特 集 2
研究解説

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Impact of Urbanization on Hydrological Cycle and Remedial Measures
都市化による水循環の変化と保全対策

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Urbanization adversely affect the hydrological cycle resulting in higher peak discharges and reduced low flows at receiving waters. Quantification of this phenomena using a simplified process model is described, based on a case study. Remedial measures consisting of infiltration systems and ground water diversion are introduced and their effectiveness assessed through simulation.

1. Introduction

During the past half a century, especially since the end of second world war, rapid urbanization has been common in many parts of the world. New suburban cities grow and expand to accommodate growing demands of population concentration into large cities affecting natural water regime through different mechanisms. On one hand, water demands by growing populations make it necessary to develop new resources such as ground water extraction which create long term associated problems in land subsidence and sea water intrusion. Flood protection works make rivers artificial, and together with industrial pollution, deprive the inhabitants of recreational functions of urban rivers. On the other hand, loss of natural infiltration areas and expansion of impervious areas affect the water cycle in the urban areas resulting in increased peak discharges and reduced river low flows.

The present paper discusses this last aspect, namely changes to natural hydrological cycle, based on mathematical modeling of the hydrology of a residential city.

2. Factors Affecting Hydrological Cycle

The prominent changes to the hydrological cycle are caused by the following factors,

1) Increase of impervious areas.
2) Loss of natural retention areas such as paddy fields due to urban construction.
3) Modification to the drainage system, which usually result in rapid concentration of storm discharge to receiving waters.
4) Reduction of natural infiltrating areas.
5) Changes in soil hydraulic properties as a result of removal of porous top soils and its replacement by compacted soils.
6) Modification to the topography which alters the drainage paths and subsurface water movement.

Factors 1, 2 and 3 make the direct runoff much larger after the urbanization, compared to pre-urbanization conditions. The runoff volume is made larger by the increased impervious areas, while factors 2 and 3 contribute to reduction of time of concentration which increase the peak discharge rate. Factors 4 and 5 result in reduced infiltration and hence lower recharge to ground water compared to undeveloped conditions. This in turn make lower river flows during dry weather or no flow at all in extreme cases. During the urbanization process landscape is altered by cut and fill, which disturb the natural soil structure. In Kanto Loam soils, laboratory tests show that soil retention capacity, defined by the moisture-suction curve, is reduced by 30%–50% while soil saturated conductivity is reduced by about 2 orders of magnitude. This means that even newly created parks and pervious areas built on filled areas would have a lesser infiltration capacity compared to undisturbed pervious areas.

While peak discharge effects are visible within a short time span, ground water depletion effects take much longer time to be noticed. Coupled with the gradual process of urbanization, this make it difficult to prepare

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for these changes through experience alone, until it is too late. Therefore modeling of hydrological changes, is an important issue in hydrology, for assessing impact of proposed urbanization schemes on environment as well as for implementing remedial measures. Remedial measures aim to minimize the adverse effects on the hydrological cycle due to urbanization by restoring some of its lost functions. Infiltration systems, which artificially infiltrate part of the storm discharge is a low cost solution for such restoration, and their effectiveness can be evaluated through coupled mathematical models.

3. Modeling Issues

Basin hydrology was traditionally done using conceptual models due to the difficulties in the handling of a number of complex and inter-related hydrological processes as well as large spatial variation of parameters affecting such processes. With the advent of powerful computers, distributed physically based hydrological models, simulating coupled systems of hydrological processes have been developed. However, the major drawbacks of such models are the large amount of data required for model calibration as well as needs for specialized computer resources. For industry practice, simplified process models, which can be used in repeated simulations to arrive at optimum development strategies are very much desired.

A model had been developed for basin simulation of dominant hydrologic processes and was applied for the assessment of hydrological changes in a new residential city under construction. Main features of this work, which had been carried out in corporation with Japan Housing and Urban Development Corporation, are described in the following sections.

4. Hydrological Model

The model is based on the following two major procedures.

1) Basin is represented by a top soil layer of about 2m depth, and underlying aquifers in the vertical direction. The intermediate soil transfer water at a constant soil moisture content.
2) In the horizontal plane, basin area is divided into a number of sub catchments and each sub catchment is divided into blocks representing different soil types.

The first criterion is supported by continuous observations of soil moisture variation at different soil depths in humid climates such as that found in Japan (Ando et. al., 1983, Musiake et. al., 1987). These observations show that on hill slopes at a depth of about 1.5m–2m the moisture content remains almost constant throughout the year. Using the second criterion, a basin can be finely sub divided into many blocks to represent more spatial variation. These blocks form a network representing the catchment hydrology. The components of basin flow which constitute the model are shown in Fig. 1.

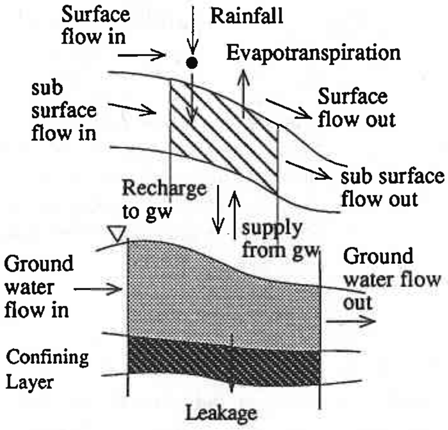


Fig. 1 Components of the Hydrological Processes Modelled

Transfer of water from one block to another depends on the types of blocks being connected as well as their respective states. For example, transfer of water between two ground water blocks depends on their water heads and transmissivity between the two aquifer areas. Rainfall and actual evaporation values are supplied as input data. The computations proceed as follows. Input to each surface block is computed as summation of rainfall and surface flow from adjoining blocks. Storage is updated due to incoming subsurface flow from neighboring blocks.

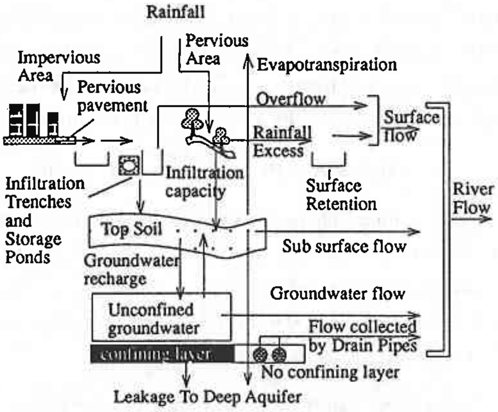
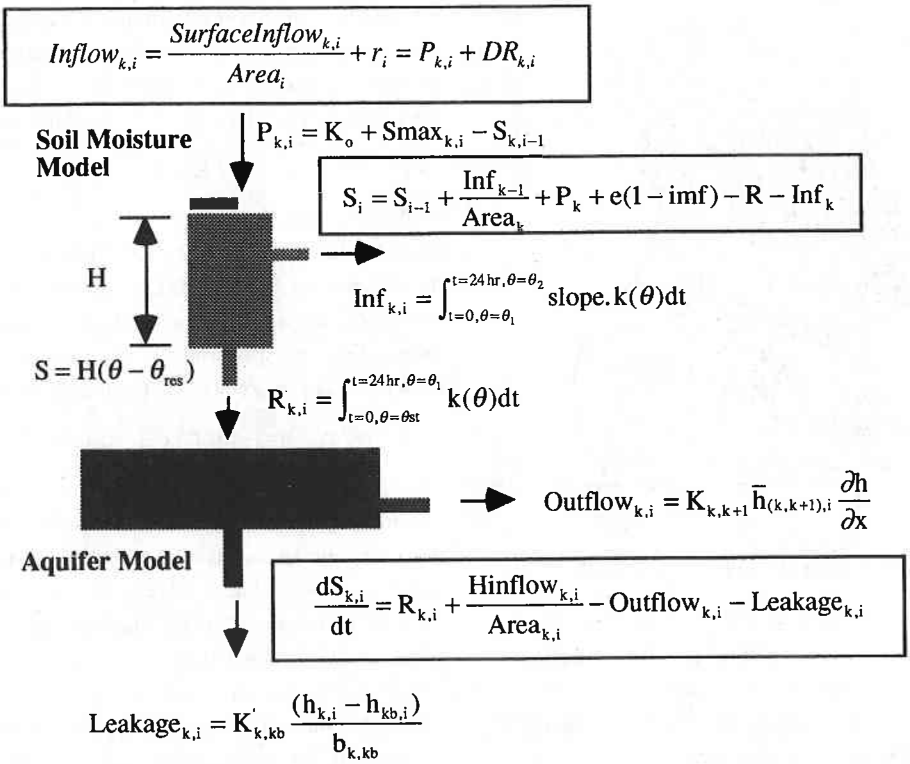


Fig. 2 Model components including artificial infiltration systems and pervious pavements



$$Inflow_{k,i} = \frac{SurfaceInflow_{k,i}}{Area_i} + r_i = P_{k,i} + DR_{k,i}$$

$$P_{k,i} = K_o + Smax_{k,i} - S_{k,i-1}$$

$$S_i = S_{i-1} + \frac{Inf_{k-1}}{Area_k} + P_k + e(1 - imf) - R - Inf_k$$

$$Inf_{k,i} = \int_{t=0,\theta=\theta_1}^{t=24\,hr,\theta=\theta_2} slope.k(\theta)dt$$

$$S = H(\theta - \theta_{res})$$

$$R_{k,i} = \int_{t=0,\theta=\theta st}^{t=24\,hr,\theta=\theta_1} k(\theta)dt$$

$$Outflow_{k,i} = K_{k,k+1}\bar{h}_{(k,k+1),i}\frac{\partial h}{\partial x}$$

$$\frac{dS_{k,i}}{dt} = R_{k,i} + \frac{Hinflow_{k,i}}{Area_{k,i}} - Outflow_{k,i} - Leakage_{k,i}$$

$$Leakage_{k,i} = K'_{k,kb}\frac{(h_{k,i} - h_{kb,i})}{b_{k,kb}}$$

Notation

k	block number	Area	block area
i	time step	θ_{res}	Residual moisture content
θ	soil moisture content = $\theta_{res} + S / H$	$k(\theta)$	Conductivity - moisture content relation for the soil
r	rainfall	R	Recharge to ground water
K_0	Saturated hydraulic conductivity of the soil	Hinflow	Inflow from the adjoining ground water block
DR	Direct run off	outflow	ground water flow
P	Percolation	leakage	leakage to deeper aquifers
S	top soil moisture storage	Inf	Interflow
imf_k	Impervious factor	e	evaporation
h	water head in aquifer	hb	water head in lower aquifer

Fig. 3 Basin model structure and governing equations

The components involved in the computation are shown schematically in Fig. 2, and the governing equations for different model components are shown in Fig. 3.

5. Model Application

The catchment under study covers an area of about 400 hectare of which about 90% remains undeveloped. According to the geological information, confining layer for phreatic aquifer, termed KM3, does not run continuously throughout the basin. Based on the topographical data and the inclination of the KM3 zone, the basin was subdivided into a number of smaller catchments as shown in Fig. 4 for simulation purposes. In order to apply the model to the catchment area, a simple GIS (Geographic Information System) was constructed using basin topography, land use, soil type, soil hydraulic properties and sub catchment boundaries. A similar set of data was generated for the post-development stage using

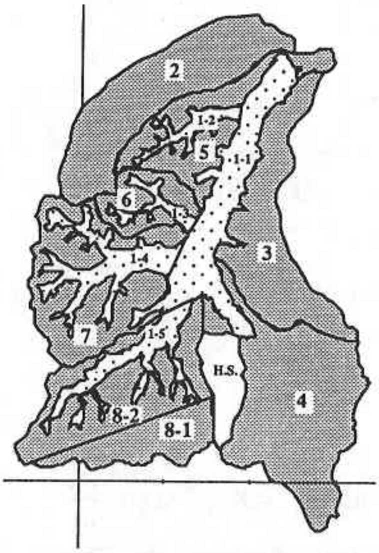


Fig. 4 Division of Catchment for Simulation.

the proposed topography and land use data. By overlaying different data, most of the parameters required for the model can be derived. Soil hydraulic properties were estimated from in-situ permeability tests for different soil types and laboratory measurements of moisture-suction relation from small soil samples. The leakage factor of the confining layer was estimated by calibrating the leakage to the deep aquifer from unconfined aquifer in an experimental catchment located within the study area, denoted by HS in Fig. 4. The model has been validated by testing against the stream flow observations of HS catchment (Herath et. al, 1992).

6. Modeling of Changes due to Urbanization and Remedial Measures

Due to the construction of the new town, topography and land use of the area will be changed. In the areas of sub catchments 2, 3, 4 & 5 the natural stream paths are filled and there will be no streams in these catchments after the development.

Infiltrating trenches and storage ponds are proposed to increase the ground water recharge volume as well as to decrease the direct run-off volume. To evaluate the effects of infiltration trenches, their capacities were estimated for each soil type using a steady state numerical simulation model of Richards' equation given by,

$$\nabla \cdot [k_r(\varphi)\, \nabla (\varphi + z)] = 0$$

The governing equation is scaled with respect to saturated soil conductivity, which makes it possible to estimate the infiltration rate from a trench independent from the soil saturated conductivity. The relation for the infiltration capacity and trench dimensions is simplified for trenches of a given width in the form of

$$q / K_0 = aH + b$$

by fitting a straight line to the values obtained through numerical simulation, where q is the infiltration rate from the trenches per unit length, H is the water head within the trench and a and b are constants obtained by the fitting. Next the performance of a trench system is modeled by applying equation of continuity to the system,

$$dS / dt = i - (q)\, L = i - L\ K_0\, (aH + b)$$

where L is the length of the trenches and S is its storage. The details of estimating infiltration capacities of trenches using numerical simulation and field conductivity tests have been published in detail (e.g. Herath and Musiake, 1987, 1991). This model is then coupled to the hydrological model for each soil type.

In the sub catchments, 1-1, 1-2, 1-3 etc., where the existing stream tributaries will disappear, drain pipes will be installed for collecting the seepage which would otherwise be lost to the confined aquifer deep below. The estimation of the volume that can be collected by the drain pipes was assumed to be 20% of the entire leakage from these areas. Development plans were drawn for the types of facilities that are feasible in the basin, and their merits were assessed using simulation.

7. Comparison of Hydrological Cycle Changes and Effect of Remedial Measures

Simulations were carried out for Natural Condition, Developed Condition and Developed Condition with Infiltration, Storage & drainage pipe facilities, to asses the changes of major components of the hydrological cycle.

The surface, sub-surface and ground water flow paths and their changes after the development were accommodated in the simulation through different network connections. The sub catchment 8 in Fig. 4 is divided into 8-1 and 8-2 in the developed state, as the ground water from the 8-2 block is diverted upstream through an underground dam.

The length of trenches that can be installed in a given area can be estimated by the land use map of the area and the policy for installing infiltration systems. Then the total effect of the infiltration facilities were modeled by

Tabel 1. Description of Items Adopted for Different Infiltration System Installation

Facility	Case 1	Case 2	Case 3
Area covered by storage ponds (ha)	43.75	77.05	77.05
Area of storage ponds (ha)	10.84	12.93	12.93
Area covered by trenches (ha)	22.02	122.69	125.95
Length of the trenches (m)	19156.00	100230.00	101856.00
Area of the pervious pavement (ha)	8.40	36.37	37.03

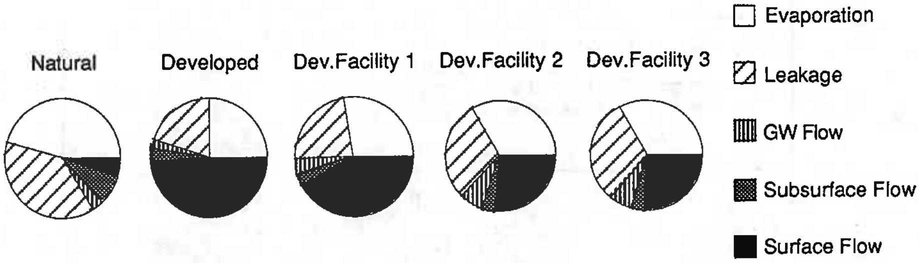


Fig. 5 Magnitude of different hydrologic components for different simulation cases

summing up the trenches in each simulation block according to the land use and soil type distribution. Various plans for the installation of infiltration systems were considered according to the ease of installation within a given land use type. Table 1 shows details of three infiltration system schemes analyzed. Case-1 employs less infiltration systems, while Case-3 employs more infiltration systems.

Fig. 5 shows the relative magnitudes of various components of the hydrological cycle for these three simulated conditions in addition to natural and developed states. The developed case represent the urbanized state of the catchment without any infiltration systems. From the results it can be seen that the direct surface flow, which was negligible under natural conditions greatly increase after the development. The infiltration has been reduced to a greater extent too. However, the effect of this on stream flow has been greatly reduced due to the reduction of evapo-transpiration after the urbanization as a result of reduced exposed soil surface. Fig. 6 shows the duration curve for the river flow at the catchment outlet for the simulated conditions. From the duration curves one can see that peak flows which were very little during natural condition have increased after the urbanization, while thile the low flows have reduced. Infiltration scheme 1 does not reduce these high flows sufficiently. Results also suggest that increasing of facilities beyond stage 2 would bring only marginal benefits. Although not directly transferred to stream flow, infiltration systems help in smoothing the duration curve, so that there is less fluctuation of river flows, and it also restores the leakage to deep aquifers.

8. Conclusions

Mathematical modeling provides a powerful tool to study impact of urbanization on hydrological cycle. Even though a simplified model has been used in the present study, it gives some important insights to hydrological cycle changes due to urbanization and possible means of its control. As expected, urbanization is found to produce increased river peak discharges and decreased ground water recharge and river low flows. Ground water levels were found to be slowly decreasing for urbanized state during the simulation period of 10 years. Infiltration systems proved to be useful in restoring ground water and reducing river peak flows. Quantification necessary for engineering practices such as design and assessment, can be achieved through mathematical simulations. Such mathematical models have to be based on physical characteristics of the catchment and physical interpretation of processes which govern the hydrological processes. In practice, the modelling is a trade-off between complex complete mathematical models and simplified process models which can be used in an operational basis. Simplified models, similar to the one described here have to be verified through long term field monitoring.

The application also shows that basin hydrologic conditions results from complex interactions between hydrological inputs, geological conditions and soil characteristics making generalizations difficult. In the future there is a need to clarify the role of evaporation under urbanization and verify the results of simplified models by

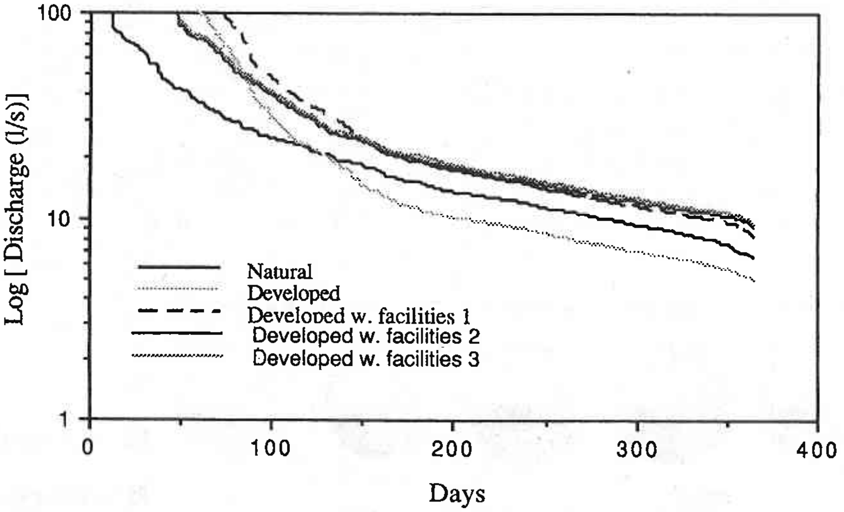


Fig. 6 Duration curve of river under various simulated conditions for a typical year (1983)

comparing with distributed complete hydrological models.

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References

1) Ando, S., Musiake, K. and Y. Takahashi, Modeling of hydrological processes in a small natural hill slope basin, based on the synthesis of partial hydrological relationships, 1983, Jnl. of Hydrology, 64. pp. 311-337.
2) Herath, S. and K. Musiake, Use of in-situ permeability tests for the analysis of infiltration facility performance. 1987, Proceedings. Urban Drainage Hydraulics and Hydrology, 4'th Int'l Conf. on Urban Storm Drainage. Laussane. pp. 61-66.
3) Herath, S., and K. Musiake, Design of Infiltration Facilities for Urban Flood Control., 1991, Proc. Intl Symposium on Environmental Hydraulics, Hong Kong, pp. 1425-1430.
4) Herath, S., Musiake, K., Hirose, N., and S. Matsuda, A process model for basin hydrological modelling and its application, Proc. Annual Conf. Japan Society of Hydrology and Water Resources, pp. 146-149, Aug. 1992.
5) Musiake, K., Y. Oka and M. Koike, Unsaturated zone soil moisture behavior under temperate humid climatic conditions-Tensiometric observations and numerical simulations, 1988 Jnl. of Hydrology, 102. pp. 179-200.
6) Musiake, K and S. Herath, Determination of hydraulic conductivity function using in-situ permeability tests. 1988, Proc. 6th APD-IHAR Congress, Japan. pp. 71-78.