Changes of rainfall infiltration and runoff process due to urbanization

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Abstract Infiltration tests on a natural hillside slope indicated that rainfall infiltration was too large for the prevailing soil character and was influenced by the macropores existing in the surface soil layer. In the urban area, the infiltration rate was nearly equal to the value derived from the hydraulic conductivity of the surface soil and the macropores were negligible. Based on these results, numerical simulation models of rainfall infiltration and runoff were investigated. From the calculated results, it was clarified that the increase of rainfall runoff due to urbanization is brought about by the decrease of infiltration due to the destruction of macropores and the increase of impervious areas, and by decrease of concentration time of rainfall due to the decrease of roughness.

INTRODUCTION

The increase of rainfall runoff due to the urbanization of naturally hilly regions increases the flood damage potential in the downstream area. The aim of this paper is to clarify the mechanisms of the increase of rainfall runoff due to urbanization.

MEASUREMENTS OF THE RAINFALL INFILTRATION RATE

The infiltration rates were measured with an artificial rainfall type equipment on a natural hillside in the River Tanida experimental basin and in housing lots in Uji city (Figs 1 and 2).

The infiltration rate of the natural hillside decreases rapidly once rainfall has begun and is far larger than the value derived from the hydraulic conductivity of the surface soil (cf. $K_T$ shown in Fig. 6). Removal of the layer of dead leaves after a series of experiments brought to light macropores, which are thought to have been caused by root-rot. It is clarified from these observed results that almost all the rainwater that reaches the slope enters these macropores, thereby increasing the rate of infiltration on a natural hillside.

The infiltration rate of the urbanized area was nearly equal to the value derived from the theory of unsaturated soil water flow and was not affected by the macropores.
MACROPORES MEASUREMENTS IN NATURALLY HILLY REGIONS

There has been no general agreement on the classification and naming of pore types present in a soil. I have roughly divided pores into two types; matrix pores produced by the contact of soil particles, and macropores formed by desiccation, animals in the soil, root-rot, etc. I have also subdivided macropores into coarse macropores that have diameters greater than 5 mm, and fine macropores that have diameters less than 5 mm.

After the removal of dead leaves and humus from the soil surface, I measured the horizontal and vertical distributions of the coarse macropores by tracing them on a transparent plastic board (Fig. 3). These holes are mainly the result of the root-rot of bamboo, and almost all are filled with dead leaves or humus. The ratio of the coarse macropores to the test area is 5 to 10%.

Fig. 1 Infiltration rates measured on the natural hillside in the River Tanida experimental basin.

Fig. 2 Infiltration rates measured at housing lots in Uji city. Solid lines represent the theoretical curves numerically obtained by using Richards equation.
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It is not easy to measure the distribution of fine macropores in naturally hilly regions because of their small size. I have measured the fine macropores as follows: (a) Porosity is measured by sampling with a small soil sampler driven into the soil at a place where no macropores are present. The sampler has an inside diameter of 4.3 cm and a length of 5.0 cm. This porosity should be regarded only as a consequence of the matrix pore. (b) Porosity is measured by sampling soil in an area with a radius of about 15 cm and depth of 20 cm, in which no coarse macropores are present. To obtain the volume of the sampled soil, the sand-replace method is used. Results of porosity measurements made around the infiltration test plots are shown in Fig. 4. The average porosity obtained with the small sampler is 0.550 and that of the porosity in the larger area, 0.628, the difference being 0.078. Consequently, fine macropores make up 7.8% of the volume.

RAINFALL INFILTRATION ANALYSIS OF SOIL WITH MACROPORES

In this study, soil water movement in soil containing fine and coarse macropores on the natural hillside have been determined using a two-step analysis as follows:
Rainfall infiltration analysis into soil with fine macropores

The flow through fine macropores can be regarded as similar to viscous flow in a capillary tube and soil water flow in soil that does not contain macropores can be expressed by the Richards equation. In this model, the viscous flow in fine macropores was assumed to be equivalent to the unsaturated soil water flow, in order to analyse simultaneously the flow in fine macropores and soil water flow in the soil with the Richards equation. In this case, it is necessary to determine beforehand the relationship between the soil suction and the soil moisture content, $\psi(\theta)$, and the unsaturated hydraulic conductivity, $K(\theta)$, of fine macropores, which can be obtained as follows: The saturated hydraulic conductivity, $K_{sat}$, is calculated from equation (1), derived from the Hagen-Pousuelle Law and the height of the capillary rise, $h_t$, from equation (2):

$$K_{sat} = \frac{r^2 g \rho}{8 \mu} \quad (1)$$

$$h_t = \frac{2 \sigma \cos \alpha}{r g \rho} \quad (2)$$

Here, $g$ is the acceleration of gravity, $\rho$ the density, $\mu$ the viscosity, $\sigma$ the surface tension coefficient, $\alpha$ the contact angle ($\alpha = 0.0$), $r$ the radius of capillary tube. Next, using these $K_{sat}$ and $h_t$ values, the $\psi(\theta)$ and $K(\theta)$ corresponding to the fine macropores can be estimated by equations (3) and (4) (Pikul et al., 1974):

$$\frac{K(\theta)}{K_{sat}} = \left[ \frac{a}{a + c(-\psi)^b} \right]^N \quad (3)$$

Fig. 5 Finite element meshes used to calculate the soil water flow in fine macropores and soil.
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Fig. 6 Relationships between unsaturated hydraulic conductivity, soil suction head and soil moisture content. $\psi_T$ and $K_T$ are curves of the surface soil in the River Tanida basin, $\psi_K$ and $K_K$ the Kita Ogurayama experimental basin, $\psi_L$ and $K_L$ correspond to fallen leaves.

$$\frac{\theta - \theta_r}{\theta_o - \theta_r} = \frac{a}{[a + c(-\psi)^b]}$$

Here, $\theta$ is the soil moisture content, $\theta_o$ the saturated soil moisture content, $\theta_r$ the residual soil moisture content and $a$, $b$, $c$, $N$ the soil parameters. Figure 5 is the analysis section and element division used in the calculations. $\psi(\theta)$ and $K(\theta)$ of the soil around the fine macropores are shown with $\psi_T$, $K_T$ in Fig. 6. These were measured in an indoor experiment for the surface soil in the Tanida River basin. $\psi(\theta)$ and $K(\theta)$ correspond to the fine macropores, are calculated by substituting $K_{sat.} = 27.8 \text{ cm s}^{-1}$, $a = 30.0$, $b = 2.0$, $c = 0.01$, $\theta_o = 1.0$, $\theta_r = 0.0$, and $N = 2$ in equations (3) and (4). Other analysis conditions were the time increment $\Delta t = 0.001 \text{ s}$ and the rainfall intensity $R = 100 \text{ mm h}^{-1}$.

The vectors of velocity and pressure distributions at $t = 10 \text{ s}$ are shown in Fig. 7. Rainwater infiltrates the fine macropores on the left side of the section after passing through the fallen leaves layer and descends at a high velocity inside these macropores. In soil containing fine macropores, rainwater descends through the fine macropores $\rightarrow$ soil $\rightarrow$ fine macropores route. Therefore, fine macropores have the effect of making the infiltration of rainwater faster.

The model of rainwater infiltration of the soil containing fine macropores shown here requires numerous calculations, and is not practical. Therefore, simplification of the rainfall infiltration analysis using a one dimensional analysis was investigated. Soil moisture distributions after $10 \text{ s}$ obtained by setting $K(\theta)$ equal to 5 times and 10 times the values of $K_{sat}(\theta)$, are shown as $K$, $K*5$, and $K*10$ in Fig. 8. In this figure, FM the soil moisture distribution, is obtained by averaging the soil moisture distributions in the horizontal direction according to the two dimensional model.
A comparison of $K*5$, $K*10$ and FM shows that the wetting front of $K*5$ is about 3 cm deep and that of $K*10$ about 4 cm deep. The soil moisture distribution of $K*10$ approaches that of FM. I therefore concluded that a vertical, one-dimensional analysis can approximate the actual rainfall infiltration of soil that contains fine macropores if $K(\theta)$ is increased by a factor of 10. Macroscopically, therefore, fine macropores have the effect of increasing the unsaturated hydraulic conductivity 5 to 10 times larger than the value of the original soil.

Analysis of rainwater infiltration of soil containing coarse macropores The infiltration of rainwater into soil containing coarse macropores was analysed with the following assumption. Although coarse macropores are three dimensional, they have been treated as two dimensional to maintain the ratio between them and the soil...
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Surface area. Coarse macropores may be considered as being filled with humus. To include the effect of fine macropores, the \( K(\theta) \) of the soil must be set 5 to 10 times larger than the actual unsaturated hydraulic conductivity. Consequently, the infiltration of rainwater can be analysed by using the Richards equation as was done for the fine macropores.

The analysis section and the finite element mesh is shown in Fig. 4. Values of \( \psi(\theta) \) and \( K(\theta) \) for the fallen leaves and the plugs in the macropores are shown in Fig. 6 (\( \psi_L, K_L \)).

Rainwater infiltrates the fallen leaves layer in the downstream direction after reaching the soil surface, then changes direction at the upper part of the coarse macropores and flows into them, where it descends with high velocity and infiltrates from the wall surface into the soil (Fig. 9). Infiltration rates derived from the calculations agree well with the results of the infiltration tests (Fig. 1). Coarse macropores play a role in increasing the infiltration rate in the natural hillside.

![Fig. 9 Velocity vector and pressure head in coarse macropores and soil.](image)

**RAINFALL RUNOFF PROCESS OF A NATURALLY HILLY REGION AND ITS MODELLING**

Based on the results of the field tests, the rainfall runoff process for a naturally hilly region may be represented with a conceptual model as shown in Fig. 10.

Almost all rainfall except that intercepted, reaches the ground surface and is stored temporarily in the fallen leaves and in depressions on the ground surface. Once these temporary storage have been filled with rainwater, some water enters into the coarse macropores and some infiltrates into the soil layer. Other water will eventually evaporate. The rainwater which enters the coarse macropores promptly reaches the groundwater table. On the other hand, the rainwater which infiltrates, flows down slowly through the unsaturated soil layer. Rainwater from these two processes reaches the groundwater table separately, and flows through the saturated aquifer and into the
stream. In this runoff model, the groundwater runoff consisting of the flow through coarse macropores is named "prompt groundwater runoff". The other, resulting from the slow moisture movement, is named "delayed groundwater runoff".

The soil water flow of a natural hillside can be analysed numerically as proposed in the previous section. However, it is quite difficult to calculate directly the prompt and delayed groundwater runoff with the numerical method on account of the practical limitations of computer speed. For this reason, the following modellings are introduced:

(a) The soil is uniform within the basin and the unsaturated hydraulic conductivity of the soil may be set 5 to 10 times larger than the actual value in order to consider the effects of fine macropores. The soil water flow in the soil containing fine macropores is one dimensional in the vertical direction and the flow from the land surface to the groundwater table may be calculated using the Richards equation.

(b) The water entering into the coarse macropores directly reaches the groundwater table. The percolation to the soil from the wall of coarse macropores is neglected.

(c) The groundwater movement in the saturated zone is analysed using the Boussinesq equation.

(d) If rain falls continuously at a rate greater than the infiltration rate, then interflow occurs through the fallen leaves. If the heavy rainfall continues, overland flow begins to occur over the fallen leaves or over the ground surface. This overland flow and the interflow were modeled using kinematic wave approximation (Ishihara & Takasao, 1962).

**Estimation of the effective soil depth** When a relatively long time has elapsed since rain has stopped, soil water contents are measured at some points in a hilly region. Using these soil water contents and observed discharge hydrograph such as the one shown in Fig. 11, an effective soil layer depth, \( z_e \), can be estimated as follows:

\[
    z_e = \frac{\int_{t_1}^{t_2} Q(t) \, dt}{(\theta_{t_1} - \theta_{t_2})A_o}
\]

where \( Q(t) \) is the discharge at time \( t \), \( \theta_{t_1} \) and \( \theta_{t_2} \) are the soil moisture at \( t_1 \) and \( t_2 \), and \( A_o \) is the drainage area.
The upper limit of rainfall rate entering the coarse macropores

The upper limit of rainwater rate entering the coarse macropores, $R_c$, must be ultimately determined by trial and error, but the following procedure is suggested to obtain the first approximation. First, the discharge hydrograph, observed during a relatively intense rainfall, is plotted on semi-logarithmic paper (Fig. 11) and the recession curve of the hydrograph is extended backward to the time of the cession rain. Another line is drawn from this plot to the start point of the rise of the hydrograph. The lower part of the hydrograph separated by these two lines may be regarded as the component of rapid and delayed groundwater runoff. And, if it may be assumed that the discharge at the rising point of the hydrograph is unchangeable as the delayed groundwater runoff, the hydrograph of the rapid groundwater runoff, $Q_c$, shown in Fig. 11, can be estimated by subtracting this discharge from the separated hydrograph as described above. Finally, the prompt groundwater runoff depth, $Q_{pg}$, may be calculated:

$$Q_{pg} = \frac{\int_0^{T_c} Q_c(t) \, dt}{A_0}$$

where, as shown in Fig. 11, $T_c$ is the time from the beginning of rainfall to the end of rapid groundwater runoff. Finally, $R_c$ can be estimated by dividing $Q_{pg}$ by the duration of the rainfall, $T_r$.

In this rainfall runoff model, after an infiltrated component to the soil containing fine macropores, $R_t$, is obtained by solving the Richards equation, the components of the prompt groundwater runoff, $R_p$, and direct runoff, $R_s$, are estimated by subtracting the infiltrated amount, $R_t$, from the original rainfall, $R$. If $(R_p + R_s)$ is less than $R_c$, all rainwater except the infiltrated part enter the coarse macropores and direct runoff does not occur in the fallen leaves. If $(R_p + R_s)$ is larger than $R_c$, $R_s$ is calculated by subtracting $R_c$ from $(R_p + R_s)$.

The simulation was performed at the River Tanida basin (Fig. 12, 0.45 km$^2$) using the following model constants: $z_e = 2.75$ m, $R_c = 2.2$ mm h$^{-1}$, $K_oH_o/S_o = 0.179$ m$^2$ s$^{-1}$. Here, $K_o$ is the hydraulic conductivity, $H_o$ the weighted mean depth and $S_o$ the effective porosity of the saturated zone, respectively. The model constants to calculate the interflow through the fallen leaves were the hydraulic conductivity $K_{Lsat.} = 17.1$ cm s$^{-1}$, the effective porosity $S_L = 0.5$ and the Manning’s roughness for the channel $n_r = 0.3$. In this calculation, total rainfall is 155.5 mm, direct runoff depth
Fig. 12 The River Tanida experimental basin.

Fig. 13 Observed and calculated hydrographs of rainfall runoff at the River Tanida experimental basin.

27.2 mm and rapid and delayed groundwater runoff depths 18.7 mm and 10.7 mm, respectively (Fig. 13). The total runoff depth is 56.6 mm which is 36% of the rainfall. The proposed runoff model has been shown to be applicable. The calculated results support the fact that macropores play a very important role in the rainfall runoff process in naturally hilly regions.

RAINFALL RUNOFF PROCESS OF AN URBANIZED AREA AND ITS MODELLING

Based on the results of the infiltration tests and soil surveys, the rainfall runoff processes in the urbanized area may be represented with the conceptual model as shown in Fig. 14.
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Fig. 14 Conceptual rainfall runoff model of the urbanized area.

The greater part of the ground surface is covered with impervious layers, such as houses and asphalt pavements etc., and pervious areas are on the decrease. In the impervious area, almost all of the rainfall flows down to the channel as a direct runoff. In the pervious area, the rainfall infiltrates into the soil layer, and only when the rainfall intensity exceeds the infiltration rate does surface flow occur.

In this model, first, one dimensional numerical analysis of the vertical infiltrations is performed by using the Richards equation to estimate the infiltrated component in the pervious area, $R_i$. Second, the excess rainfall rate for the whole basin has been calculated with equation (7):

$$ R_e = R_{\text{imp.}} \frac{A_{\text{imp.}}}{A} + R_{\text{per.}} \frac{A_{\text{per.}}}{A} \tag{7} $$

where $R_e$ is the excess rainfall rate, $R_{\text{imp.}}$ the rainfall rate in the impervious area, $R_{\text{per.}}$ the non-infiltrated rainfall rate in the pervious area $A$, $A_{\text{imp.}}$ and $A_{\text{per.}}$ the total, impervious, and pervious area of individual subcatchment, respectively. In the calculation of the excess rainfall rate, it is assumed that the depression storage in the impervious area is negligible. Finally, rainfall runoff analysis is performed by using a kinematic runoff model.

The rainfall runoff analysis was performed at the Kita Ogurayama residential catchment area (Fig. 15, 0.17 km$^2$). In this catchment area, the impervious area is 0.088 km$^2$ and the pervious area is 0.082 km$^2$. The surface soil is clay with gravel.

Fig. 15 The Kita Ogurayama residential catchment area.
mixed in and has the physical characteristics shown in Fig. 6. In this calculation the Kita Ogurayama residential area was divided into 14 subcatchments. The equivalent roughness for the slope of individual subcatchments was 0.03 and the Manning’s roughness for the channel was 0.01.

The calculated hydrograph of rainfall runoff agree well with the observed hydrograph (Fig. 16). The total rainfall was 64.0 mm, total runoff depth 36.7 mm, runoff depths from impervious and pervious area 64.0 mm and 11.2 mm, respectively. Total runoff volume exceeds 57% of the rainfall.

CONCLUSIONS

The rainfall infiltration rate on a slope in naturally hilly regions is far larger than the value derived from the hydraulic conductivity of the surface soil. This phenomena is brought about by the fine and coarse macropores in the surface soil layer. On the other hand, the infiltration rate of urbanized areas is nearly equal to the value derived from the theory of unsaturated soil water flow and is not affected by the macropores.

The runoff model of the naturally hilly region was constructed by surface runoff, interflow runoff and rapid and delayed groundwater runoff. The model of the urbanized area was constructed by surface runoff and delayed groundwater runoff. At the residential catchment in the hilly region, almost all rainwater flowed down the impervious and ground surface as surface flow.

These changes of ground surface conditions by urbanization, especially the disappearance of fallen leaves from the hillside, the destruction of fine and coarse macropores and the increase of impervious areas, affects the rainfall runoff process and increases the volume and the peak discharge of rainfall runoff.

In order to prevent the increase of flood damage potential in down stream regions by the urbanization of upstream regions, it is necessary to decrease the flood discharge in urbanized areas by using a storm runoff control method, for example, which makes part of the rainwater infiltrate into soil layer with the aid of buried pipes (Oka, 1990).
REFERENCES


