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MODELLING BASIN HYDROLOGICAL CHANGES DUE TO URBANIZATION AND REMEDIAL MEASURES

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Abstract:
Cette étude porte sur la modélisation des changements dans le cycle hydrologique provoqués par l'urbanisation et sur des possibilités de rétablissement de ce cycle. Tout d'abord, un modèle de processus hydrologique est développé pour une simulation par ordinateur puis appliqué à un basin hydrographique mantagneux d'une surface d'environ 400 ha situé dans la banlieue de Tôkyô (Japon) et où une ville nouvelle est en construction. Les paramètres du modèle sont déterminés physiquement à partir des cartes topographique, géologique, de distribution et d'occupation des sols du basin. Le modèle a été vérifié par comparaison avec les débits mesurés des cours d'eau. En utilisant les données modifiées pour les propriétés citées plus haut, le cycle hydrologique est simulé pour l'état urbanisé. Finalement, différentes configurations de systèmes pour la rétention et l'infiltration sont étudiées afin de déterminer un schéma raisonnable pour le rétablissement du cycle hydrologique.

Abstract:
This paper describes a study on the modeling of changes to the hydrological cycle due to urbanization, and effectiveness of infiltration systems in its recovery. A lumped parameter hydrological process model is developed, and is applied to a hilly catchment with an area of about 400 ha in the suburbs of Tokyo, Japan, where a new town is being constructed. The model parameters are physically determined from the topographic, soil distribution, land use and geological maps of the basin. Model

performance is verified by comparing with measured stream flows. Using the changed catchment properties, the hydrological cycle is simulated for the urbanized state. Finally, alternate plans of infiltration trenches and on-site retention-infiltration systems are investigated to find out a reasonable scheme for hydrological cycle restoration.

1. Introduction

Modelling of hydrological process in changing environments is an important topic in hydrology. The present study has been conducted to asses the impact of urbanization on the hydrological cycle due to urbanization, and to find means to maintain major components of the hydrological cycle close to undeveloped conditions of the catchment.

A new town, called 'Hachioji new town' covering an area of about 400 hectare has been planned as a satellite residential area to Tokyo city, located about 60 km away from it. A stream called 'Huoye gawa' flows through the area of which about 90% remains undeveloped As a result of the creation of the new town, it is expected that river peak discharges would increase due to the increase of impervious areas, and that river low flows would reduce due to the reduction of pervious areas through which recharge to ground water takes place. To rectify this situation, it was decided to introduce infiltration systems consisting of infiltration trenches and infiltrating retention areas, which would dampen the peak discharges and increase the infiltration so that the hydrological cycle could be recovered.

In order to assess the change due to urbanization and the effect of different infiltration systems, a computer model capable of simulating basin hydrology as well as a predictive model for infiltration systems are required. According to the requirement of the study, a physically based distributed numerical model is the most suitable model for the purpose. However considering the data availability (daily rainfall and stream flows) as well as the time limitations, it was decided to develop a lumped parameter process model capable of simulating the hydrological processes, in which parameters are physically determined. It is important to estimate the model parameters from physical characteristics of the basin, as the model is to be used to simulate the changes in the catchment. A simple GIS (geographical information systems) was made for developed and undeveloped state of the catchment area, and model parameters were derived from it.

Numerical simulations of Richards' equation using a 2-D finite difference model were carried out to establish relations between water head and infiltrating volume for the infiltration trenches, for different soil types found in the area. An infiltration system model employing these relations and continuity equation was coupled with the hydrological model to assess the effectiveness of the infiltration systems.

2. Hydrological Model

Lumped parameter models cannot be complete hydrological process models, as most of the hydrological processes depend on the spatial distribution of the hydrologic variables. On the other hand, storage type lumped parameter models, such as TANK model and NAM model, would preserve the mass balance in routing the input into various components, which are conceptual rather than physical.

The model developed in the present study (PLUMP) was a combination of process and storage type of models. It implements the hydrological processes in storage components using soil hydraulic parameters.

The model is based on the following two major criteria.

1) The basin hydrology is represented by a top soil layer of about 2m depth, and the underlying aquifers in the vertical direction. The intermediate soil transfer the 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, basin can be finely sub divided using many blocks to represent more spatial variation.

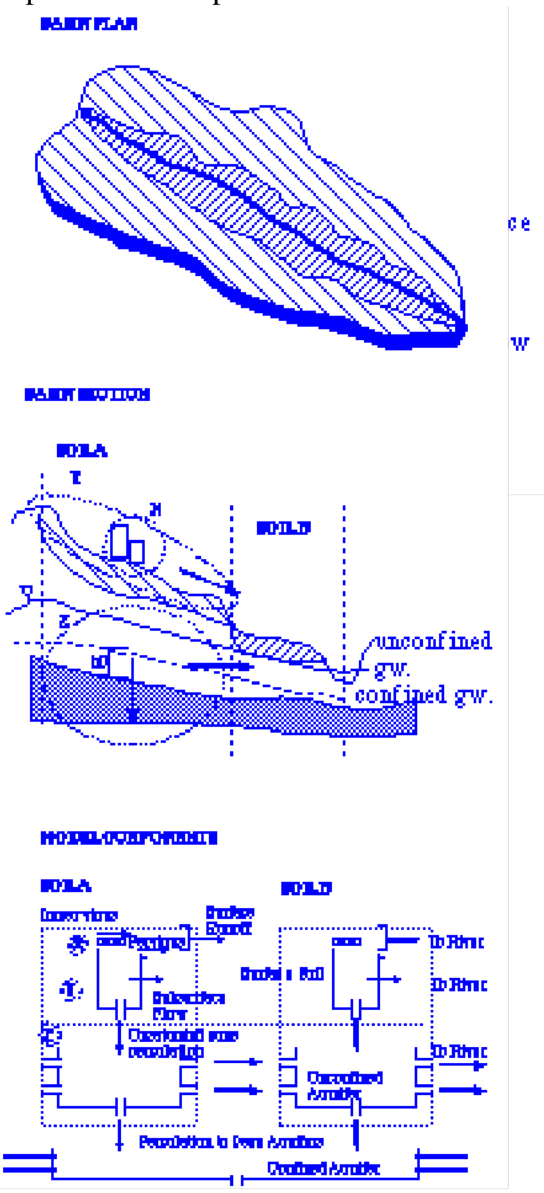

Fig. 2 Representation of a catchment using model cpmponents

The components of basin flow which constitute the model are shown in fig. 1. Fig. 2 shows the representation of a catchment using different model components. Each of the blocks are simulated separately and form a network representing the basin.

The 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 tanks. Computations at each block is carried out for a unit area and finally all the outputs are multiplied by the block area. The block areas are expressed as a fraction of the total basin area, such that their summation equals to 1. 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 in coming subsurface flow from neighboring blocks. This input is then scaled with respect to the block area and the new surface flow and the infiltration components are computed. Input to the impervious areas result in direct runoff. The components involved in the computation are shown schematically in fig. 3

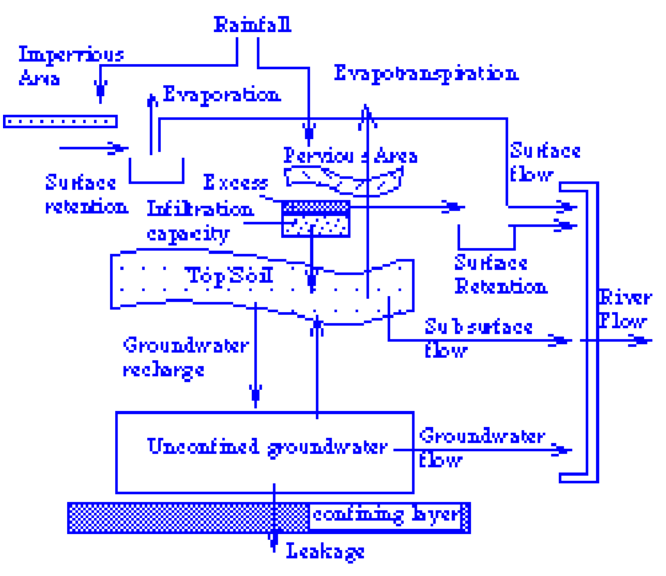

Fig. 3 Simulation procedure and components

The surface flow generation from pervious areas result from two mechanisms. If the inflow rate is higher than the saturated conductivity of the soil, surface flow takes place after the top soil storage is exceeded (Hortonian mechanism). In the second mechanism, rising ground water prevent additional infiltration, thus producing surface run-off (Dunn mechanism). Once the infiltrating volume is computed, recharge and subsurface components are computed. Next, the flow from ground water blocks is computed. The basic equations are as follows,

Continuity at the surface,

$$0 = Inflow_{k,i} - Per_{k,i} - DR_{k,i}$$

Mass balance for the moisture storage,

$$S_i = S_{i-1} + \frac{Interflow_{k-1,i}}{area_k} + Per_{k,i} - e_i *(1- imf_k) - Rech_{k,i} - Interflow_{k,i}$$

The recharge is expressed as,

$$Rech_{k,i} = \int_{t=0,\ \theta=\theta_{st}}^{t=24\ hr,\ \theta=\theta_1} k(\theta)\, dt \quad \text{with } \theta_1 >= \theta_{res}$$

The interflow is given by,

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

$$\theta_1 >= \theta_{res}$$

Mass balance for the groundwater is given by,

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

where $\quad Outflow_{k,i} = K_{k,k+1} \, L_{k,k+1} \, H_{k,k+1} \frac{\partial h}{\partial x} \quad$ and $\quad Leakage_{k,i} = K'_k \frac{(h_{k,i} - h_{kb,i})}{b_{k,k+1}}$

Notation for the above equations,

subs. k	block number	subs. i	time step
K_0	Saturated hydraulic conductivity of the soil	θ_{res}	Residual moisture content
area	block area	$k(\theta)$	Conductivity - moisture content relation for the soil
e	evaporation	Rech	Recharge to ground water
DR	direct run off	outflow	ground water flow
Per	percolation	leakage	leakage to deeper aquifers
K_0	saturated hydraulic conductivity of top soil	Hinflow	horizontal inflow from the adjoining ground water block
S	top soil moisture storage	$L_{k,k+1}$	Interface length between k and k+1th aquifers.
imf	Impervious factor	K'	conductivity of aquitard
K	conductivity of aquifer	Outflow	ground water flow
H	contact water height between aquifer blocks	$h_{k,i}$	Head of the k th block
b	aquitard height	$h_{kb,i}$	Head of the aquifer below the k th block

θ soil moisture content ($= \theta_{res} + S / H_t$ where H_t is the height of soil layer being modeled)

3. Description of the catchment area

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 smaller catchments as shown in the fig. 4.

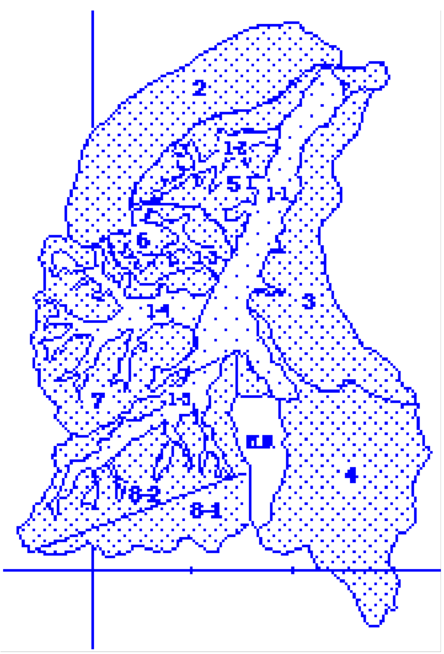

Fig. 4 Division of Hachioji Basin for Simulation.

Hydrological processes in the sub catchments from 2 to 7 and 8-1 and 8-2 are expected to be of the type shown in fig. 5.

However in the blocks 1-1, 1-2, 1-3, 1-4 and 1-5, there is no confining layer which would support an unconfined aquifer, and hence the entire river flow has to consist of surface and subsurface flow from the adjoining mountainous areas. This is described in the fig. 6. According to this concept, unconfined zone ground water seeps on top of the KM3 zone and constitute a kind of surface flow on the lower plane, which consist of Alluvium. As the flow takes place on the surface, part of it will seep into the subsurface strata and give rise to a subsurface flow, which would feed the river water. Another portion will infiltrate into the confined aquifer. Furthermore, the river bed itself is assumed to be leaking to the underlying water table along the course. The leakage amount is estimated as equivalent to steady state infiltration from a channel.

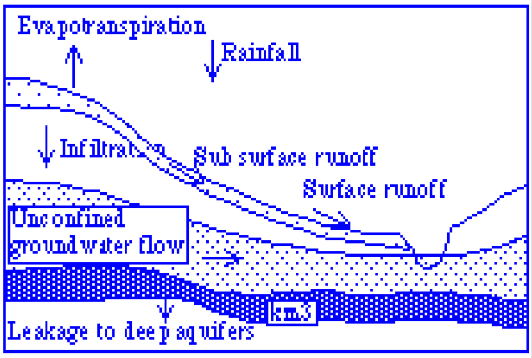

Fig. 5 Hydrological processes in catchments covered by KM3 zone

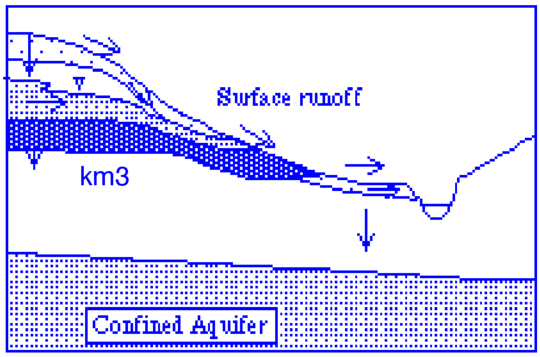

Fig. 6 Hydrological processes in catchments not covered by KM3 zone.

4. Model validation

The model was applied to a sub-catchment within the study area termed H.S. in fig. 4 for verification . Daily run-off data at the site were available for the period of 1988 July to end of 1989. The rainfall data from the adjoining Hachioji station were used for the computations. To estimate the parameters required for the modelling, a DTM (digital terrain model) of the whole basin was made. Then, soil map, landuse map and the confining layer of the unconfined aquifer (KM3 zone) were overlain on it. The soil conductivity was determined from field borehole tests, whereas the moisture characteristics were determined from pF tests conducted on small soil samples. From these data, all the parameters required for the top moisture tanks can be determined.

For the ground water tanks, transmissivity between the ground water zone and the river as well as the leakage factor with the deep aquifer have to be determined. Transmissivity was estimated assuming a contact depth of 50 cm between ground water and river water level and using the contact length between river and ground water from the topographic map.

Observation well data suggests that the deep (or confined) aquifer water level to be lower than the river water level and hence there is no recharge to the river from the confined aquifer. In the modelling, water level of the confined aquifer was assumed to be at a constant level. The leakage was roughly estimated assuming the conductivity of the KM3 zone to be of 10^{-6} cm/s and later calibrated using the observed recession curve of the river flow during the November and December months of 1988 data.

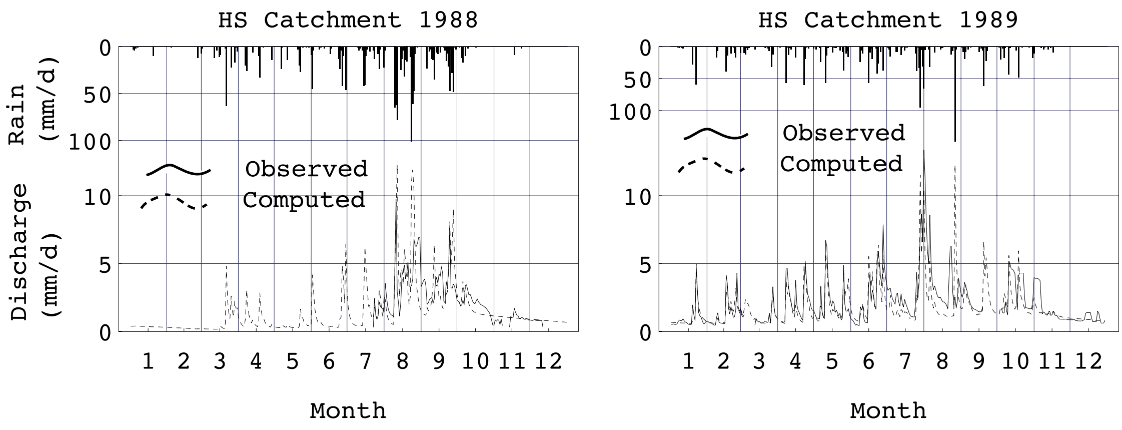

Fig. 7 Model validation at Hotarunosawa catchment

The model performance was checked by daily simulations conducted from the beginning of 1980 to end of 1989 and plotting the observed river flow during the 1988 and 1989 period. The simulation results for the last two years are shown in fig. 7. The figure shows good agreement between the observed and computed results.

5. Modelling 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 stream in these catchments after the development.

Infiltrating trenches and storage ponds were 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,

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

The governing equation is scaled with respect to saturated soil conductivity, which make 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 for Kanto Loam soil is shown in Fig. 8. This figure is simplified for trenches of a given width in the form of $q / Ko = a H + b$, 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 constants obtained by the fitting. Next the performance of a trench system is modeled by

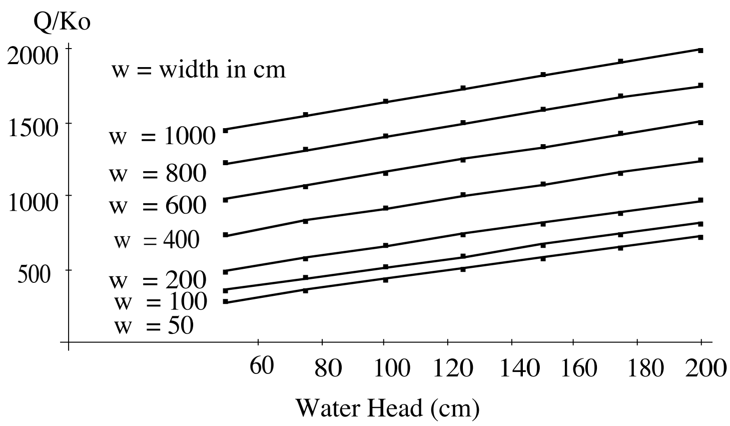

Fig. 8 Relation between water head Infiltraiton rate for different trench widths in Kanto Loam soil

applying equation of continuity to the system,

$$dS/dt = i - (q) L = i - L\ Ko\ (a H + b),$$

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 (eg. 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, it was proposed to install drain pipes, 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. The components involved in the modelling of these plans are shown in fig. 9.

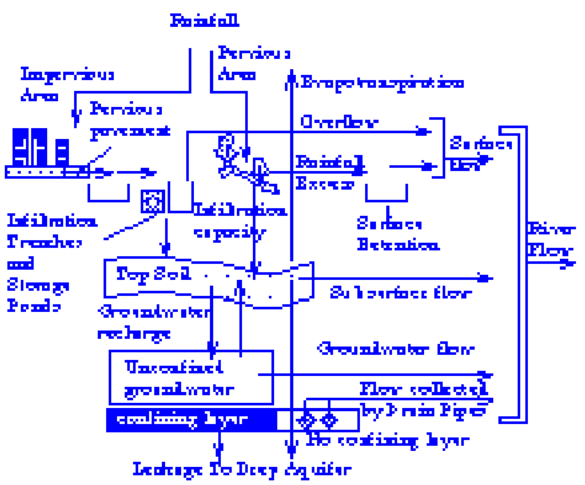

Fig. 9 Hydrologic components modelled after land development.

6. Simulations

Simulations for the whole basin was carried out for Natural Condition, Developed Condition and Developed Condition with Infiltration, Storage & drainage pipe facilities.

The simulation network and the interaction of flows between sub-blocks in a unit are shown in fig. 10. The surface, sub-surface and ground water flow paths and the their changes after the development are shown by different types of lines. The sub catchment 8 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 summing up the trenches in each simulation block according to the landuse and soil type distribution. Various plans for the installation of infiltration systems were considered according to the type of infiltration system that can be installed within a given landuse type. Table 1 shows details of three infiltration system schemes analyzed. Facility-1 case employs less infiltration systems, while Facility-3 case employs more infiltration systems.

Fig. 11 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 is for the developed 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 to have greatly increased 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. Fig. 12 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 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 there is less fluctuation of river flows, and also restores the leakage to deep aquifers.

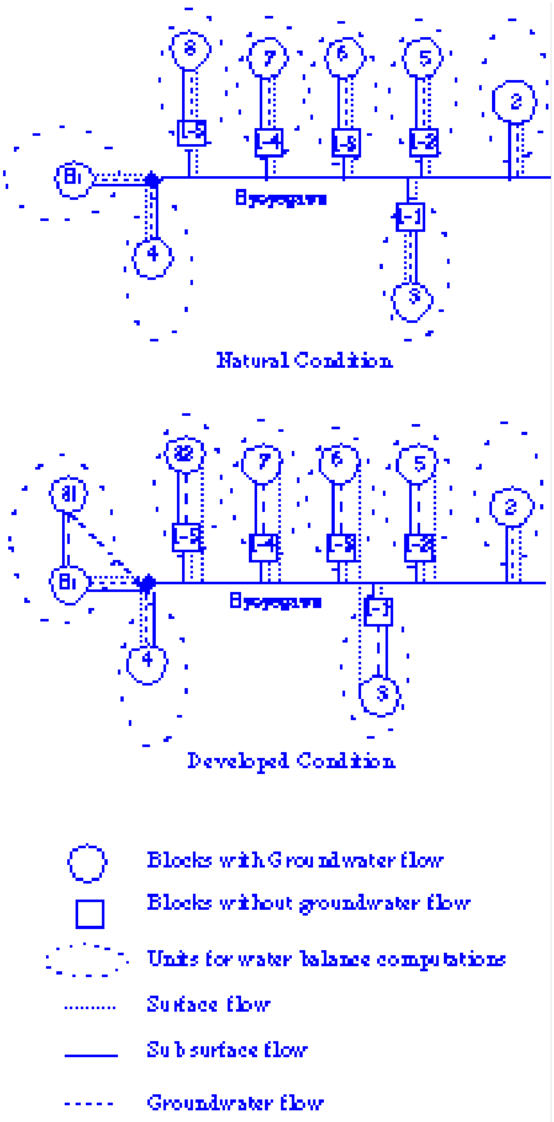

Fig. 10 Simulation Network and Drainage paths for Developed and Natural Conditions

7. Conclusions

Due to the increasing awareness of the effects of human activities on nature, there will be a growing demand for the modelling of processes such as urbanization described in this paper. The classical hydrological modelling cannot accommodate the changing environments in these situations and there is a need to develop new models based on physical hydrology, which are computationally viable. The model developed in this study (termed PLUMP for *P*hysically-based *Lum*ped *P*arameter model) is only a preliminary step in this direction. Keeping up with the needs of the industry, such models have to be refined and new features added, based on the field monitoring of experimental basins and new developments in the related fields.

Such models are required to avoid the excessive computational time and calibration data requirements of full 3 dimensional hydrological models, in the planning stages of projects such as described here. PLUMP model was originally developed as a planning tool for the evaluation of proposed infiltration facility schemes. However, its success in modelling the hydrological processes of the basin holds promise for the future development of simplified distributed models simulating hydrological processes.

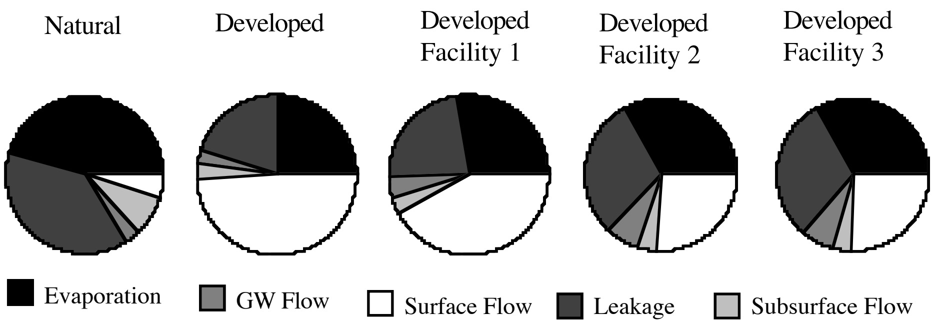

Fig 11. Magnitude of different hydrologic components for different simulated cases

There are over simplifications in the assumptions made in the study as well as difficulties with input data resolution. However, it is planned to monitor the hydrological variables in this area over a number of years, and during that time, it is hoped that modeling would improve with additional observations.

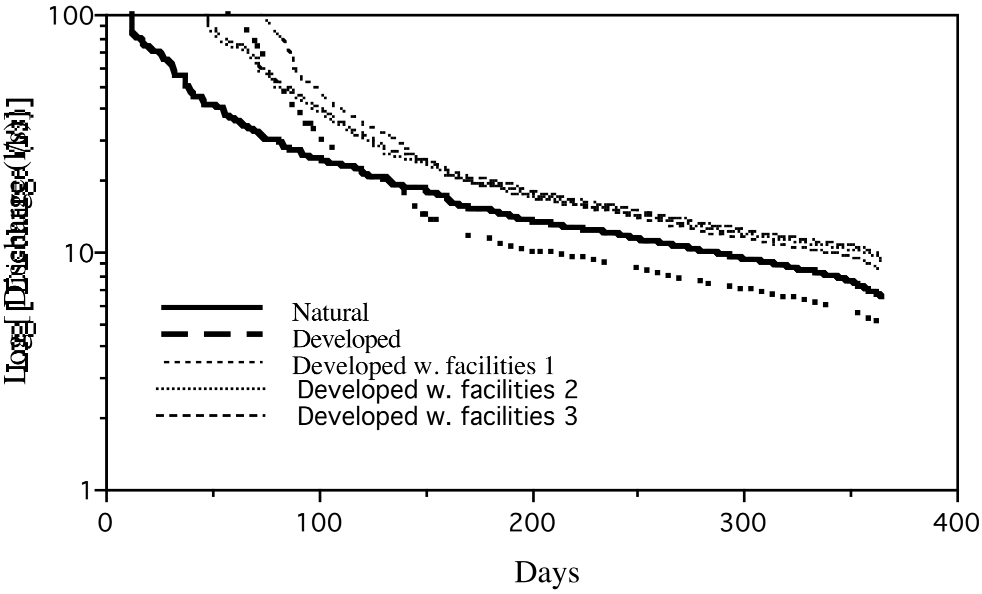

Fig. 12 Duration curve of river under various simulated conditions for a typical year (1983)

Acknowledgment

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