ANALYSIS OF HYDROLOGICAL CYCLE CONSIDERING THE INFILTRATION VARIATION IN AN URBAN HILLS BASIN

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The infiltration model proposed by Diskin and Nazimov is a fairly simple conceptual model that comprises two elements and contains only three parameters, and it can also be used to calculate the variation of infiltration rate for unsteady rainfall. The lumped hydrological model presented by Ando et al. (1984) performs long-term simulations with simple procedures calculating by hourly time-step for urban basins. In order to improve the ability of this lumped hydrological model, the Diskin-Nazimov infiltration model is used to estimate the effective rainfall for runoff analysis. The Kotta River basin used in this study is situated in the western suburbs of Tokyo. The analysis was carried out for two terms in about five years between 1997 and 2000. The results showed that the calculated hydrograph agree with the observed hydrograph.

INTRODUCTION

In order to carry out an accurate runoff analysis, a better understanding of the infiltration process is required for the estimation of the direct runoff and infiltration. During a natural rainfall event, the rainfall intensity varies constantly and is sometime higher / lower than the infiltration rate in upper soil layer. At the same, the infiltration rate itself also varies when the rainfall intensity varies, because the infiltration rate depends on the moisture content in upper soil layer which in turn depends on the rainfall intensity and percolation to the below. However, many infiltration models do not consider the rainfall intensity variations during a rainfall event. There is a difference in the phenomena between the modeled infiltration and the actual event. Diskin and Nazimov [1] proposed a simple conceptual infiltration model, which takes the temporal variability of rainfall intensity into consideration. However, the validity of this model has been considered mainly using values from the literature. Fujimura et al. [2], [3] investigated the validity of the Diskin-Nazimov model for accessing the variation of the infiltration rate under steady rainfall and unsteady rainfall using a rainfall simulator.

The lumped hydrological model presented by Ando et al. [4] performs long-term simulations with simple procedures calculating by daily step calculation, which was later modified to an hourly time-step calculation [5]. The structure of the model is a combination of direct runoff, infiltration, evapotranspiration, groundwater recharge and groundwater runoff. However, the infiltration into the soil is estimated by using only the ratio of pervious area to the basin area. The purpose of this study is to improve the ability of this lumped hydrological model by coupling with the Diskin-Nazimov infiltration model.
**STUDY AREA**

The study basin is the Kotta River basin (Figure 1) which is located in Tama New Town, an urban development in the Tama hills, in the western suburbs of Tokyo. The basin has a catchment area of 13.4 km². This basin is covered with Kanto loam, characterized by high permeability, whereas most of the area was primarily developed and urbanized as Tama New Town, a bedroom community of Tokyo since 1960s. Land use in this basin consists of impervious areas, such as paved roads (35.4%) and roofs of buildings and houses (21.2%), and pervious areas, such as private lawn gardens (22.5%), sports grounds (5.2%), cleared land for new residences (6.7%) and forests (9.0%) as shown in Table 1. The impervious area occupies 56.6% and pervious occupies 43.4% of the basin. The soil of sports grounds is sandy, while lawn gardens consist of loamy soil, and cleared land is typically hardpan soil. The three types of land use were chosen as sports grounds, lawn gardens and cleared land, for which the final infiltration rates were measured with a

![Figure 1. Map of the Kotta River basin](image)

<table>
<thead>
<tr>
<th>Land use percentage (%)</th>
<th>Roads, etc.</th>
<th>Roofs</th>
<th>Lawn gardens</th>
<th>Sports grounds</th>
<th>Cleared land</th>
<th>Forests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final infiltration rate (mm/h)</td>
<td>—</td>
<td>—</td>
<td>22.2</td>
<td>7.1</td>
<td>5.3</td>
<td>—</td>
</tr>
</tbody>
</table>
rainfall simulator. The median of the values are given as 7.1 mm/h for sports grounds, 22.2 mm/h for lawn gardens and 5.3 mm/h for cleared land, and are shown in Table 1. The rainfall data and temperature data were recorded at the Tama City hall indicated by ● and the water level data were recorded at ▲ in Figure 1.

INfiltration Model Considering Rainfall Intensity

Outline of the Diskin-Nazimov model
The schematic structure of the Diskin-Nazimov model is shown in Figure 2. The model comprises two simple elements; the reservoir element and the input-regulating element of the reservoir. The reservoir element represents the soil moisture content in the upper soil layer. The relationship between the storage in the reservoir and the infiltration capacity is assumed to be specified by a decreasing linear relationship and is expressed as Equation (1). At the same time, the output of the reservoir element, representing the percolation from the upper soil layer (the infiltration into the unsaturated soil layer), is assumed to be specified by an increasing linear relationship between the storage in the reservoir and the infiltration capacity and is expressed as Equation (2). Both relationships are shown in Figure 3.

\[
\begin{align*}
f(t) &= f_0 - \frac{(f_0 - f_c)S(t)}{S_{m}} \quad (1) \\
g(t) &= \frac{f_c}{S_{m}}S(t) \quad (2)
\end{align*}
\]

Where, \( f \) is the infiltration capacity, \( f_0 \) is the initial infiltration rate, \( f_c \) is the final infiltration rate, \( f(t) \) is the infiltration capacity, \( f_0 \) is the initial infiltration rate, \( f_c \) is the final infiltration rate, \( q(t) \) is the rate of infiltration into the upper soil layer, \( S(t) \) is the soil moisture in the upper soil layer, \( S_{m} \) is the maximum value of soil moisture, \( g(t) \) is the rate of percolation from the upper soil layer, and \( y(t) \) is the intensity of rainfall excess.

Figure 2. Schematic structure of the Diskin-Nazimov model
Figure 3. Relationship between infiltration capacity and soil moisture and between percolation rate and soil moisture.

infiltration rate, $S$ is the soil moisture in upper soil layer, $S_{m}$ is the maximum value of soil moisture, $g$ is the rate of percolation from the upper soil layer and $t$ is the time.

The input-regulating element calculates the actual infiltration rate into the reservoir element considering the rainfall intensity and infiltration capacity, according to the following equations:

\[
\begin{align*}
\text{if } R(t) < f(t) & \quad \text{then} \quad q(t) = R(t) \quad \text{and} \quad y(t) = 0 \\
\text{if } R(t) > f(t) & \quad \text{then} \quad q(t) = f(t) \quad \text{and} \quad y(t) = R(t) - f(t)
\end{align*}
\]

where $q$ is the actual infiltration rate, $y$ is the rainfall excess and $R$ is the rainfall intensity. The equation of continuity for storage in the reservoir element is expressed by subtracting the percolation rate from the actual infiltration rate as below.

\[
\frac{dS(t)}{dt} = q(t) - g(t) \quad (0 \leq S(t) < S_{m})
\]

**Method of infiltration analysis for unsteady rainfall**

Diskin and Nazimov described the method of computation of the infiltration variation for unsteady rainfall, by carrying out calculations for successive time intervals. The procedure is divided to the following three cases of the relationship between the rainfall intensity and infiltration capacity.

- **Case (a)** The value of the infiltration capacity is lower than the rainfall intensity.
- **Case (b)** The value of the infiltration capacity is higher than the rainfall intensity.
- **Case (c)** The value of the infiltration capacity varies from higher to lower than the rainfall intensity in one time interval.
Figure 4, cases (a), (b) and (c) indicate each of the above relationships between the infiltration capacity and rainfall intensity. In order to calculate the infiltration capacity for each time interval using Equation (1), the variable $S(t)$, the storage in the reservoir, is must be calculated for each time interval. Equation (3) is written for one time interval using the subscript $b$ for the beginning of the interval and $e$ for the end of the interval, as

$$S_e - S_b = \frac{q_b + q_e}{2} \Delta t - \frac{q_b + q_e}{2} \Delta t.$$  

(4)

Diskin and Nazimov derived the $S_c$ expression by solving $S_c$ in Equation (4) for all cases:

Case (a)  
$$S_c = \frac{1}{2S_m} \left( \frac{f_s \Delta t}{2S_m} S_b + \frac{f_s \Delta t}{1+\frac{f_s \Delta t}{2S_m}} \right),$$

Case (b)  
$$S_c = \frac{1}{2S_m} \left( \frac{f_s \Delta t}{2S_m} S_b + \frac{\Delta t}{1+\frac{f_s \Delta t}{2S_m}} R \right),$$

Case (c)  
$$S_c = \frac{1}{2S_m} \left( \frac{f_s \Delta t}{2S_m} S_b + \frac{f_s \Delta t}{1+\frac{f_s \Delta t}{2S_m}} \right),$$

where $\Delta t_1 - \Delta t_2$ is the time at which the infiltration capacity equals the rainfall intensity in the considered time interval.

Eventually, the infiltration rate variation can be calculated using these $S_c$ in Equation (1).

**APPLICATION TO THE KOTTA RIVER BASIN**

The fundamental hourly hydrological model is a combination of direct runoff, infiltration, evapotranspiration, groundwater recharge and groundwater runoff as shown in Figure 5. Direct runoff (D) and infiltration into the unsaturated soil layer (g) are calculated by the Diskin-Nazimov model. The infiltration into the unsaturated soil layer increases soil
moisture storage of the unsaturated soil layer (Ms) and evapotranspiration from infiltration area (E) decreases soil moisture storage. Leaking from the pipes of the artificial water supply (WS) is considered in this study. Evapotranspiration is calculated using Hamon’s formula. Groundwater recharge (G) is proportional to soil moisture excess. Groundwater runoff (Qg) is proportional to the second power of groundwater storage (Sg). The total runoff (Q) is the sum of direct runoff and groundwater runoff.

\[ R(t) \]

\[ q(t) = \begin{cases} R(t) & R(t) < f(t) \\ f(t) & R(t) \leq f(t) \end{cases} \]

\[ D(t) = \begin{cases} 0 & R(t) < f(t) \\ R(t) - f(t) & R(t) \leq f(t) \end{cases} \]

\[ Ms'(t) = Ms(t) + g(t) - E(t) + WS \]

\[ G(t) = \begin{cases} 0 & Ms'(t) \leq Mn \\ \beta (Ms'(t) - Mn) & Ms'(t) > Mn \end{cases} \]

\[ Ms(t+1) = Ms'(t) - G(t) \]

\[ Sg(t+1) = Sg(t) + G(t) - Qg(t) - SP \]

\[ Qg(t) = Au^2 \cdot Sg(t)^2 \]

\[ Q(t) = Qg(t) + D(t) \]

\[ R: \text{ Rainfall (mm/h)} \quad Sg: \text{ Groundwater storage (mm)} \]
\[ f: \text{ Infiltration rate of the upper soil layer (mm/h)} \quad Qg: \text{ Groundwater runoff (mm/h)} \]
\[ q: \text{ Infiltration rate into upper soil layer (mm/h)} \quad D: \text{ Direct runoff (mm/h)} \]
\[ g: \text{ Infiltration rate into unsaturated soil layer (mm/h)} \quad Q: \text{ Total runoff (mm/h)} \]
\[ Ms: \text{ Soil moisture storage (mm)} \quad \beta: \text{ Constant of groundwater recharge} \]
\[ Mn: \text{ Normal soil moisture} \quad gg: \text{ Capacity of groundwater recharge (mm/h)} \]
\[ E: \text{ Evapotranspiration (mm/h)} \quad h: \text{ Constant of soil moisture excess (mm)} \]
\[ G: \text{ Groundwater recharge (mm/h)} \quad Ws: \text{ Leaking from the water supply pipes (mm/h)} \]
\[ SP: \text{ Groundwater runoff to outside the basin (mm/h)} \quad t: \text{ Time step (in this case, 1 hour)} \]
\[ Au: \text{ Recession constant of groundwater runoff from unconfined aquifers} \]

Figure 5. Sequence of the hourly hydrological model of the Kotta River basin

Although the sewers of the Kotta River basin are separate sewers, wastewater flows into the Kotta River. To separate wastewater, we assume the minimum discharge in the drought period to be equivalent to groundwater runoff. Wastewater of the Kotta River is estimated to be 0.0356 mm/day. The analysis was carried out for two terms, from 28th March 1996 to 30th September 1998 for 917 days and from 20th February 1999 to 28th February 2001 for 740 days. Table 2 shows the parameter of the hydrological model for
Kotta River basin, 1999.2.20 - 2001.2.28, 740 days

Rainfall (mm/day)

Runoff (mm/day)

Ms = 50 mm, Sg = 246 mm

Mn = 50, Au = 0.002, β = 0.7, e = 0.6

Figure 6. Calculated and observed hydrographs (1996 - 1998)

Kotta River basin, 1996.3.28 - 1998.9.30, 917 days

Rainfall (mm/day)

Runoff (mm/day)

Ms = 50 mm, Sg = 267 mm

Mn = 50, Au = 0.002, β = 0.7, e = 0.6

Figure 7. Calculated and observed hydrographs (1999 - 2001)
Table 2. Parameter of the hydrological model for the Kotta River basin

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>Recession constant of groundwater runoff</td>
<td>0.002</td>
</tr>
<tr>
<td>Mn</td>
<td>Normal soil moisture</td>
<td>50.0 mm</td>
</tr>
<tr>
<td>β</td>
<td>Constant of groundwater recharge</td>
<td>0.7</td>
</tr>
<tr>
<td>WS</td>
<td>Leaking from the water supply pipes</td>
<td>0.14 mm/day</td>
</tr>
<tr>
<td>SP</td>
<td>Groundwater runoff to outside the basin</td>
<td>1.1 mm/day / 1.5 mm/day</td>
</tr>
<tr>
<td>Ms(1)</td>
<td>Initial value of soil moisture storage</td>
<td>50.0 mm</td>
</tr>
<tr>
<td>Sg(1)</td>
<td>Initial value of groundwater storage</td>
<td>267 mm / 246 mm</td>
</tr>
</tbody>
</table>

the Kotta River basin. The observed and calculated hydrographs for two terms, which show good agreement, are shown in Figure 6 and Figure 7, respectively.

CONCLUDING REMARKS

The lumped hourly hydrological model presented by Ando et al. [4] was coupled with the infiltration model proposed by Diskin and Nazimov. Analyses were performed for two terms in about five years, and the results indicated that the model has good applicability to the Kotta River basin (an urban hills basin) in Japan.

REFERENCES