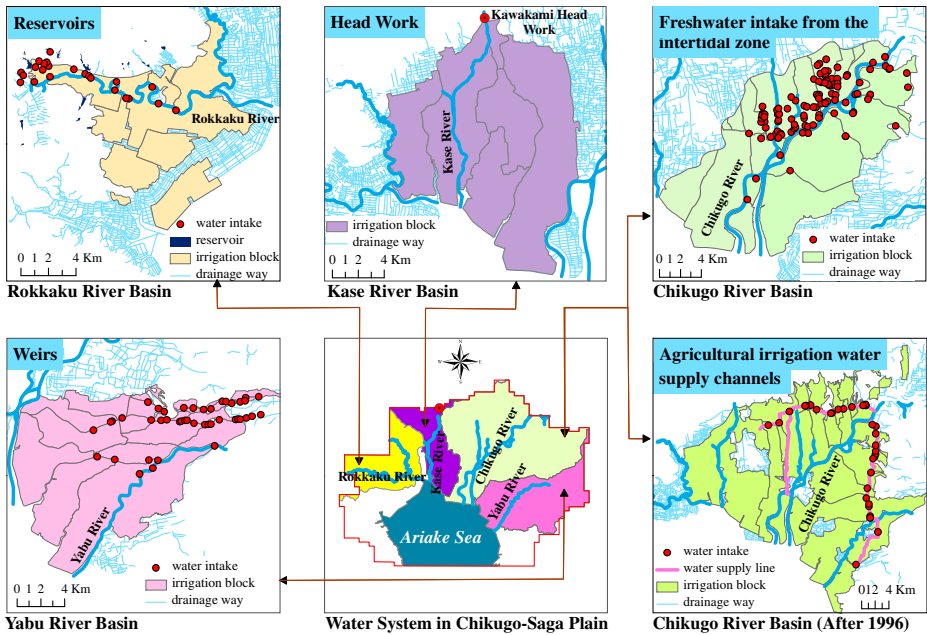


Fig. 4 Irrigation-use water diversion modes for four river basins in Chikugo-Saga plain

water diversion modes vary among the river basins. The water is diverted from reservoirs, Kawakami head work and weirs in Rokkaku, Kase and Yabu river basins, respectively. As for Chikugo river basin, large quantities of freshwater (known as “Ao” in Japan) from the lower Chikugo river are utilized periodically in response to tidal backward effect (Sakamoto and Yamashita 1989). Furthermore, the agricultural irrigation water transfer project was completed in 1996 and then has been used to divert water from middle Chikugo river to agriculture lands in low Chikugo basin. Considering the various water diversion modes, the surface water consumption for different river basins was estimated separately. In Japan’s agricultural sector, water rights (i.e. property rights of using water) were routinely issued to irrigation associations (IA) that are responsible for the management of their water intake and water use (Kobayashi 2005). For the purpose of utilizing water efficiently, the area that each IA governs generally consists of several, or sometimes many, of IA-based irrigation blocks. The water allocation between irrigation blocks sharing an IA has been managed based on the principle of equal usage among water users. The surface water for agricultural production is mainly consumed for irrigating paddy rice (in summer and autumn) and wheat & bean widely cultivated in dried paddy fields as rotate cultivation crops (in winter and spring) in the plain. The surface water consumption for each irrigation block can, therefore, be computed as represented in Eq. 4.

$$SWC_{(i,l)} = \frac{Ap_{(i,l)}}{TAp_{(i,l)}} \times TWIQ_{(i,l)} \tag{4}$$

where *SWC* is the surface water consumption of a given irrigation block in m³; *Ap* the area of paddy field in the block specified in ha; *TAp* the total area of paddy field in the domain under the authority of the IA governing the block in ha; *TWIQ* the total discharge from the

water intakes belonging to the IA governing the block in m^3 ; i the time scale (daily); and l is the space scale (by irrigation block).

3 Data Preparation

3.1 Meteorological and Agricultural Data

Daily weather data for the period 1979–2006 were collected from 12 meteorological stations where six stations are used for the multi-variables observation concerning rainfall, temperature, wind, solar radiation and humidity and the other stations only for rainfall measurements. Figure 5 illustrates the location of the multi-variables observation stations and the corresponding Thiessen polygons created where point data can be converted to areal data. The distribution map of the consumptive-water-use (CWU) for paddy rice cultivation in the plain was prepared by using GIS based on the technical report by West Japan Engineering Consultants Inc (2002). The types of crop grown and their respective cultivation area are available in the local statistical yearbooks 1979–2006. According to the crop cultivation area, 33 types of crops (e.g. paddy rice, wheat, bean, potato, cabbage and tomato) were chosen for irrigation requirement estimation. The Kc value corresponding to the different growth stages (initial, middle and late) for a specific crop studied is contained in the design criterion by MAFF (1997).

3.2 Land Use and Soil Type Data

The land use data for any 100 m mesh grid cell within the study area were processed and compiled in GIS format. The 100-m mesh was created by dividing 1-km mesh (i.e. 3rd-order

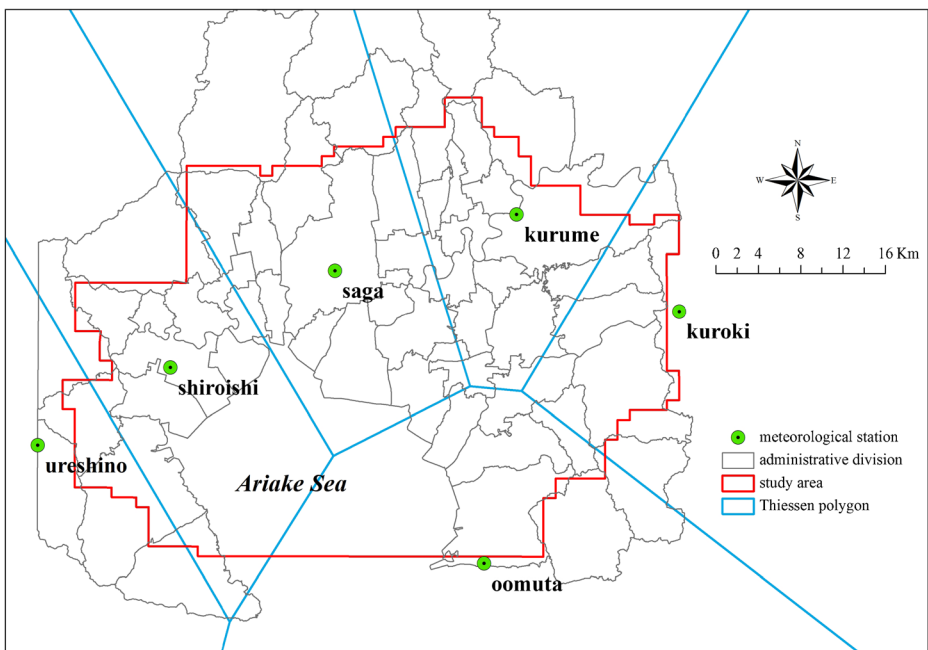


Fig. 5 Uniform meteorology zones created by the Thiessen method

mesh system in Japan) by 10 in both horizontal and vertical directions (Matsuda 1980). Figure 6 presents the four land-use maps prepared for 1976, 1987, 1991 and 1997 where the land use classification is based on the land use data of 1976 as follows: i) paddy; ii) patch; iii) orchard; iv) other orchard; v) forest; vi) barren land; vii) structure A; viii) structure B; ix) traffic lot; x) other traffic lot; xi) reservoir; xii) river A; xiii) river B; xiv) seashore; xv) sea (15 categories in total). A general soil map of Kyushu Island at a scale of 1: 500,000 was employed to prepare the digital soil map of the study area under GIS environment. Figure 7 shows the distribution of different soil types in the study area. It is indicated that the fine-textured fluvic gleysols (known as “Ariake clayey soil” in Japan) is widely distributed in the plain.

3.3 Surface Water Diversion and Groundwater Withdrawals Data

The monthly surface water diversion data from 1979 to 2006 were collected from Takeo River Office in Saga prefecture (the amount of water diverted from reservoirs in Rokkaku river basin) and Chikugo River Office in Fukuoka prefecture (the water amount diverted from Kawakami headwork in Kase river basin, those from different weirs in Yabu river basin and those from “Ao” water intakes and the agricultural irrigation water transfer project in Chikugo river basin). Considering that the amount of water consumed daily varies little within one month, daily surface water consumption in a calendar month was estimated as the average daily water diversion amount based on the corresponding monthly value. The yearly groundwater withdrawals data for industry and waterworks (by administrative division) are available in statistical yearbooks of Saga and Fukuoka prefectures (1979–2006). The monthly values were computed by equally apportioning the yearly data to any month. Moreover, the location map of wells for waterworks was prepared for any particular year of the study period. Figure 8 illustrates the location of waterworks-use wells in 2002.

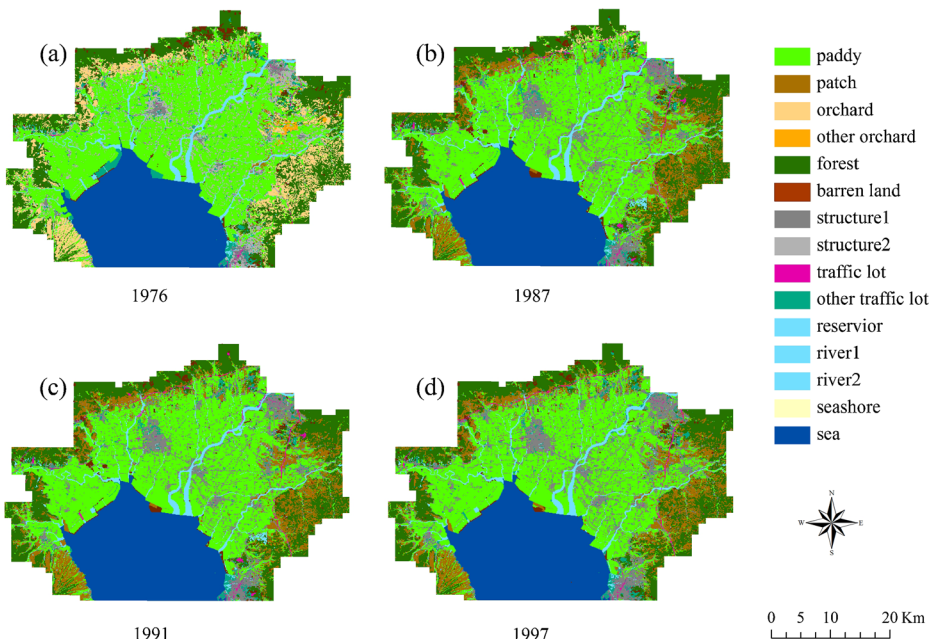


Fig. 6 Land use maps of Chikugo-Saga plain in 1976, 1987, 1991 and 1997

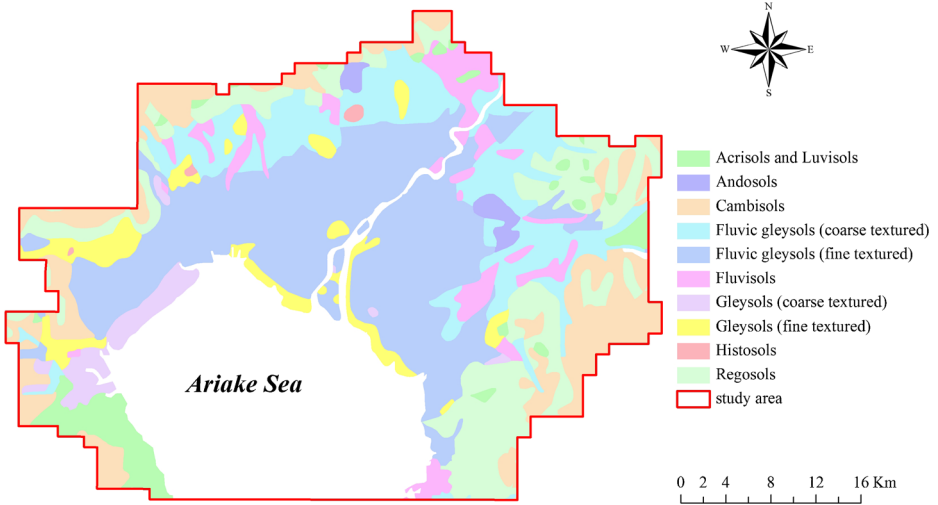


Fig. 7 Distribution of soils existing in Chikugo-Saga plain

4 Description of a GIS-Based Assessment Model of Groundwater Withdrawals

The assessment model was established based on prepared multi-layer spatial data concerning meteorology, agriculture, soil, land use, water resources utilization, administrative divisions and 1-Km regional mesh. By using Spatial Analyst tools and compiling the Visual Basic for Application (VBA) code in GIS, feature-based calculations were automatically performed and finally, the distribution of groundwater withdrawals was assessed monthly at 1-Km scale.

The distribution of irrigation water demand in July of 2002 is presented in Fig. 9a. The distributions of groundwater pumpage for agriculture, industry and waterworks in July 2002

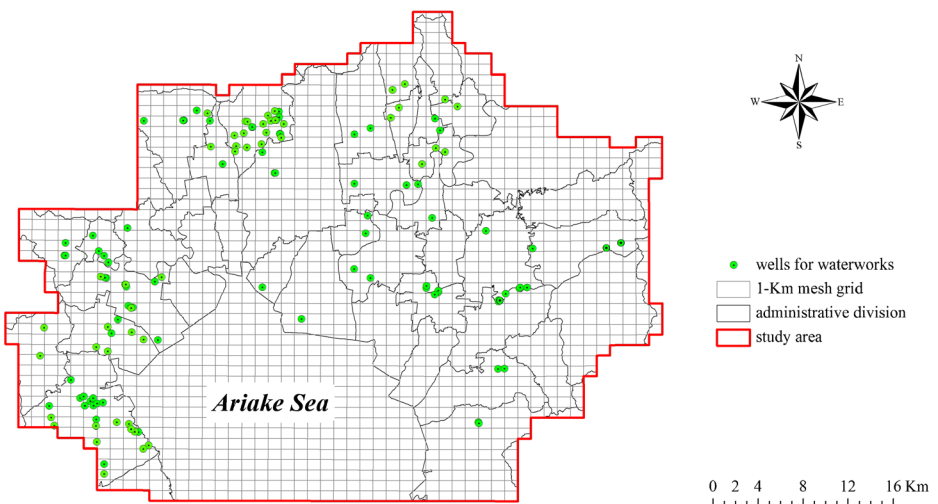


Fig. 8 Location of waterworks-use pumping wells distributed in Chikugo-Saga plain in 2002

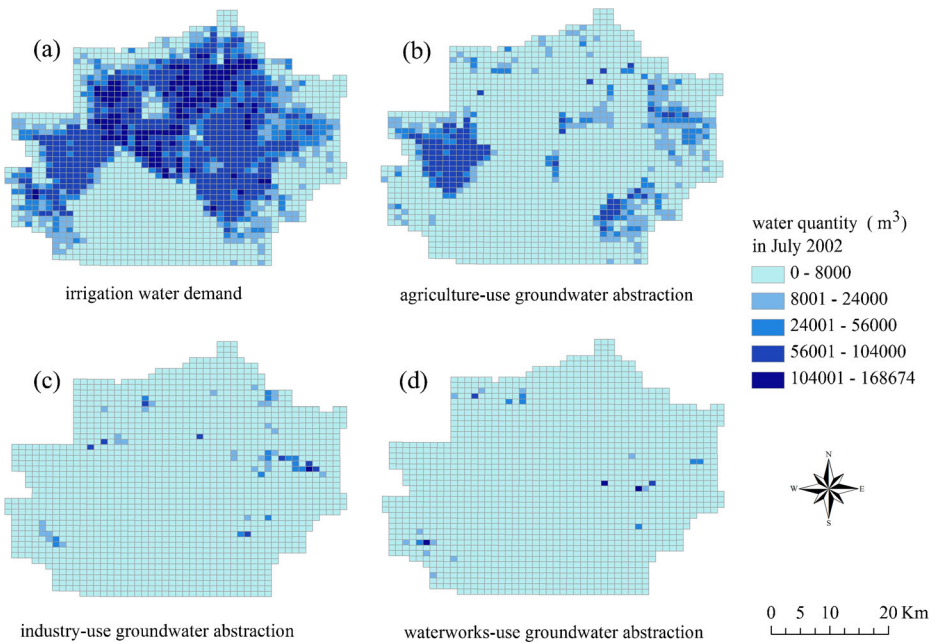


Fig. 9 Distribution of irrigation requirement and groundwater withdrawals in Chikugo-Saga plain in July 2002

are given in Fig. 9b, c and d, respectively. It is shown that the irrigation water demand for crop growth is approximately 4 times greater than the groundwater pumpage for agriculture in July 2002. It may be due that some irrigation projects make a great deal of surface water available for crop cultivation. Furthermore, it is clearly seen that nearly 80 % of the groundwater withdrawn is consumed for agricultural irrigation in July 2002.

5 Results and Discussion

Considering the outline of measures for preventing ground subsidence formulated in 1985 for the plain (MOE 1995) and the significant effect of Agricultural Irrigation Water Transfer Project, Chikugo weir and Western Saga water works, four stages were taken into account for studying the variation of groundwater withdrawals: 1979–1984, 1985–1995, 1996–2000 and 2001–2006.

5.1 Variation of Groundwater Consumption for Agriculture

In order to clearly describe the variation of groundwater withdrawals for agriculture irrigation, the distribution of mean annual agriculture-use groundwater consumption in any particular stage was prepared based on monthly groundwater withdrawals estimated in each 1-km mesh grid cell. Figure 10 illustrates the variation of agricultural groundwater withdrawals during the study period. It is obviously shown that there is a decline in mean annual groundwater consumption for agriculture in both eastern Saga area and Chikugo area from the second stage (1985–1995) to the third stage (1996–2000) while little change found in that in western Saga area. It is indicated through the comparison that the mean annual agricultural

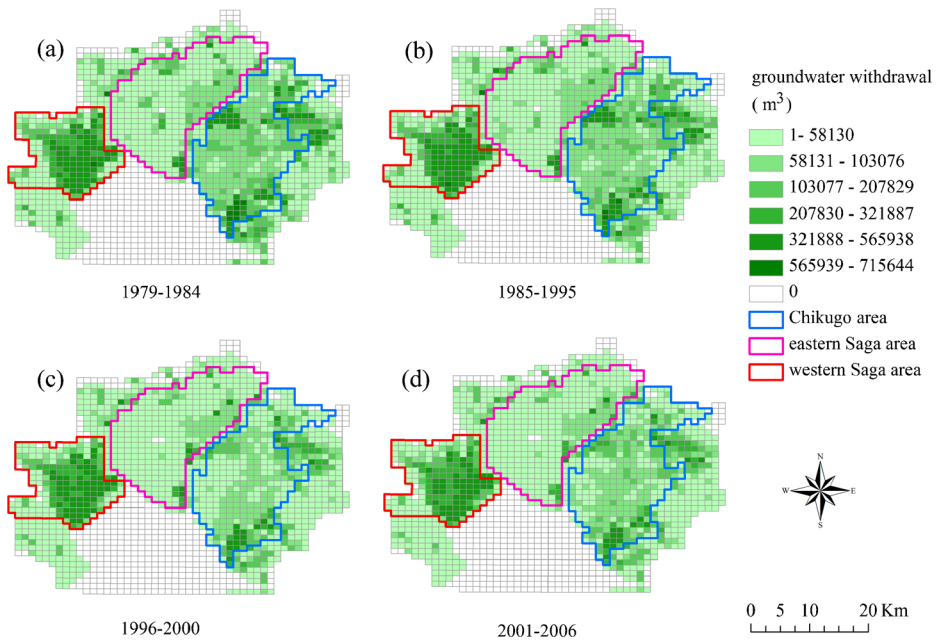


Fig. 10 Distribution of mean annual agriculture-use groundwater consumption in Chikugo-Saga plain for each stage of the study period 1979–2006: **a** stage I (1979–1984), **b** stage II (1985–1995), **c** stage III (1996–2000), **d** stage IV (2001–2006)

groundwater abstracted decreases by 27.5 % from 40 to 29 million tons/year (hereinafter referred to as “MTY”) for Chikugo area; it decreases by 23.5 % ranging from 17 to 13 MTY for eastern Saga area; and that it changes little from 39 to 38 MTY for western Saga area, when times moves from the first two stages to the last two stages. As far as the entire plain is concerned, the agricultural groundwater pumpage decreases by 19.5 % from 128 to 103 MTY at the third stage (after 1996). It is mainly due that Chikugo area and eastern Saga area benefit from “Agricultural Irrigation Water Transfer Project” which has transferred a large quantity of water from Chikugo river to these two areas for agriculture irrigation since 1996 and as a result, the agriculture-use groundwater pumpage is reduced.

5.2 Variation of Groundwater Consumption for Industry

The distribution of mean annual industrial groundwater withdrawals in each stage of the study period is presented in Fig. 11. It is clearly shown that there is a dramatic decline in industrial groundwater consumption in Saga city (a major industrial city in eastern Saga area) from the first stage to the second stage. Furthermore, it is found that there is a gradual decrease in industrial groundwater consumption in Kurume city (a major industrial city in Chikugo area). These variations may be said to be caused by the implementation of “Outline of Measures for Preventing Ground Subsidence” established for Chikugo-Saga plain in 1985 and the operation of Chikugo weir commencing in 1985. The outlines stipulate limits on groundwater withdrawals in the greatly subsided areas like Saga city and consequently promote the development of substitute water projects.

With the increasing of providing capacities of the two industry-use substitute water projects (i.e. Eastern Saga Industrial Water Supply and Kishima Industrial Water Supply), more and

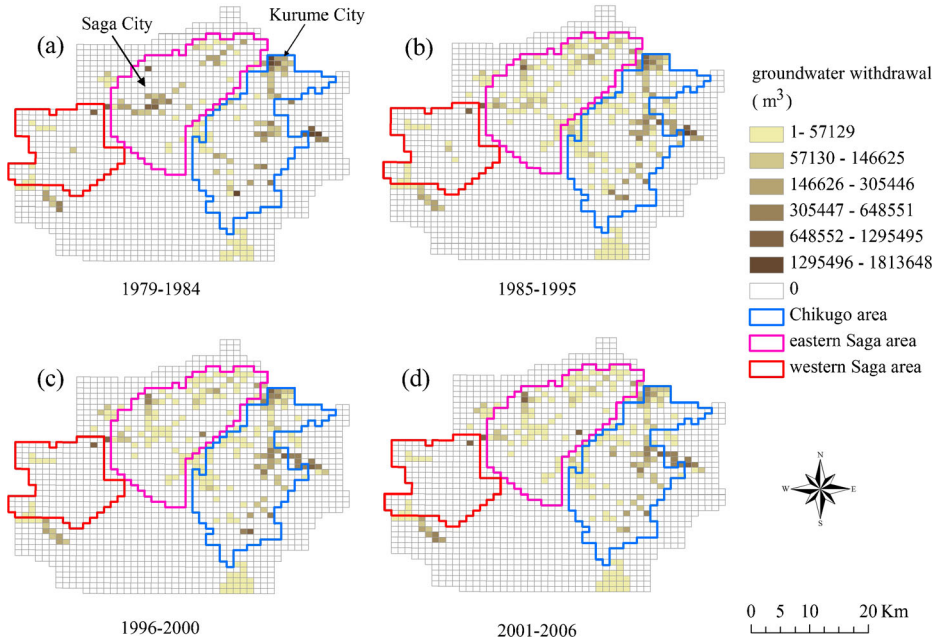


Fig. 11 Distribution of mean annual industry-use groundwater consumption in Chikugo-Saga plain for each stage of the study period 1979–2006: **a** stage I (1979–1984), **b** stage II (1985–1995), **c** stage III (1996–2000), **d** stage IV (2001–2006)

more surface water has been transferred to Saga area to reduce industrial groundwater abstraction since 1985. Owing to the prevalence of industry in eastern Saga area and agriculture in western Saga area, the industrial groundwater pumpage experiences a distinct decrease from 8 to 4 MTY in eastern Saga area and a slight decrease from 0.9 to 0.8 MTY in western Saga area during the study period. After the construction of Chikugo weir, a large amount of surface water has been diverted into Kurume city for industrial production, which leads to a notable decline in the industrial groundwater consumption. Since there is not an industrial water supply line in Chikugo area, the industry-use groundwater pumpage (ranging from 12 to 8 MTY) in Chikugo area is much more than that in Saga area during the study period. For the plain, there is a decrease by 33.3 % from 30 to 20 MTY in the industrial groundwater pumpage from the first stage to the last stage.

5.3 Variation of Groundwater Consumption for Waterworks

The distribution of mean annual groundwater withdrawals for waterworks in each stage of the study period is represented in Fig. 12. It is distinctly seen that the waterworks-use groundwater consumption in western Saga area experiences little change at the first three stages followed by a dramatic decline from 4 to 0 MTY at the last stage. Furthermore, it is found that there is a decrease from 3.3 to 1.2 MTY in the waterworks-use groundwater abstraction value in eastern Saga area, while an increase from 3.7 to 5 MTY in that in Chikugo area from the first stage to the last stage. It may be explained that “Western Saga Water Works” project has transferred sufficient freshwater from Kase river to western Saga area for waterworks use and hence no groundwater been required since 2001. “Eastern Saga Water Works” project, completed in 1980, derives water from Chikugo river to provide freshwater for waterworks in eastern Saga

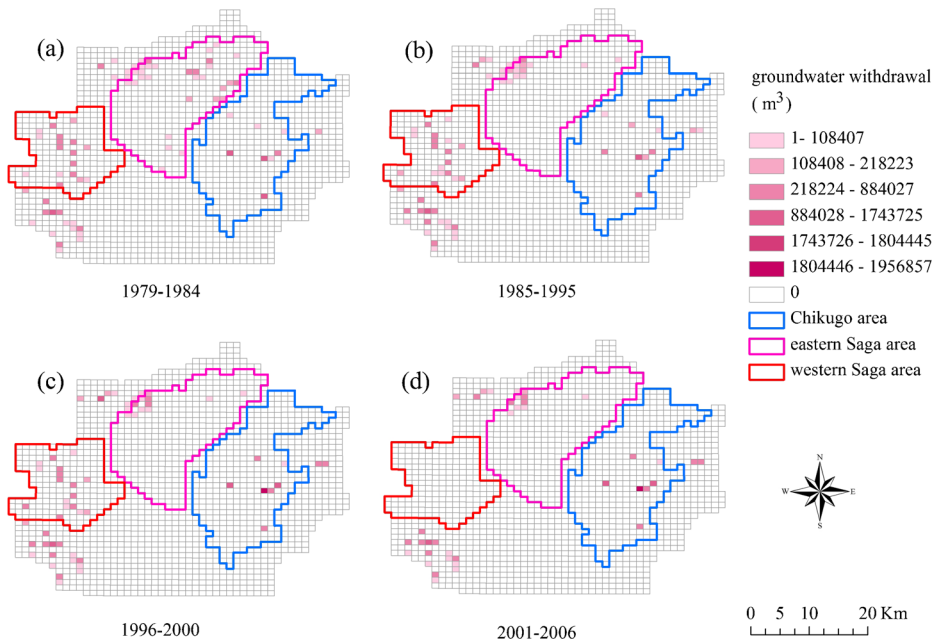


Fig. 12 Distribution of mean annual waterworks-use groundwater consumption in Chikugo-Saga plain for each stage of the study period 1979–2006: **a** stage I (1979–1984), **b** stage II (1985–1995), **c** stage III (1996–2000), **d** stage IV (2001–2006)

area, which contributes to a notable decrease in waterworks-use groundwater pumpage from the first stage to the second stage. “Southern Fukuoka Water Works” project began to supply water in 1989, deriving water from Chikugo river. Since the project was expanded in 1993, Ooyama reservoir (located in the upper-stream of Chikugo river) and underground water (extracted from pumping wells within Chikugo area) have become the main sources, instead of Chikugo river. This may be the reason why the waterworks-use groundwater pumpage experiences a gradual increase from the first stage to the third stage. For the plain, there is a decrease by 20 % from 15 to 12 MTY in the groundwater withdrawals for waterworks use with time moving from the first stage to the last stage.

5.4 Variation of Total Groundwater Withdrawals

By overlaying three layers of groundwater abstractions for agriculture, industry and waterworks under GIS environment, the distribution of mean annual total groundwater withdrawals was obtained for each stage of the study period, as illustrated in Fig. 13. It is clearly seen that the total groundwater withdrawals experiences a significant decrease along with the advance of the substitute water projects in the plain. From the first stage to the last stage, the value of total groundwater withdrawals declines by 25.9 % from 58 to 43 MTY in Chikugo area, decreases by 35.7 % from 28 to 18 MTY in eastern Saga area and is reduced by 15.9 % from 44 to 37 MTY in western Saga area. Among the three areas studied, the volume of groundwater abstracted in eastern Saga area falls fastest from 1979 to 2006 thanks to the presence of the substitute water projects for agricultural irrigation, industrial production and waterworks. For the plain, there is a decline by 23.2 % from 176 to 135 MTY in groundwater withdrawals under the effect of the substitute water projects from the first stage to the last stage. It is

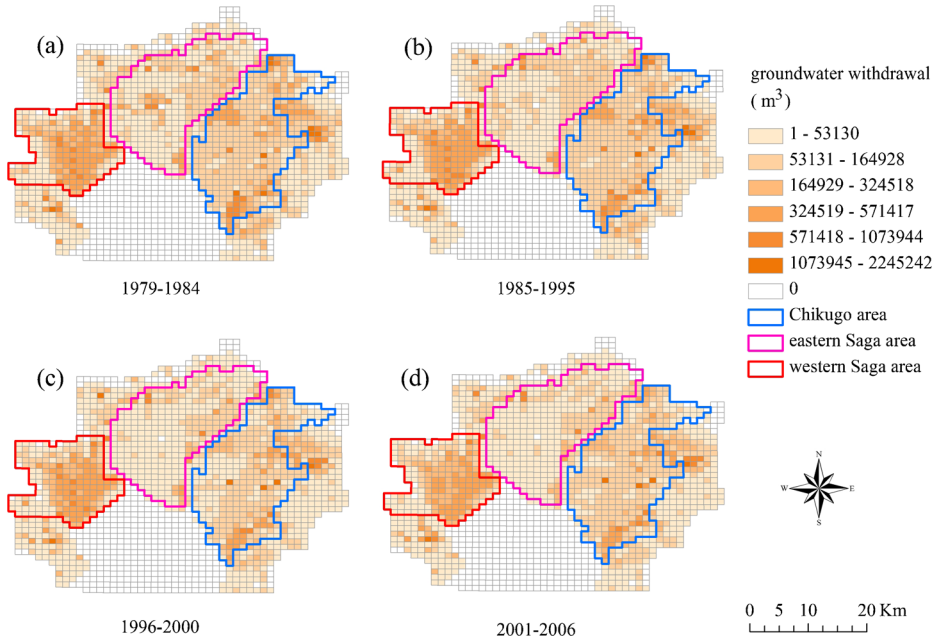


Fig. 13 Distribution of mean annual total groundwater withdrawals in Chikugo-Saga plain for each stage of the study period 1979–2006: **a** stage I (1979–1984), **b** stage II (1985–1995), **c** stage III (1996–2000), **d** stage IV (2001–2006)

indicated from Fig. 10–13 that reducing the agriculture-use groundwater consumption in western Saga area and the industry-use consumption in Chikugo area is essential for an effective control of groundwater withdrawals in the plain in future. Fortunately, a new agriculture-use substitute water project is under construction in western Saga area, which is expected to reduce the agricultural groundwater withdrawals and consequently to mitigate the environmental impact of land subsidence.

6 Conclusions

A GIS-based quantitative model was proposed to describe the monthly distribution of groundwater withdrawals with a spatial resolution of about one square kilometer for various water use categories in the investigation. Through comparisons of the groundwater pumpage distributions at four stages of the study period, the tempo-spatial variation of groundwater withdrawals was analyzed and the effect of substitute water projects on groundwater pumpage distributions in the plain discussed. Some findings are concluded as follows:

The proposed model can provide a quantitative and efficient tool for quantifying groundwater abstractions spatially and temporally in some areas where the recorded data on groundwater withdrawals are incomplete or unavailable and consequently, is helpful to understand fully regional groundwater utilization and its impact on the environment.

The groundwater consumption for each water use category varies geographically and physically in the plain during the study period. There is a decrease by approximately 25 % in mean annual agriculture-use groundwater withdrawals in eastern Saga area and Chikugo area which benefit from “Agricultural Irrigation Water Transfer” project, with time moving

from the early two stages (1979–1995) to the last two stages (1996–2006). Mean annual industrial groundwater pumpage declines distinctly in both Saga city and Kurume city at the second stage (1985–1995) due to the expansion of “Eastern Saga Industrial Water Supply” project and the utilization of “Chikugo Weir” in 1985. A dramatic decline to zero in waterworks-use groundwater withdrawals is found in western Saga area at the last stage (2001–2006) owing to the utilization of “Western Saga Water Works” project. Furthermore, the use of “Eastern Saga Water Works” project with Chikugo river serving as a substitute water source contributes to a decrease in waterworks-use groundwater withdrawals in eastern Saga area, while the use of “Southern Fukuoka Water Works” project with a reservoir and underground water as substitute sources contributes to an increase in that in Chikugo area with time moving forward.

Along with the advance of the seven substitute water projects studied, mean annual total groundwater pumpage in the plain experiences a significant decrease by about 23 % from the first stage to the last stage. In order to effectively control the groundwater withdrawals in future, it is necessary to develop new substitute water supply plans to reduce the agriculture-use groundwater withdrawals in western Saga area and the industry-use withdrawals in Chikugo area. The findings from the investigation are expected to be conducive to effective management and rational utilization of regional water resources in future.

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