MONITORING AND MODELING OF URBAN HYDROLOGY – A CASE STUDY OF TWO JAPANESE CATCHMENTS

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ABSTRACT

Urban water cycle is driven by rainfall and water supply for municipal and industry use. These two inputs are found to be comparable in two urban catchments in the suburbs of Tokyo, Japan. In order to model urban water cycle components for long-term impact assessment and integrated water management, a distributed hydrological model has been constructed to account for both natural water cycle and artificial water cycle. The water movement resulting from rainfall input is simulated by governing equations whereas the human water usage and discharge is modelled using unit hydrograph concept. The model is applied to urban catchments where the components of natural water cycle are continuously monitored. The water supply and discharge characteristics are estimated through statistics as well as through periodic measurements. The various components of the simulated and monitored water cycle are found to agree well. Using the model, long term variations in hydrological responses as well as impacts of artificial infiltration are analysed.

KEYWORDS

Artificial water cycle, Infiltration trench, Mathematical modelling, Urban hydrology, Water supply and drainage

INTRODUCTION

Due to the varied land use and water uses, the urban catchments have a response distinctly different from that of natural catchments. A systematic estimation of the different components of the urban water cycle was carried out by Musiake et. al. (1990) for the Shakuji river basin in Nerima Ward, Tokyo. The study made it clear that the amount of water entering catchment in the form of water supply is nearly equal to annual rainfall, and that untreated raw sewage and leakage from water supply mains account for the bulk of river low flows in the study area. It also showed that understanding this flow mechanism as well as quantifying various components of the system are fundamental to the understanding of hydrologic environment in urban areas. Among the different hydrological processes that constitutes urban hydrology, some depend on the physical laws governing the water movement, whereas the others are determined by the practice of water users. Based on this, it is possible to consider two water cycles resulting from the two major inputs to the catchment, namely the rainfall and water supply, as natural and artificial water cycles. As it is physically impossible to equip all the flow paths with monitoring equipment to estimate the different components of water cycle and their interactions, a combined approach of monitoring and modelling is necessary for a full representation of urban hydrological cycle. In this study, based on field observations, an efficient distributed hydrological model is developed to simulate main components of both natural and artificial water cycle in urban catchments. Using the model, long-term catchment responses to infiltration facilities are investigated in an urban catchment in the suburbs of Tokyo, Japan.

MODELING URBAN WATER CYCLE

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 it is possible to assume that each element is homogeneous in relation to physical characteristics and water supply pattern, it is possible to model water movement employing governing equations for transport of each component of the hydrologic cycle. To model urban hydrology, main variables to be treated are, 1). Topography which determines surface slopes and drainage, 2). Landuse which can be used to estimate perviousness, surface roughness, evapotranspiration and surface storage, 3). Soil distribution for estimating soil hydraulic properties, 4). Catchment boundaries for rainfall response modelling, 5). Water supply boundaries for estimating inputs from water supply, and 6). Drainage network consisting of natural drainage paths and water discharges.

Complete physically based descriptions of these processes using governing equations result in complex coupled systems requiring extensive computer resources. Also when the model domain is very finely discretized, the spatial heterogeneity could be represented adequately, but would in turn lead to high computational demands making the approach unattractive for practical use. Previous modelling using such complete models could simulate the total response well, but the excessive computational requirements made continuous simulations more than a few months difficult (Herath et. al., 1996). Therefore, the modelling approach should be viewed as a compromise between the model complexity and spatial resolution of the input data. Computational efficiency is important as the model is to be used for long-term impact assessment as well as for repeated simulations required in urban drainage design practice.

In the present study, the approach adopted is to use high-resolution spatial information, but to use simplified approximations to the governing equations for computational efficiency. An important factor taken into account was the potential size of the catchments where such detailed studies would be required. The target catchment size is considered to be of the 10 sq. km. order considering river basin management aspects. Two characteristics in the artificial water cycle influence the selection of temporal resolution to be adopted in simulation. The first is that unlike flow resulting from rainfall, which has a very high variability, water supply and discharge due to human water usage tend to be rather uniform throughout the year. Second is that many components of water supply, pumping, drainage and other water related activities are generally not monitored continuously, making it difficult to treat these processes at high temporal resolutions. Therefore hourly time step is considered for the simulation of the complete model, even though sub processes can be simulated at a higher resolution. Based on the above considerations, an explicit solution scheme is used in the modelling.

MATHEMATICAL MODEL FOR URBAN CATCHMENT

For the mathematical model, the catchment is discretized by a uniform grid on the horizontal plane, and at each grid a layered column represent the surface, unsaturated and groundwater domains. At first, from the digital elevation model (DEM) of the catchment, flow direction for each grid is computed as the steepest gradient considering the 8 neighbouring grids. This flow direction map is an essential component of the simulation model and the following notation is adopted in the paper to describe its usage. The flow direction vector at *n*th grid (G_n) is denoted by u_n, and $G_n u_n$ represents the adjoining grid to which water from grid G_n would flow under gravity. A similar map for the artificial water discharge is prepared from drainage network for the catchment and is denoted by u_a. Once the flow direction data sets are prepared, a flow accumulation grid is computed such that each grid has a value representing the accumulated flow at the grid if a unit discharge is assigned to every grid (Gn) and flow to the $G_n u_n$ grid. Using the flow accumulation grids two computational orders are constructed such that grids are sorted according to the flow order. For natural water cycle this means the flow order $1..N$ is arranged such that at *i*th grid G_i $(1 < i < N)$ the subset $N - i$ will not contain any grid that would lie in the flow path up to G_i. A similar flow order is prepared for the grids where river flows as $1..NT$ corresponding to flow accumulation. The computational procedure adopted in the mathematical model together with the concepts and equations for each process is described below.

Surface flow. Surface characteristics at each grid is described by, land cover (*lc*), impervious ratio which is the ratio of paved area to pervious area (*ifr*), soil type, maximum storage for pervious areas including depression areas ($sp_{\max}$) and maximum storage for impervious area ($si_{\max}$). 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 yields the following,
For the impervious area,

$$\frac{\partial (si)}{\partial t} = R \times ifr - Ds_i \qquad (1)$$

where, R is the rainfall, Ds_i is the surface discharge from impervious area and si is the surface storage.

$$Ds_i = si - si_{\max} \text{ for } si > si_{\max} \text{ and } Ds_i = 0 \text{ otherwise.} \qquad (2)$$

For the pervious fraction,

$$\frac{\partial (sp)}{\partial t} = R \times (1 - ifr) - Ds_p - I \qquad (3)$$

where I is the infiltration, Ds_p is the surface flow and sp is the pervious storage.

$$Ds_p = sp - sp_{\max} \text{ for } sp > sp_{\max} \text{ and } Ds_p = 0 \text{ otherwise.} \qquad (4)$$

In estimating infiltration rate, first the excess rainfall amount where the rainfall rate is greater than the saturated conductivity is computed assuming exponential distribution of rainfall during the rainfall interval as,

$$Rx = (1 - ifr) \times R \times e^{-Ko/R} \qquad (5)$$

The maximum infiltration capacity of soil is estimated as,

$$Infcap = K(\theta)\frac{\partial H}{\partial z} + (\theta_0 - \theta)\Delta z \qquad (6)$$

where H is the total water head in the subsurface layer beneath surface and θ_0 is the saturated moisture content, θ is the moisture content and ΔZ is the thickness of the sub surface layer. From equations (5) and (6) the infiltration I is estimated as,

$$I = R \times (1 - ifr) - Rx \text{ for } I > Infcap\ I = Infcap \text{ otherwise} \qquad (7)$$

Evaporation from impervious area is estimated as,

$$E_{imp} = Ep \times ifr \text{ for } E_{imp} > si;\ E_{imp} = si \text{ otherwise} \qquad (8)$$

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

$$E_{per} = Ep \times \alpha \times (1 - ifr) \qquad (9)$$

where α is a parameter modifying potential evaporation to actual evaporation E_{per} for the pervious area. For most Japanese catchments a value of α = 0.7 can be used. When $Eper > sp$, surface storage of pervious area, the remainder is removed from the subsurface soil moisture. Infiltration is modelled using moisture based governing equation for the near surface layer as,

$$\frac{\partial SS_k}{\partial t} = Int.u_{k-1} + I_k - Eps_k - \mathrm{Re}_{k,i} - Int_k \qquad (10)$$

where SS is the subsurface storage, Int is the interflow in the subsurface domain, Re is the recharge to groundwater and Eps denote water removal due to evaporation given by $Eper - sp$ when the quantity is >0. Recharge and interflow are estimated by equations (11) and (12) respectively.

$$\mathrm{Re}_k = \int_0^{\Delta t} K(\theta)dt \qquad (11)$$

$$Int_k = \int_0^{\Delta t} slope.K(\theta)dt \qquad (12)$$

Equations (11) and (12) are simplified infiltration equations resulting when the pressure term of Richards' equation is neglected, assuming that gravity term is dominant. Equations (11) and (12) have been found to be adequate for Japanese climatic and soil conditions in previous applications (Herath et. al., 1991) and has been verified for different soil characteristics through detailed numerical simulation (Ni et. al, 1993). Ground water movement is modelled along flow paths using Darcy's law as,

$$\frac{\partial S_g}{\partial t} = R_k + 0.5K_g\left(h_{k+1} + h_k\right)\frac{\left[h_k - h_{k+1}\right]}{\Delta X} - W_k \qquad (13)$$

where S_g is the groundwater storage, K_g is the saturated conductivity for groundwater, ΔX is the grid size and W_k is the groundwater withdrawal.

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 for the purpose water is used. The approach adopted in the present study is to distribute the water supply or demand for each grid based on landuse 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 Figure 1. The discharge at any time *t* is expressed using the following equations.

$$QS_{l,i}(T) = qs_l \times \rho_i \qquad (14)$$

$$QL_{l,i}(T) = QS_{l,i}(T) \times lc_l \qquad (15)$$

$$QC_{l,i}(T) = qc_l \times \rho_i \qquad (16)$$

$$QD_{i,i}(T) = QS_{l,i}(T) - QL_{l,i}(T) - QC_{l,i}(T) \qquad (17)$$

$$qd_{l,i}(t) = QD_{l,i}(T) \times f(t) \qquad (18)$$

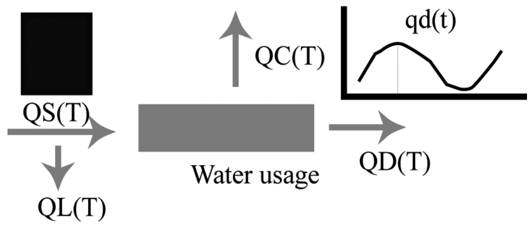

Figure 1. Water usage model

where *T* is the time period for which supply estimations can be made (e.g. a day), subscripts *l* and *i* denote the landuse and grid identity respectively, *QS* is the supply over time *T*, *qs* per capita supply (e.g. water supply per person), ρ is the density (e.g. population at the *i*th grid), *QL* is the transmission loss, *lc* is the loss coefficient, *QD* is the total discharge, *qd* is the discharge at time *t*, *f(t)* is the normalised unit discharge function at the point of interest for artificial water use.

Computational procedure. The processes described through equations (1) to (18) are carried out in the computational order for the natural water cycle represented by u_k vector in the 1..N order described above for all grids except for the stream network. The surface (equations (2) and (4)) and subsurface flow accumulation is carried out using the u_k order for natural flows up to the stream network. The water discharges (*qd*) are accumulated over 1..NT order until they reach the stream network. These flows together with the accumulation of groundwater discharge computed using Darcy's law for river grids and adjacent catchment grids form the lateral inflow along the river network. The river flow is computed using the +Kinematic wave model.

MODEL APPLICATION

The model described was applied to a catchment located in the Ebi river basin of Chiba prefecture, Japan. Two stream gauging stations were set up, one at the main stream at a point representing a catchment area of

8.26 km^2 and another at a tributary point covering a catchment area of 3.25 km^2 (Maehara sub catchment). Fig. 2 shows the catchment together with the measuring point locations. In addition to the stream flow, rainfall, ground water levels and climatic variables have been measured at locations shown in Figure 2. The catchment is not served by drainage, and household, commercial wastewater is directly discharged to streams together with return flow from cultivated land.

Catchment Information

Topographic Data. To apply the model, a GIS of Ebi river catchment was prepared. The topographic data were obtained from the numerical elevation data sets of Japan Geophysical Survey Institute. To check the validity of the data set, flow directions were estimated from the elevation data set and the rivers were generated. Then this was overlain with the digitised actual river and found to be agreeing well.

Landuse Data. A SPOT scene (20m x 20m resolution) was classified using supervised classification method to obtain the landuse maps. To check the accuracy of the classification, aerial photos of a section of the catchment was digitised and the total landuse areas were compared and found to agree within about 2% for different land classes. The map obtained was re-gridded at 50m resolution to match with the base topographic map. Different landuse classes and their extent is given in Table. 1.

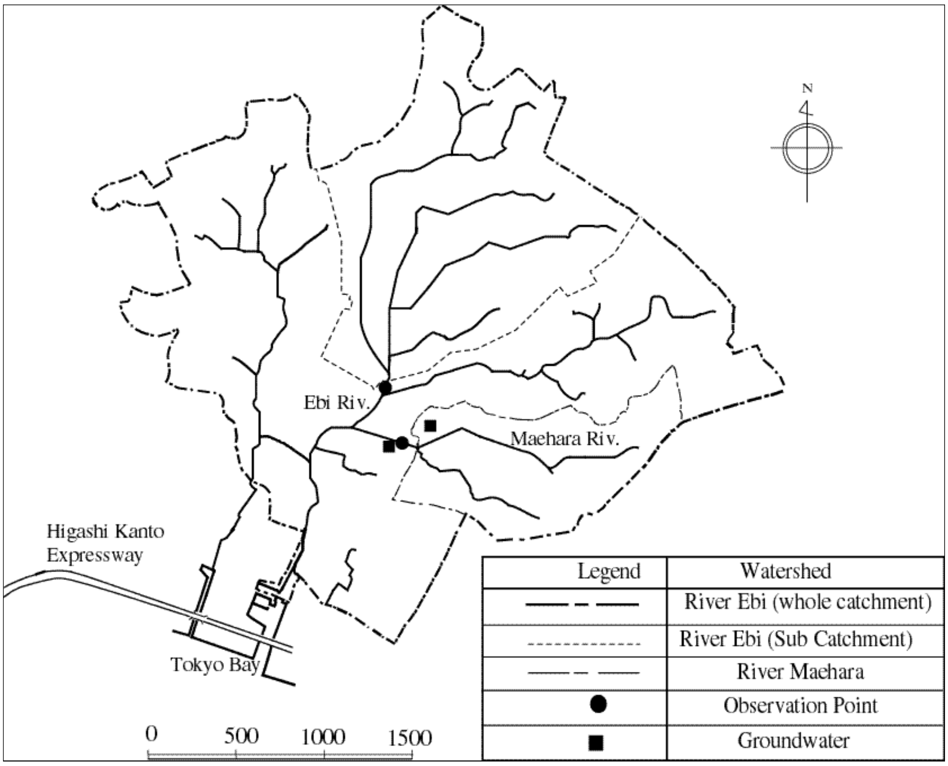

Fig.2 Monitored Urban Catchment

Perviousness. From the detailed plans (1:2500 scale) the pervious and impervious area ratio for different landuse categories was established. From the above, pervious fraction was set to 35% for dense residential areas, 50% for residential areas, 0% for water bodies and 100% for other landuse categories.

Soil Data. Soil distribution map was digitised 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 field borehole test method described in Herath et. al., 1990. The moisture-suction curves were approximated using Van-Genuchten equation given in (19). The soil properties used in the simulation for two types of soils found in the catchment are given in Table 2.

Table 1. Landuse distribution

use type	Area fraction (Maehara)	Area fraction (Ebi)
iculture	0.17	0.24
:es soil	0.06	0.09
Residential	0.22	0.12
orest	0.01	0.07
addy	0.05	0.15
idential	0.50	0.33
al Area	3.57 (km^2)	6.8 (km^2)

$$S_e = \left[1 / \left\{ 1 + \left(\alpha \mid \varphi \mid^{\beta} \right)^n \right\} \right]^m \qquad (19)$$

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 and θ is the moisture content.

Population Distribution and Water Supply Data. Population distribution data available for administrative units were first brought in to 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 command areas under each pump.

Table 2. Soil hydraulic properties used in the simulation

Soil type	α	M	N	θ_s	θ_r	K_o(cm/s)
Kanto Loam	2.11	0.401	1.670	0.684	0.545	.00457
Alluvial deposits	1.56	0.348	1.534	0.571	0.247	.00001

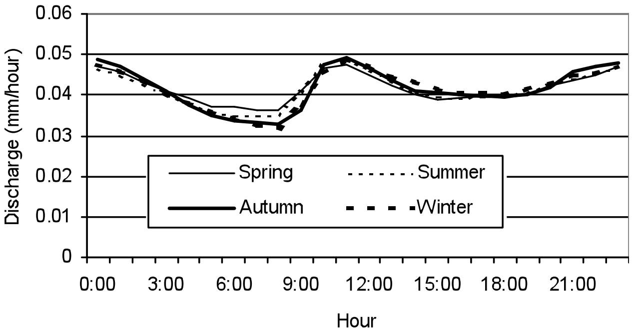

Figure 3. Unit discharge function for artificial discharge at gauge A

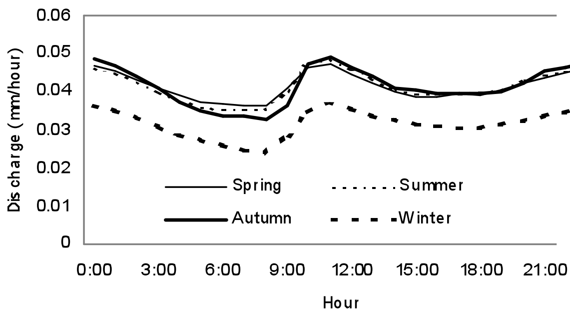

Figure 4. Unit discharge function for artificial discharge at gauge B

Measurement of the discharge pattern. From the stream flow observations, a distinct diurnal pattern of the stream flow could be observed. Diurnal pattern of artificial water cycle response at the measuring points were obtained after subtracting groundwater base flow from the stream records selected from low flow periods. These flows were averaged for the four seasons and normalised to derive the unit response to daily water supply. Figures 3 and 4 show the unit discharge functions for artificial water discharge derived from stream flow observations at gauging stations A and B respectively.

Simulations

Two sub-catchments corresponding to discharge gauges A (Maehara sub catchment) and B (Ebi sub-catchment) in Figure 2 were considered separately for the simulation study. First using 1992 data, the model performance was checked. The only parameter calibrated was the saturated hydraulic conductivity of Kanto Loam soil, which was adjusted to .0057 cm/s by comparing discharge hydrograph at gauge A. Continuous simulation from 1992 to 1995 for model verification and scenario simulation for assessing impact of infiltration systems on the reduction of direct stream discharge and groundwater enhancement for 3 different trench installation plans were carried out.

RESULTS

Model verification

Simulations were carried out for the rainfall and evaporation parameters for the years 1992 to 1995. Figures 5 and 6 show samples of observed and computed discharge hydrographs for the month of October, 1995 at station A and for the month of September, 1995 for station B. Good agreement between the observed and computed hydrolgraphs can be seen for both low-flow conditions. The Figure 7 shows the annual water balance components for both Maehara and Ebi catchments obtained from simulations.

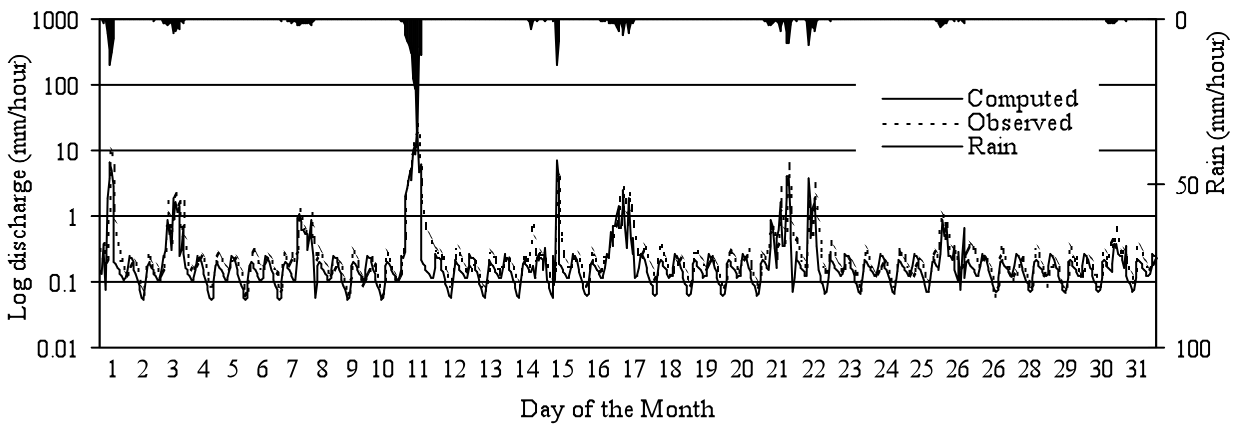

Figure 5. Comparison of computed and observed hydrographs at gauge A for the month of October, 1995

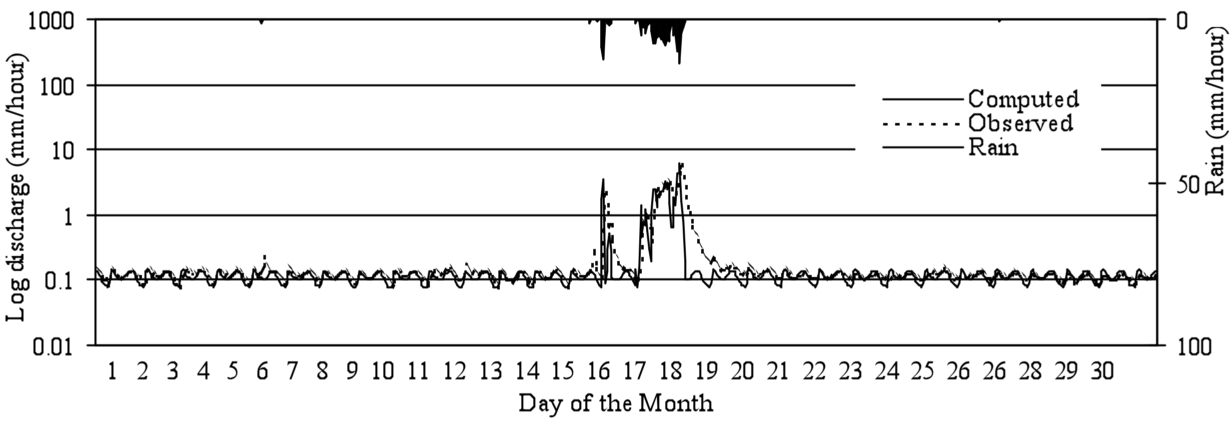

Figure 6. Comparison of computed and observed hydrographs at gauge B for the month of September, 1995

Scenario Simulation

Effect of Infiltration facilities on peak reduction. Infiltration trenches help in recharging the ground water and reducing the direct discharge to streams from impervious areas. The infiltration capacities of these trenches can be estimated from soil hydraulic properties and dimensions of the facilities (Herath et. al., 1994). Figure 8 shows the peak reduction due to infiltration facilities installed in urban residential areas for three cases of trench lengths equal to 50 m, 100m and 200 per grid, which account for 1%, 2%, and 4% of surface area, against a peak 50 mm/hr design rainfall of 24 hr duration. Figure 9 shows the total discharge reduction with respect to the normal conditions (without infiltration facilities) in percentage, for the same rainfall conditions for different trench installation plans.

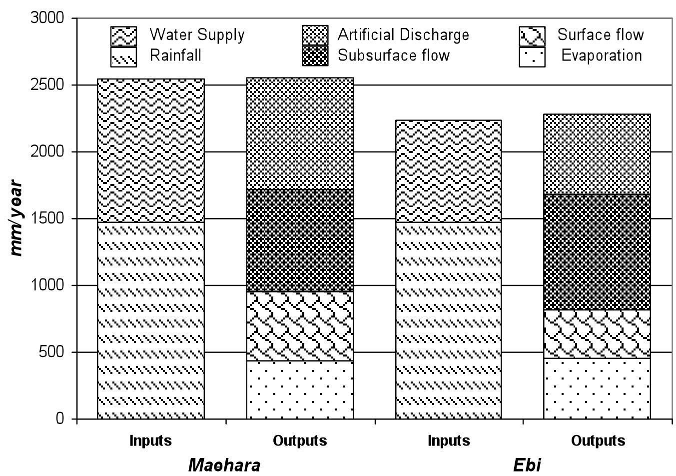

Figure 7. Annual water balance component for Ebi and Maehara catchments for 1995

Effect of infiltration facilities on groundwater recharge. Groundwater recharge from infiltration facilities leads to increased river base flow. Figure 10 compares the base flow increase at the end of a 4 year term starting from 1995 for simulation conditions with and without infiltration facilities, at Maehara basin for infiltration trenches covering 1% of the surface area in residential areas.

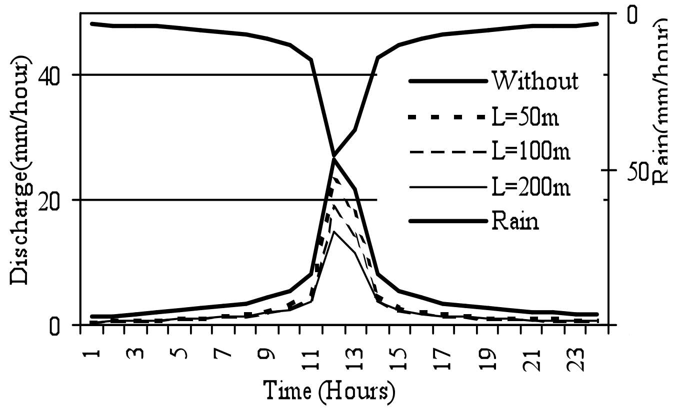

Figure 8. Reduction of peak discharge due to infiltration facilities for Maehara catchment

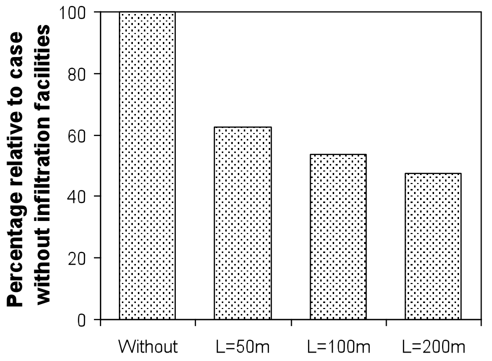

Figure 9. Total surface flow reduction effect by different trench length configurations

CONCLUSIONS

A distinct difference between the diurnal pattern of artificial water discharge of adjoining urban catchments could be seen from the observations. This can be attributed to landuse differences as Maehara catchment, which is predominantly a residential area, compared to Ebi catchment which is a mixed residential and agricultural area (Table. 1). This variability is explained by the present modelling approach. Even though the normalised diurnal cycles in two catchments have the same form (figures 3 and 4), the total catchment response estimated from them considering the water discharge volumes at each grid, shows larger amplitude for residential catchment (figures 5 and 6) as the total discharge volume is higher there (figure 7). Further the seasonal variation of agriculture return flows can also be accommodated easily as shown in figure 4.

In the proposed model simplified governing equations are to describe the natural flow components and whereas a lumped-response function, similar to unit hydrograph concept is used to estimate the temporal distribution of drainage. The simulated hydrographs for both low flows and high flows agree well with those observed. As low flows are dominated by the water discharges and the high flows are dominated by natural water cycle components resulting from rainfall response, it can be concluded that model can simulate both

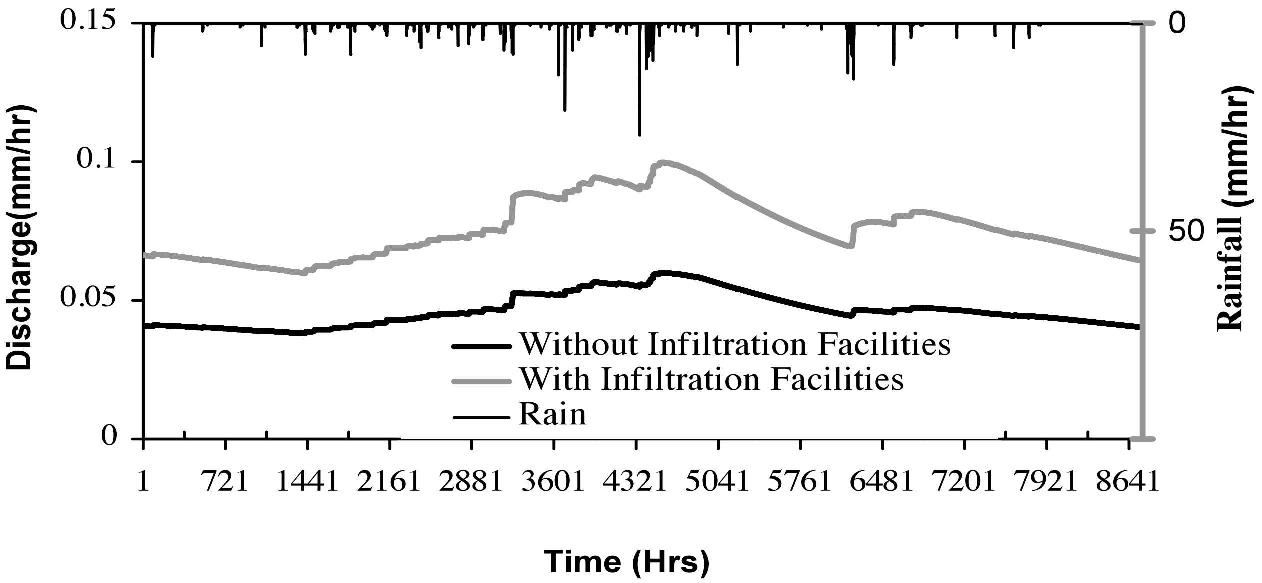

Figure 10. Effect of Infiltration facilities with different trench lengths

natural and artificial water cycle components adequately. A significant flood peak reduction, total flood volume reduction and low flow increase could be observed as a result of installing infiltration trenches in urban residential areas when infiltration trenches equal to 1% of urban area are implemented.

The model required only about 7 min for one-year simulation at 1-hour time steps in a 300 MHz PC computer, for 72 x 46 grid catchment at 50 m grid resolution. Due to this high efficiency, it is possible to use the modelling approach to carry out analysis related to long term effects of urbanisation and effect of different measures to improve the urban environment considering spatial characteristics as well as phased implementation plans.

REFERENCES

Herath S., Hirose N. and Musiake K. (1990) *A computer package for the estimation infiltration capacities of shallow infiltration facilities,* Proc. 5th International Conference on Urban Storm Drainage, Japan, pp. 111-118.

Herath S., Musiake K., Hirose N. and Matsuda S. (1992). *A process model for basin hydrological modelling and its application,* Proc. Japan Annual Conference of Society of Water Resources and Hydrology, pp. 146-149

Herath S. and Musiake K. (1994). *Simulation of Basin Scale Runoff Reduction by Infiltration Systems,* Water Science and Technology Journal, Vol.29, No. 1-2, pp 267-276.

Herath S., Musiake K., and Hironaka S.(1996). *Development and Application of a GIS based Distributed Catchment Model for Urban Areas*, Proc. 7th International Conference on Urban Storm Drainage, Germany, pp. 1695 - 1700.

Ni G., Herath S., Musiake K. (1993). *Simulation of Subsurface Flow in a Hillslope*, Proc. Japan Annual Conference of Society of Water Resources and Hydrology, pp. 246 – 247.

Musiake K., Okamura J. and Matsumoto J. (1990).*The Urban Hydrological System with Shallow Infiltration Facilities – A Case Study of an Area in TOKYO Metropolis*, Proc. 5th International Conference on Urban Storm Drainage,Vol.1, pp.113-118.