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A simulation study of infiltration facility impact on the water cycle of an urban catchment

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Abstract The hydrological cycle of an urban catchment consisting of both natural and artificial flow components is modelled. Improvement of the water cycle with the use of infiltration systems that increase the groundwater recharge and reduce the flood flows is simulated considering feasible installation densities associated with urban renewal. Infiltration facility installation options are assessed and changes to the urban water environment over a decade and its restoration potential is modelled assuming that infiltration facilities can be implemented at the time of rebuilding or during new construction.**[key words??]**

INTRODUCTION

The urban water cycle consists of natural water cycle components such as surface runoff, evapotranspiration, infiltration and subsurface processes, as well as discharge components arising from human water use such as water supply and irrigation. In addition, the urban water cycle is strongly influenced by human intervention as urbanization significantly alters infiltration, evaporation and runoff processes. Due to the complex interaction of these processes and requirements for long term careful monitoring, there are only a few water balance measurements reported in the literature, whereas many studies tend to be model-based projections (Grimond *et al.* 1986, Van de Ven, 1996). In this paper the authors assess the urban water balance through distributed hydrological modelling in a well-equipped urban catchment located in the suburbs of Tokyo, Japan, which has high-resolution spatial and temporal data accumulated for more than a decade, to analyse the effects of continued urbanization and remedial measures.

One of the major adverse effects of urbanization has been the increase of impervious areas that has resulted in an increase of surface runoff, both in volume and peak discharge, and the associated reduction of infiltration and groundwater recharge that leads to reduced river low flows in dry periods, deteriorating amenity functions and water quality. In order to restore the urban water cycle, artificial infiltration through infiltration facilities has been proposed, where infiltration trenches and collection boxes installed at residential areas collect rainwater and let it infiltrate, recharging the groundwater. Similar studies have been proposed elsewhere and, especially pervious pavements were found to be effective at catchment scale (Niemczynowicz, 1990).

During the past few years, a water cycle management committee has been set up in the study catchment, with the participation of various stakeholders, to improve the urban water cycle. One of the measures adopted has been to install infiltration systems systematically in all residential housing complexes within the catchment. In this paper a study is reported on the effect of infiltration systems using a distributed hydrological model that has been set up for the catchment at 50 m spatial resolution coupled to a grid level infiltration facility modelling system. Using the statistics of the new housing construction as well as housing renewals that have been carried out from 1990 to 2000, the increase of impervious areas has been estimated. Assuming that infiltration facilities can be installed for the new constructions and houses under renewal at the density of conventional drainage, the effect of infiltration systems in restoring the water cycle has been assessed.

METHOD

Considering the heterogeneity of the urban water cycle, it is clear that a distributed modelling approach is necessary for the estimation of various components. After delineating a catchment into discrete elements where the assumption of homogeneity of each element in relation to physical characteristics and water supply patterns is plausible, it is possible to model water movement employing governing equations for transport of each component of the hydrologic cycle. To model urban hydrology, the main catchment characteristics considered are:

(a) Topography that determines surface slopes and drainage;
(b) Land use which can be used to estimate permeability, surface roughness, evapotranspiration and surface storage;
(c) Soil distribution for estimating soil hydraulic properties;
(d) Catchment boundaries for rainfall response modelling;
(e) Water supply boundaries for estimating inputs from water supply; and
(f) Drainage network consisting of natural drainage paths and household and industrial discharges.

Hydrological model

For the mathematical model, a uniform grid on the horizontal plane discretizes the catchment, and at each grid a layered column represents the surface, unsaturated and groundwater domains. The computational procedure adopted in the mathematical model, together with the concepts and equations for each process, are described in Herath *et. al.* (1996) and only briefly here. Surface characteristics at each grid element are described by land cover, impervious ratio (*ifr*), which is the ratio of paved area to pervious area, soil type, maximum storage for pervious areas including depression areas, and maximum storage for impervious areas. For the surface flow component state variables are the storage in the pervious area (*sp*) and storage in the impervious area (*si*). The mass conservation at the surface is applied separately to the impervious area and the pervious fraction. In estimating infiltration rate from pervious areas, first the excess rainfall amount, *Rx,* where the rainfall rate is greater than the saturated conductivity is computed assuming an exponential distribution of rainfall (*R*) during the rainfall interval as:

$$Rx = (1 - ifr) \times R \times e^{-Ko/R} \tag{1}$$

where, *Ko* is the saturated hydraulic conductivity.

The maximum infiltration capacity of the soil, *Infcap*, is estimated as,

$$Infcap = K(\theta)\frac{\partial H}{\partial z} + (\theta_0 - \theta)\Delta z \tag{2}$$

where, *K* is the hydraulic conductivity, *H* is the total water head in the subsurface layer beneath the surface and θ_0 is the saturated moisture content, θ is the moisture content and ΔZ is the thickness of the subsurface layer. Infiltration *I* is estimated from equations (1) and (2) as:

$$\begin{aligned} I &= R \times (1 - ifr) - Rx \text{ for } I < Infcap \\ I &= Infcap \text{ otherwise} \end{aligned} \tag{3}$$

Evaporation from impervious areas is estimated as:

$$E_{imp} = Ep \times ifr \text{ for } E_{imp} > si;\ E_{imp} = si \text{ otherwise} \tag{4}$$

where *Ep* is the potential evaporation. For the pervious areas, evaporation is estimated as:

$$E_{per} = Ep \times \alpha \times (1 - ifr) \tag{5}$$

where α is a parameter modifying potential evaporation to actual evaporation E_{per} for the pervious area. Infiltration is modelled using a moisture-based governing equation for the near surface layer up to the first 2 m and then represented as vertical steady gravity flow until the water reaches groundwater. These modelling approaches have been found to be adequate for Japanese climatic and soil conditions in previous applications (Herath *et al*., 1992) and have been verified for different soil characteristics through detailed numerical simulations (Ni *et al*., 1993). Groundwater movement is modelled using Darcy's law with an explicit numerical scheme.

Artificial water use

Unlike the natural water cycle, the artificial water cycle cannot be described by governing equations. The water use depends on the consumers and the purpose for which water is used. The approach adopted in the present study is to distribute the water supply or demand to each grid element based on land use from different water supply information available at the highest spatial resolution, and then to model the discharge using a unit discharge function concept as explained in Fig. 1. In the figure, *QS* is the supply over time unit *T* (day) over which it is possible to quantify the input, *QL* is the transmission loss, *QD* is the total discharge, *qd* is the discharge at time *t*, *f(t)* is the normalized unit discharge function at the point of interest for artificial water use.

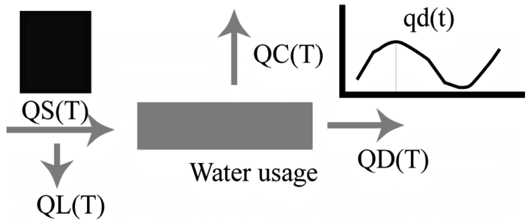

Fig. 1 Water usage model

Infiltration System Model

Integration of infiltration systems to the continuous simulation scheme is achieved by using the continuous accounting model described by Herath & Musiake (1994). Based on numerical simulation of Richards' equation for different trench water heads, a relation between infiltration rate and the water head within the trench is developed as:

$$\frac{Q}{K_o} = a \times h + b \tag{6}$$

where Q is the infiltration rate per unit length of the trench, K_o is the saturated hydraulic conductivity, h is the water level within the trench and a and b are coefficients. The trench system within a grid element is represented as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = i - LK_o(a.h + b) \quad for \quad S \le S_{\max} \tag{7}$$

where i is the input to the trenches, L is the trench length and S is the trench storage. When S is greater than the maximum storage, $S_{\max}$ (= maximum head × width × length × void ratio), the excess becomes the overflow. Equations (6) and (7) represent a lumped model for the behaviour of an infiltration system consisting of a number of trenches within each grid element.

DATA

Catchment Information

The model described was applied to a subcatchment of the Ebi River basin of Chiba prefecture, Japan, shown in Fig. 2. The digital elevation model (DEM) was prepared from the numerical elevation data sets of the Japan Geophysical Survey Institute. A SPOT scene (20m × 20m resolution) was classified using a supervised classification method to obtain the land use map. The map obtained was re-gridded at 50 m resolution to match with the base topographic map. Different land use classes and their extent are given in Table 1. From the detailed plans (1:2500 scale) the pervious and impervious area ratios for different land-use categories were established. From the above, the pervious fraction was set to 35% for dense residential areas, 50% for residential areas, 0% for water bodies and 100% for other land-use categories. The soil distribution map was digitized to obtain the soil class data layer. The moisture-suction relation for different soils was measured in the laboratory from field soil samples. In the present study, the field soil conductivity was estimated from the field borehole test method described in Herath *et. al.,*(1990). The moisture-suction curves were approximated using the Van Genuchten equation given in (8). The soil properties used in the simulation for two types of soils found in the catchment are given in Table 2.

$$S_e = \left[1/\left\{1 + \left(\alpha \mid \varphi \mid^{\beta}\right)^n\right\}\right]^m \tag{8}$$

where α, β, n and m are parameters for the soil and S_e, the saturation degree, is given by $S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$ where θ_s is the saturated moisture content, θ_r is the residual moisture content, θ is the moisture content and φ is the corresponding soil suction. Population distribution data available for administrative units were first brought into the GIS and overlaid on the whole catchment area map. Water demand per person was determined from the annual water usage records of the city office and adjusted for the present catchment population to arrive at the figure of 345 l/day/person. The agricultural water pumping records available for monthly data were distributed for the capture zone of each pump.

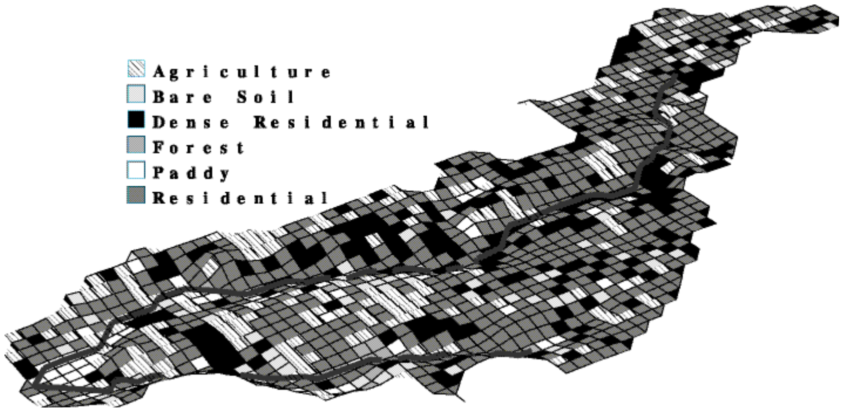

Fig. 2 Maehara sub-catchment with landuse distribution (grid size 50 m × 50 m).

Table 1 Land-use distribution in Maehara sub catchments.

Land use type	Area fraction
Agriculture	0.17
Bares soil	0.06
Dense residential	0.22
Forest	0.01
Paddy	0.05
Residential	0.50
Total Area	3.57 (km^2)

Table 2 Soil hydraulic properties used in the simulation.

Soil type	α	m	N	θ_s	θ_r	K_o($cm\ s^{-1}$)
Kanto Loam	2.11	0.401	1.670	0.684	0.545	0.00457
Alluvial deposits	1.56	0.348	1.534	0.571	0.247	0.00001

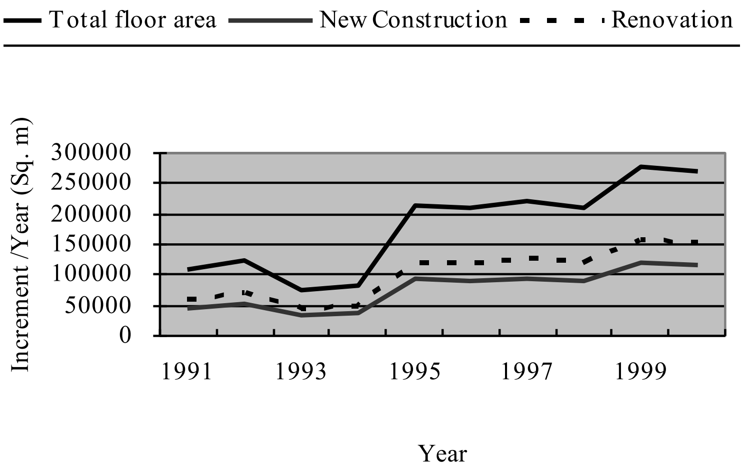

Fig. 3 Floor area increase in Maehara catchment.

Urban renewal

The urban expansion of the whole Ebi River basin is shown in Fig. (3). The ratio of new construction to total new area (which results from both new construction and reconstruction) is 43% in Funabashi district compared with 28% for the whole country, which indicates an active new housing construction programme in the basin. The increase of floor area due to new construction amounts to 0.2–0.6% of the basin area annually. Compared to the 1990 land cover categories, this translates into a 1.2% increase in dense residential areas and a 5.3% increase in residential areas during the 1990s due to the new constructions. Similarly, total renovation areas account for about 9% during the same decade. Here we investigate the effect of this urban expansion on the water cycle and how introducing artificial infiltration of rainfall can minimize these changes. For the purpose of infiltration facility installations, both renewal and new construction areas are targeted. In general, a trench density of about 1 m length for 10 m^2 area is considered practical in designing drainage networks as the ordinary drainage system can be converted to infiltration trenches quite easily.

RESULTS

The model application was carried out for 1992 data, only after calibrating the saturated hydraulic conductivity of the Kanto Loam soil, which was adjusted to 0.0057 cm s^{-1} by comparing discharge hydrographs for the months of April and May. A validation result for the month of October, 1992 is shown in Fig. 4. The results show good agreement between the observed and computed hydrographs for both high and low-flow conditions. In order to assess the effectiveness of infiltration systems, the following scenarios for runoff conditions were analysed: (a) for 1992; (b) for 2000 without any land use changes; (c) for 2000 with land use changes; and (d) for 2000 with infiltration systems and land use changes. The purpose of the scenarios corresponds to: (a) model validation, while for (b)–(d) providing the reference output data for comparison with year 2000 rainfall conditions; assuming (b) no urbanization

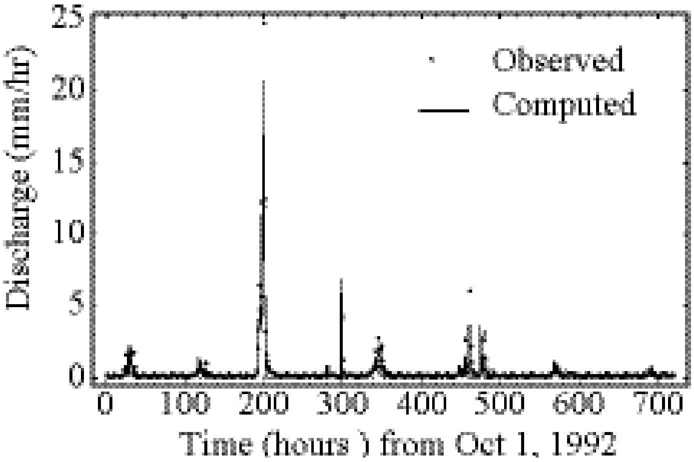

Fig. 4 Comparison of observed and computed discharge for the year 1992.

process; (c) the effect of urbanization; and (d) the effect of infiltration systems. Figure 5 shows the water balance components for the 1992 conditions. The total input by precipitation and water supply are comparable while the outflow components, drainage, overland flow, ground water recharge and evaporation are in comparable proportions. The components of the hydrological cycle that change under different scenarios are shown in Fig. 6. As can be seen, the increased overland flow due to land use change is reduced to a level below no land use change conditions and the recharge to the groundwater increases beyond the 'no land use change' conditions. To investigate the effect of infiltration facilities at high flows, duration curves were prepared for conditions of no land use change (nc), land use change according to urban expansion (lc) and land use change accompanied by infiltration facility installations (lci). Figure 7 compares the lc–nc and lci–nc, relative duration curves. As can be seen, the increase of high flows, which would be significant for about 500 events, can be eliminated by the infiltration systems while the base flow throughout the year is increased.

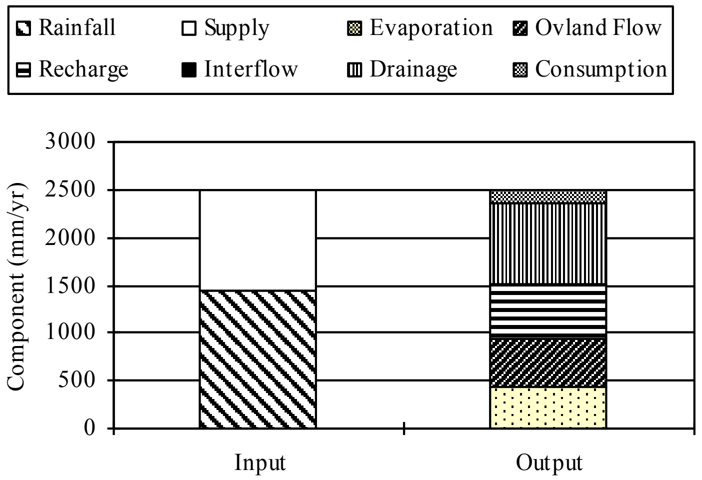

Fig. 5 Water balance components for scenario without land use change.

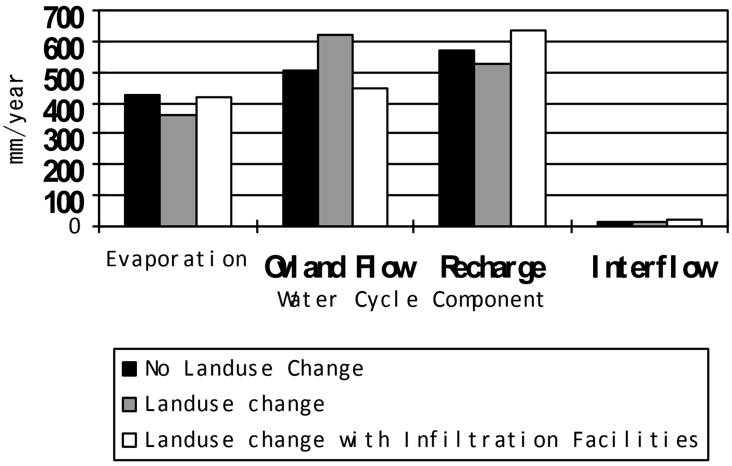

Fig. 6 Main water balance components affected by land use change and recovery measures.

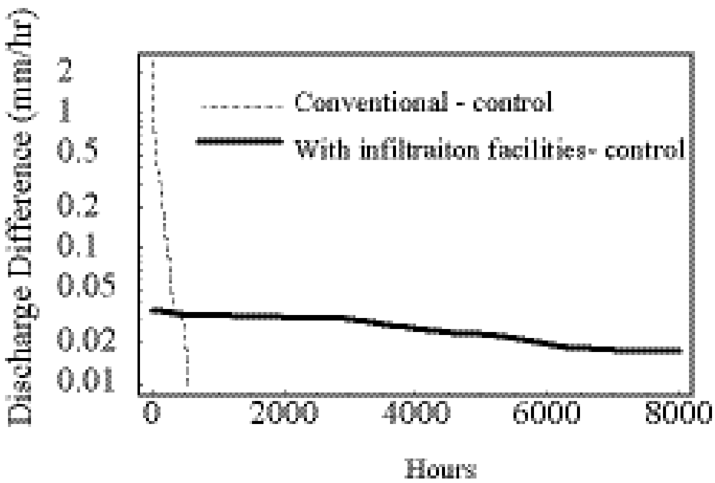

Fig. 7 Relative duration curves where control refers to no land use change scenario.

CONCLUSIONS

The gradual increase of impervious area of an already urbanized catchment can produce significant changes to the hydrological cycle. The change of conventional drainage facilities to infiltrating drainage systems during new constructions and urban renewal can not only revert these adverse impacts but also increase the recharge to groundwater and decrease direct runoff compared to the existing conditions. They are also expected to provide significant impacts during the times of floods, reducing the load on the receiving systems.

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