Estimated groundwater recharge including water pipes leakage in Kumagaya City

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Abstract: The drying up of seepage in Kumagaya City was caused by the increase of impermeable area with urbanization. The project of rain fall infiltration facilities has been planned for improvement of a hydrological cycle in Kumagaya City. With GIS and remote sensing, the most suitable arrangement for the rainfall infiltration inlets was examined. Distribution maps for infiltration, evapotranspiration and groundwater recharge at each town in Kumagaya City was designed from the land cover classification map with hydrological analysis. In these distribution maps, influence of the leak from drinking water and sewage networks was counted to the hydrological cycle.
Keywords: groundwater recharge, GIS, remote sensing

1. Introduction

The drying up of ground water in Kumagaya City was caused by the increase of impermeable area with urbanization. The basin countermeasures by rainfall infiltration inlets are executed for improvement of such a water cycle. Then, the most suitable arrangement of rainfall infiltration inlets was examined using GIS and remote sensing. Estimate of infiltration capacity in present situation was obtained in this study from land cover classification, soil experiment and hydrological analysis results.

2. Study area

Kumagaya City is located in the New Arakawa Alluvial Fan, where the surface water flows and becomes river-bed water, and seeps (Fig. 1). Therefore abundant subsurface water is recharged. However, in late years the water level fell down by the increase of pump-up water for industrial use and pavement area in development.

3. Methods

A quantity of groundwater recharge was estimated from precipitation, evapotranspiration, infiltration, outflow and leak from drinking water and sewage network each land cover. The final results were summed up each town block.

1) Land cover classification

Land cover classification was carried out using Landsat-TM data. When land cover classification is carried out using Landsat-TM data, it is difficult that paddy fields are extracted with good accuracy from a 1 scene. Therefore the classification was carried out using two periods of data for the cultivation and the fallow seasons. Used data are shown in Table 1 Land cover classes are forest, paddy fields, crop fields, grassland, urban area, water and bare soils. The area rate of each land cover was shown in Table 2.

Table 1. Satellite data used in this study

Landsat-TM: Path=107, Row=35
25 February, 1997 (The fallow season)
4 August, 1997 (The cultivation season)

2) Evapotranspiration

A quantity of groundwater recharge each land cover class was calculated from evapotranspiration estimated with Penman's method [1].

$$E = \frac{\Delta}{\Delta + g} Q_n + \frac{g}{\Delta + g} f(u)(e_a^{\,*} - e_a)\,, \qquad (1)$$

$$Q_n = \frac{R_n}{L_l}\,, \qquad (2)$$

$$R_n = R_s(1 - a_s) + e_s R_{ld} - R_{lu}\,, \qquad (3)$$

$$R_{ld} = e_a s T_a^{\,4}\,, \qquad (4)$$

$$e_a = 1.24\left(\frac{e_a}{T_a}\right)^{1/7}\,, \qquad (5)$$

$$R_{lu} = e_s s T_s^{\,4}\,, \qquad (6)$$

where E is the evapotranspiration, $\Delta = (de^{*}/dT)_T$, $g \equiv c_p P / el$, Q_n is the available energy flux density (mm/day), $f(u)$ is a wind function (mm/day), u is the mean wind-speed (m/s), $e_a^{\,*}$ is the saturated vapor pressure (hPa), e_a is the vapor pressure (hPa), R_n is the net radiation (W/m²), L_l is the latent heat ($\fallingdotseq 2.454 \times 10^6$ J/kg), R_s is the short-wave radiation (W/m²), a_s is the albedo [2], R_{ld} is the downward long-wave or atmospheric radiation (W/m²), R_{lu} is the upward long-wave radiation (W/m²), e_s is the emissivity of the surface (=0.97), e_a is the atmospheric emissivity, s is the Stefan-Boltzmann constant (5.67×10^{8} Wm^{-2}K^{-4}), T_a is the air temperature (K), T_s is the soil temperature (K).

3) Infiltration capacity

Soil samples were picked up each land cover, and infiltration tests were executed. The results of infiltration capacity each land cover were calculated. The following Green-Ampt's equation are used to describe one-dimensional vertical infiltration. This equation was applied for Darcy's law at wetting front in the soil.

$$i = k_s\left(H + z + H_f\right)/z \qquad (7)$$

where i is the infiltration rate, k_s is the saturated hydraulic conductivity, H is the ponding depth, z is the wetting front depth, H_f is the capillary suction (>0). When an infiltration phenomenon is described including evaporation, Richards' equation is used generally. This equation was expanded from Darcy's law to non-saturation infiltration.

$$\partial \boldsymbol{q} / \partial t = \nabla \cdot \left(k \nabla \Phi\right), \qquad (8)$$

$$\Phi = H + z - \boldsymbol{f} \qquad (9)$$

where $\boldsymbol{q}$ is the volumetric water content, k is the unsaturated hydraulic conductivity, Φ is the total potential, z is the depth, $\boldsymbol{f}$ is the matric potential. Philip applied the Richards' equation to a one-dimensional semi-infinity soil column, and obtained the following approximate solution.

$$i = \frac{1}{2} S t^{-1/2} + K \qquad (10)$$

where S is the sorptivity, K is constant. However, when the Richards' equation is used for numerical analysis, soil water characteristic must be required experimentally generally. For example, the following Campbell's formulas are needed.

$$\boldsymbol{f} = \boldsymbol{f}_e\left(\boldsymbol{q}/\boldsymbol{q}_s\right)^{-b}, \qquad (11)$$

$$k = k_s\left(\boldsymbol{q}/\boldsymbol{q}_s\right)^{2b+3} \qquad (12)$$

where $\boldsymbol{f}_e$ is the air entry potential, $\boldsymbol{q}_s$ is the saturated volumetric water content, b is constant. The Philip's equation is equivalent with the Green-Ampt's equation, and it was converted as follows [3].

$$i = \frac{1}{2} S t^{-1/2} + k_s / \boldsymbol{b}, \qquad (13)$$

$$S = \sqrt{k_s \Delta\boldsymbol{q}\left(H + H_c\right)/\boldsymbol{b}} \qquad (14)$$

where H_c is the effective capillary drive, $\Delta\boldsymbol{q} = \boldsymbol{q}_s - \boldsymbol{q}_i$, $\boldsymbol{b}$ is viscous correction factor ($\boldsymbol{b} \approx 1.4$). $\Delta\boldsymbol{q}$ and H_c are derived from the following equation through the Campbell's equations.

$$\boldsymbol{a} = -\left(\boldsymbol{f}_e/\boldsymbol{q}_s\right)b \approx H_c/\Delta\boldsymbol{q} \qquad (15)$$

Infiltration capacity of each land cover was estimated with the above-mentioned method. A ratio of the rainwater for infiltration was defined as a permeability coefficient as follows.

$$P_c = \frac{\Sigma(P_i - I)}{P_a}, \qquad (16)$$

$$I = S t^{1/2} + k_s t / \boldsymbol{b} \qquad (17)$$

where P_c is the permeability coefficient, P_i is rainfall for each event, I is the accumulated infiltration for each event, P_a is the annual rainfall.

4) Agriculture water requirement

A large quantity of water is used for farmland (paddy fields and farms) in the cultivation season from May to October. During this season, evapotranspiration in paddy fields are 3.5-7.5 mm/day. Then the total evapotranspiration in the cultivation season becomes 440-550mm. On the other hand, infiltration becomes 15-25mm/day. Accordingly the total infiltration in the cultivation season yields about 3,500mm [5]. The annual rainfall in Kumagaya City is 1,310mm on average. However, 4,000mm water in paddy fields and 400mm water in farms are used for agriculture requirement. Therefore this quantity of water was added to the rainfall, and the balance analysis was carried out. An infiltration equation is used to describe infiltration capacity.

5) Leak of drinking water and sewage network

Leak of drinking water and sewage network was estimated from the leakage each town block rate. A quantity of use for drinking water is 366l/day per capita. Accordingly a quantity of the total use was estimated from population each town block. A quantity of drinking water leak is estimated from water leakage rate of 15% [4]. The sewer is equivalent to a quantity of use for waterworks. According to the survey of Tokyo, water leakage rate is 10-30%. It is almost equal to water leakage rate of drinking water.

4. Results

1) Infiltration capacity

Land cover classification result in Kumagaya City was shown in Fig. 2 and Table 2. Permeability coefficients were estimated from the infiltration capacity and rainfall record in 1997, shown in Table 3. Infiltration and its distribution map were shown in Table 4.

Table 2. Land cover area rate (%)

Paddy field	Crop field	Forest	Grassland	Bare soil	Urban	Water
31.2	12.8	2.6	4.1	3.9	44.9	0.4

Table 3. Permeability coefficient (%)

Paddy field	Crop field	Forest	Grassland	Bare soil	Urban	Water
100	100	100	100	100	0	100

Table 4. Annual rainfall and agriculture water requirement (mm)

Paddy field	Crop field	Forest	Grassland	Bare soil	Urban	Water
5,310	1,693	1,310	1,310	1,310	0	1,310

2) Groundwater recharge

Evapotranspiration was derived from infiltration (Table 5 and Fig. 3). With the leak of drinking water and sewage network each town block, groundwater recharge was estimated from results shown in Tables 4 and 5. This result was shown in Table 6. A groundwater recharge distribution each town block was shown in Fig. 4.

Table 5. Annual evapotranspiration (mm)

Paddy field	Crop field	Forest	Grassland	Bare soil	Urban	Water
954	835	970	908	783	781	1,023

Table 6. Groundwater recharge (mm)

Paddy field	Crop field	Forest	Grassland	Bare soil	Urban	Water
2,956	875	340	402	527	108	287

5. Discussion

The construction of rainfall infiltration inlets is effective in order to improve a water cycle in the urban area. In rain of 50mm/h for a roof area of 60m^2 each house, runoff of 3m^3/h occurs and two infiltration inlets of 1.6m^3/h capacity absorb it. If the whole urban area turns into infiltration area, annual groundwater recharge of 585mm is expected. However, urban area is 38.2km^2. If two rainfall infiltration inlets cover for a lot of 100m^2, 765,000 sets will be required. The construction of permeable pavement must be also examined to install infiltration facilities effectively. Estate development and the decrease of paddy field area cause the decrease of ground water in Kumagaya City, shown in this calculation. Therefore, there maybe the upper limit to the construction of infiltration facilities for regaining the former ground water.

6. Conclusions

The construction of rainfall infiltration inlets for improvement of a water cycle in Kumagaya City was designed. Fundamental analysis for application use of this effect to the maximum was carried out. Land cover classification was computed with satellite data, and the rainfall infiltration distribution map, the evapotranspiration distribution map and the groundwater recharge distribution map in Kumagaya City each town block were made from hydrological analysis. Plans of rainwater infiltration facilities construction will utilize these distribution maps. The decrease of ground water in Kumagaya City was caused by the urban development and the decrease of paddy field area. For regaining the former ground water, there maybe a limit to the construction of infiltration facilities.

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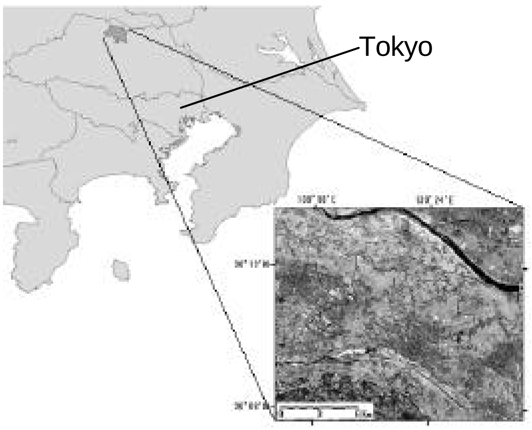

Fig.1 Study area

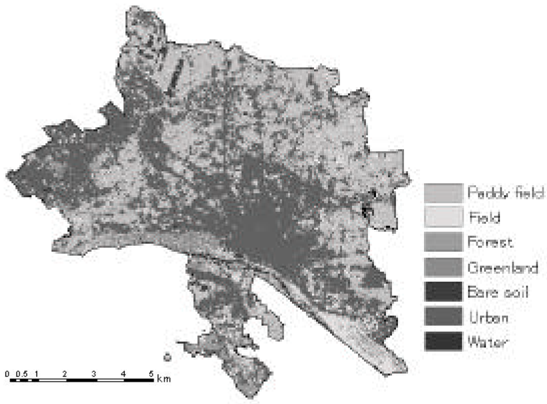

Fig.2 Land cover classification

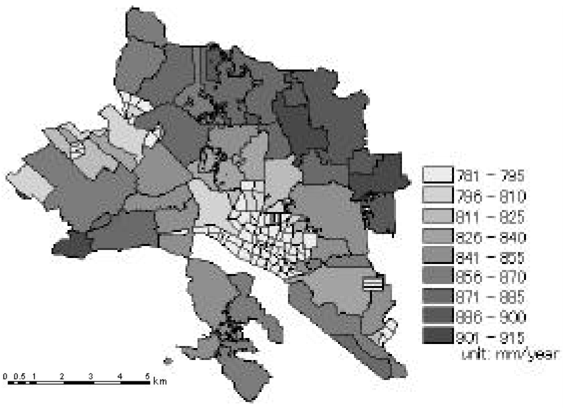

Fig.3 Evapotransration (unit: mm/year)

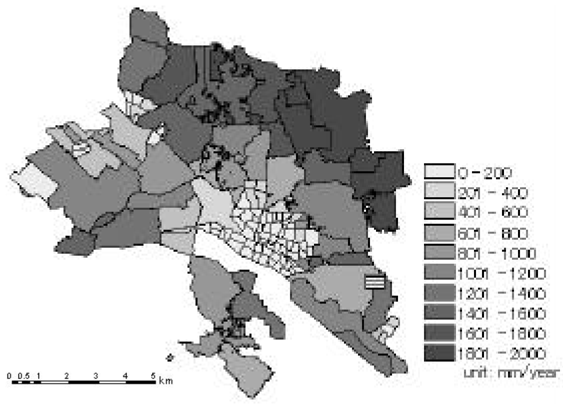

Fig.4 Groundwater recharge distribution (unit: mm/year)