Balancing the hydrological system

A Japanese approach to sustaining urban areas

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A three-pronged approach, focusing on stormwater control, effective water utilization and environmental improvement, is being followed in Japan to regain a balanced hydrological system in urban areas. This article points out that rainwater storage and infiltration facilities, permeable pavements, rainwater utilization by each household and effective reuses of treated wastewater are effective measures to attain this objective. It is also important to explain the effectiveness to the people so that they cooperate in taking such measures.

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Introduction

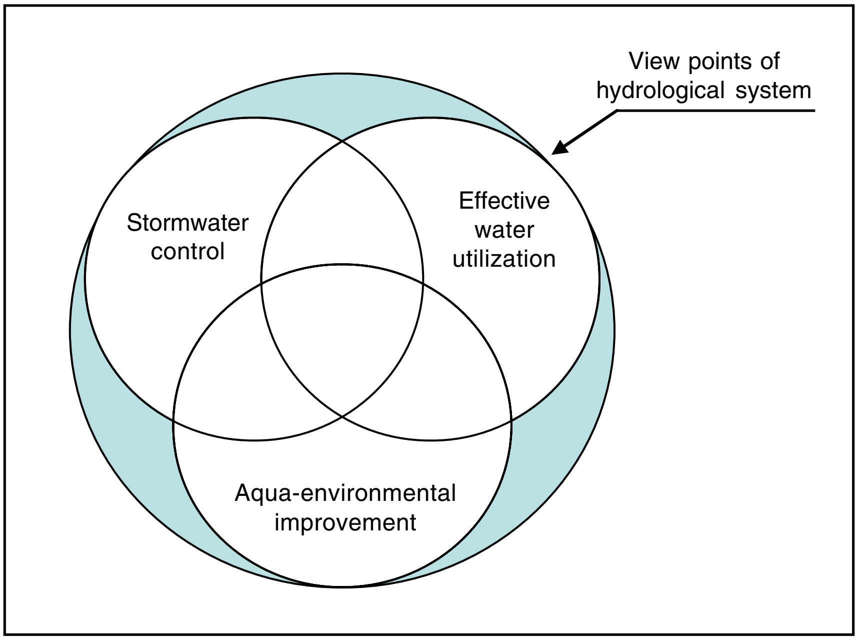
The expansion of urbanization brought in more roofs and pavements and hence more areas become impermeable to rain and water. In addition, improvements in urban stormwater drainage systems meant concentrating river flow discharge during flooding.

But it has also brought in its wake such problems as a decrease in ordinary river discharge, a drying up of spring water and a decrease in groundwater levels. In terms of urban hydrological systems, the risk of drought has increased; and there has been a deterioration of water quality, the cityscape and hydrophilic properties. In heavily urbanized areas, the loss of water areas, green lands and forests will eventually lead to a deterioration in living conditions, an example being the heat island phenomenon.

To reduce this deterioration in the natural and living environments in urbanized areas, it is essential to regain a well-balanced hydrological system. In addition, such lifestyles must be strongly encouraged that support energy conservation and coexistence with the environment.

The authors have reviewed a previous paper[1] on the problems in the hydrological systems of urban areas. Their basic idea was to find out the most effective approach to a solution. They recognized rainwater storage and infiltration facilities as an effective measure. They believe it has become very important for the preservation and recovery of a well-balanced hydrological system to explain the effectiveness of rainwater storage and infiltration facilities to ordinary people,

Figure 1: View points of hydrological system in urban areas



who could then cooperate to introduce these facilities in their own houses.

In order to explain the advantages of setting up permeable boxes in individual houses, this article presents a case study for a typical urban river basin in the suburbs of Tokyo.

Urban hydrological systems

The hydrological system in urban areas is not merely a water circulation system but a far more sophisticated system.[2] Such a system consists of a water cycle, its circulation route, a mechanism to maintain the route and the water exchange between the route and the surrounding area (including the exchange of pollution load transported by water). It results in a change in weather, climate, topography and biological activities, including human activities.

This understanding leads us to three overlapping aspects of the hydrological system in an urban area (Figure 1). These are stormwater control, effective water utilization and environmental improvement. All involve the actions of human beings, who have a relationship with the hydrological system. The three circles overlap as these behaviours are linked to one another. The central area where the three circles overlap shows a balanced hydrological system in coexistence with human beings and nature. It is necessary to understand the hydrological system not only as an environment in which we work but also as a natural hydrological system. This part is shown as the shaded area outside the three circles.

The deterioration of the hydrological system caused by urbanization is analyzed from these perspectives and a flow chart (Figure 2) clarifies each cause and effect. The chart divides the theme into six issues - maintenance of normal flow; flood control; reservation and development of water resources; preservation and recovery of the ecosystem; pollution control; and improvement of the heat environment (Figure 3).

The hydrological system

The hydrological system in an urban area is a combined system of natural and artificial flows. The natural flow consists of rainfall, storage in lakes and marshes, surface flow, infiltration, underground water flow and evapotranspiration. The artificial flow consists of water supply transmitted from rivers or pumped up from underground; and a drainage system for both rainwater and domestic water, such as a sewer network, including treatment plants. In this water cycle, not only the flow discharge but also the pollution load transported by the water flow should be taken into account in assessing water quality. The water cycle has the characteristic of being reusable for ever.

Based on considerations of the six issues shown in Figure 2, measures can be suggested that can contribute to make the water cycle slow by applying the storage and infiltration function. The connection to the six issues is tabulated (Table 1). It is understood that many measures are connected to not just one issue but several issues. These measures, especially the preservation of green land and the promotion of rainwater storage and infiltration facilities, affect all six issues and are sustainable for a well-balanced hydrological system in urban areas, as they naturally preserve the water cycle.

Promotion of facilities

Rainwater storage and infiltration facilities have been promoted in both public and private spaces in Japan. School buildings and yards, parks, stadiums, museums and public buildings such as city halls are the typical public spaces for these facilities. On the other hand, housing complexes and individual houses are the typical private spaces.

Since private spaces are generally more than public spaces, it becomes very important to introduce these facilities into private spaces. But it is very difficult to persuade people to install infiltration facilities in their own houses unless they see some advantage. It is therefore necessary to consider two approaches - regulation and monetary incentives. In the case of new construction or reconstruction, many local governments in Japan have brought in regulations that make the installation of these facilities mandatory. In the case of existing houses, some local governments have introduced a financial support system. But budgets are too limited to promote enough facilities.

On the other hand, it is necessary to develop facilities that are easy for residents to maintain, are low in cost

Figure 2: Causal relation concerning deterioration of hydrological system due to urbanization

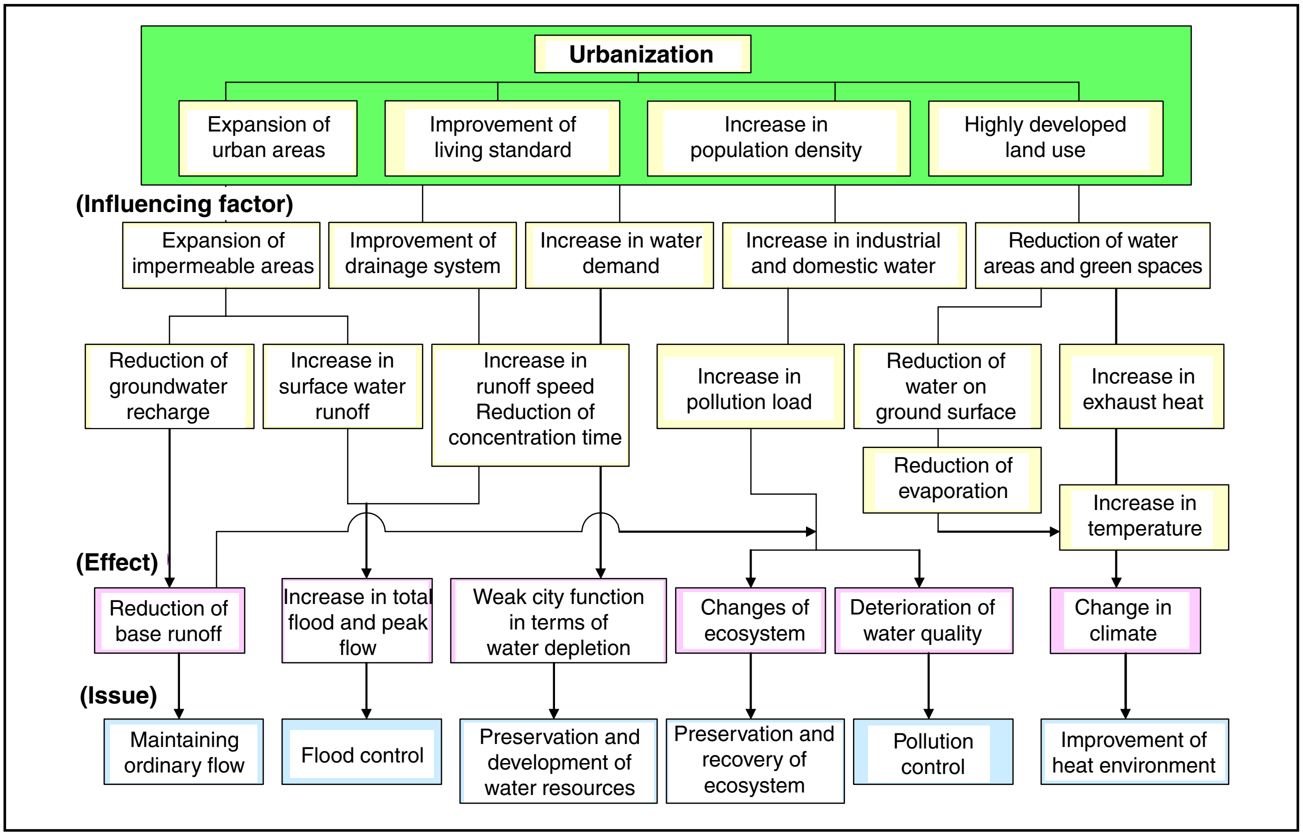


Figure 3: Sub-flow of heat energy

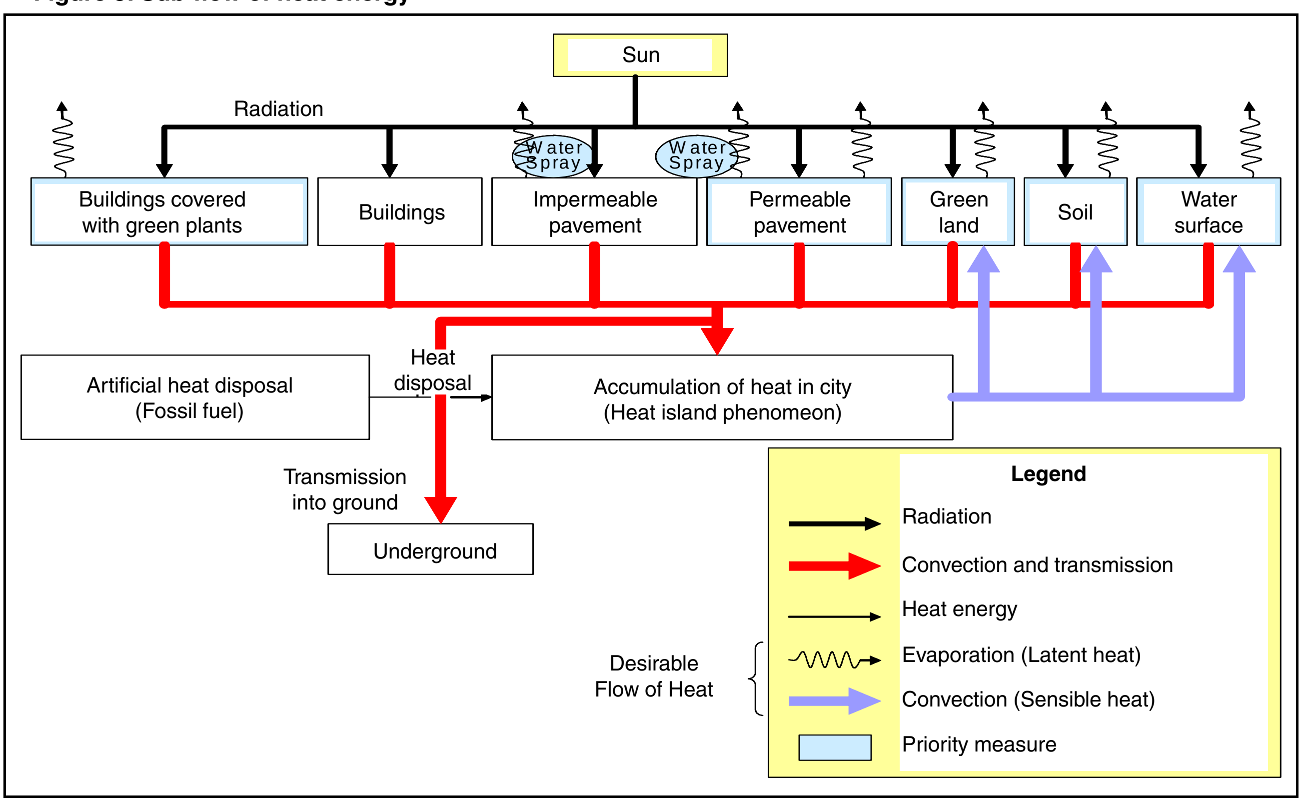


Table 1: Connection between selected measures and six Issues

	Selected measures	Flood control	Ordinary water	Water resources	Ecological system	Heat environment
1.	Preservation of natural land	?	?		?	?
2.	Appropriate land reform	?	?		?	
3.	Promotion of rainwater Infiltration	?	?		?	?
4.	Promotion of rainwater storage	?	?	?		?
5.	Improvement of sewerage system	?			?	
6.	Improvement of rivers	?			?	?
7.	Promotion of water resistance	?				
8.	Utilization of water resources	?	?	?		
9.	Increase in the awareness			?		
10.	Utilization of rainwater		?	?		
11.	Preservation of groundwater flow		?	?		
12.	Appropriate groundwater usage		?	?		
13.	Purification of rivers, ponds and lagoons			?	?	
14.	Point source measures			?	?	
15.	Non-point source measures			?	?	
16.	City greening	?			?	?
17.	Utilization of non-used energy					?

Note: Mark "?" indicates the strong connection with the issue on the top of column

and are in harmony with their houses and gardens.

Figure 4 shows a typical facility set up around an individual house. This kind of voluntary effort will contribute to a well balanced hydrological system (or aqua environment) in urban areas.

Method of estimation

Physically based distributed grid model

A runoff model to describe water circulation in catchment areas has been developed in order to estimate the hydrological system in urban areas. The physically based distributed grid (PBDG) model[3] is able to reflect topography, land use and rainwater storage and infiltration facilities. One advantage of the model is that it can set up physical constants automatically. The model is generally used for long-term water cycle analysis to calculate the annual water balance, including both the natural and the artificial water cycles.

The model consists of three-dimensional cubes connecting in a reticular pattern to describe the topography and river channel. The surface runoff is calculated by an unsteady flow analysis through the kinematic wave method. The infiltration rate in the surface layer of unsaturated zone is calculated by Richard's Equation. The groundwater flow in the aquifer is calculated on the basis of Darcy's Law. Evapotranspiration is calculated with Harmon's empirical formula. The model image is illustrated in Figure 5. The time interval is usually set up to be one day for the long-term analysis, but it can be applied for a short-term analysis of flooding by setting up the time interval to be one hour.

Numerical model example

The effectiveness of measures on flood discharge, ordinary flow discharge, groundwater and evapo-transpiration by rainwater infiltration facilities was estimated for the Azuma River Basin. The effectiveness for the hydrological system by introducing rain-

Figure 4: Typical storage and infiltration facilities image around individual house

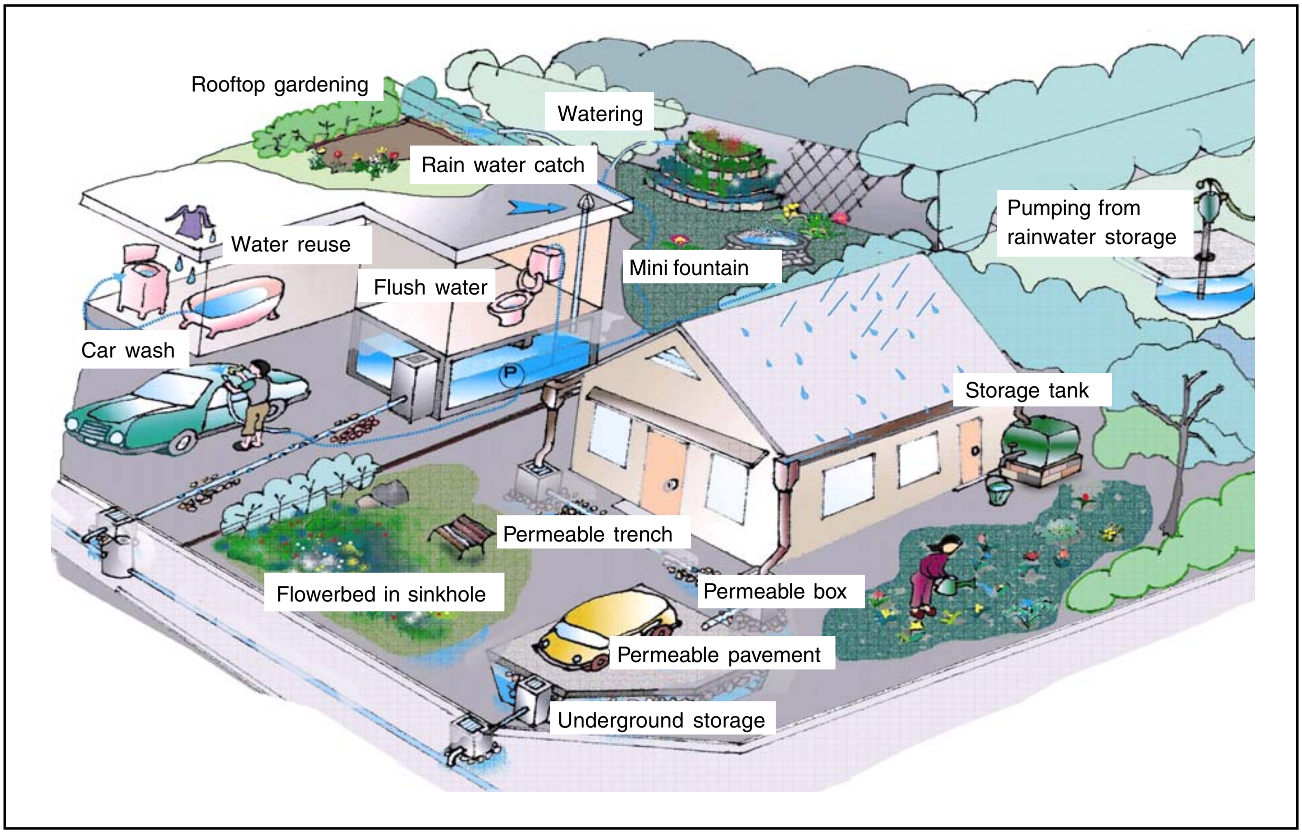


Figure 5: Image of physically based distributed grid model

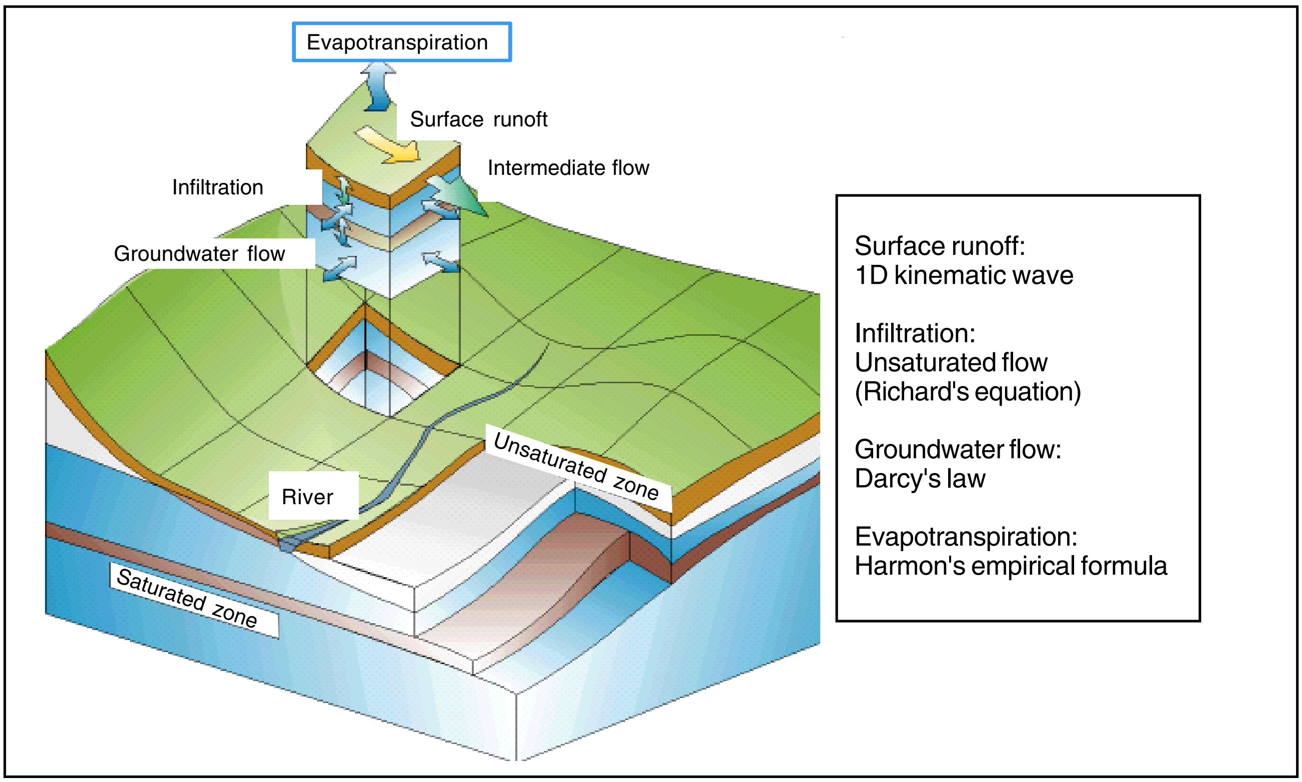
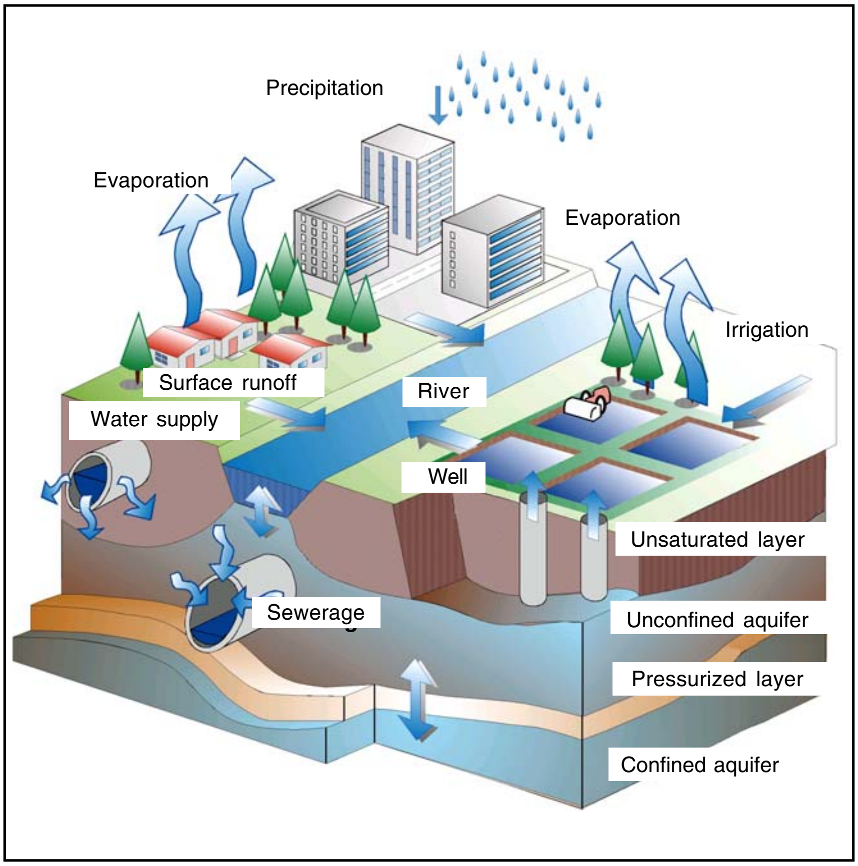


Table 2: Outline of Azuma river basin

	Area, Length	Percentage
Frist-class river	?	?
Basin area	18.2 km^2	?
River length	14.0 km	?
Urbanization-designated area	11.0 km^2	60.7%
Urban area (1994) Individual house	11.3 km^2 4.6 km^2	62.0% 40.05%
Urban area (Future*)	13.5 km^2	74.0%
Area for infiltration	16.0 km^2	88.0%

*Assume that forest and farm land in the urbanization-designated area will be developed to be an urban area in the future around Year 2030.

Figure 6: Subjected items of analysis



water infiltration facilities was calculated by a grid type (50m mesh) analytical model.

The Azuma River Basin is located in Tokorozawa-city, Saitama Prefecture. The Azuma River is a tributary of the Yanase River and a typical urban river, since Tokorozawa city has been rapidly urbanized as a commuter town of the Tokyo Metropolitan Area. The Yanase River Basin is located 25 km from central Tokyo.

The PBDG Model was used to quantify the components illustrated in Figure 6.

The increased population is assumed to be distributed evenly in the newly developed urban area proposed in city planning. The constituent elements of an artificial water cycle are evaluated by unit value multiplied by the assumed future population.

Numerical calculations were done and the results compared with the observation data in order to confirm the applicability of the modelling.

It is found that the numerical results are accurate enough to apply the model and thus further estimate the effects likely to be due to the promotion of infiltration facilities at individual houses.

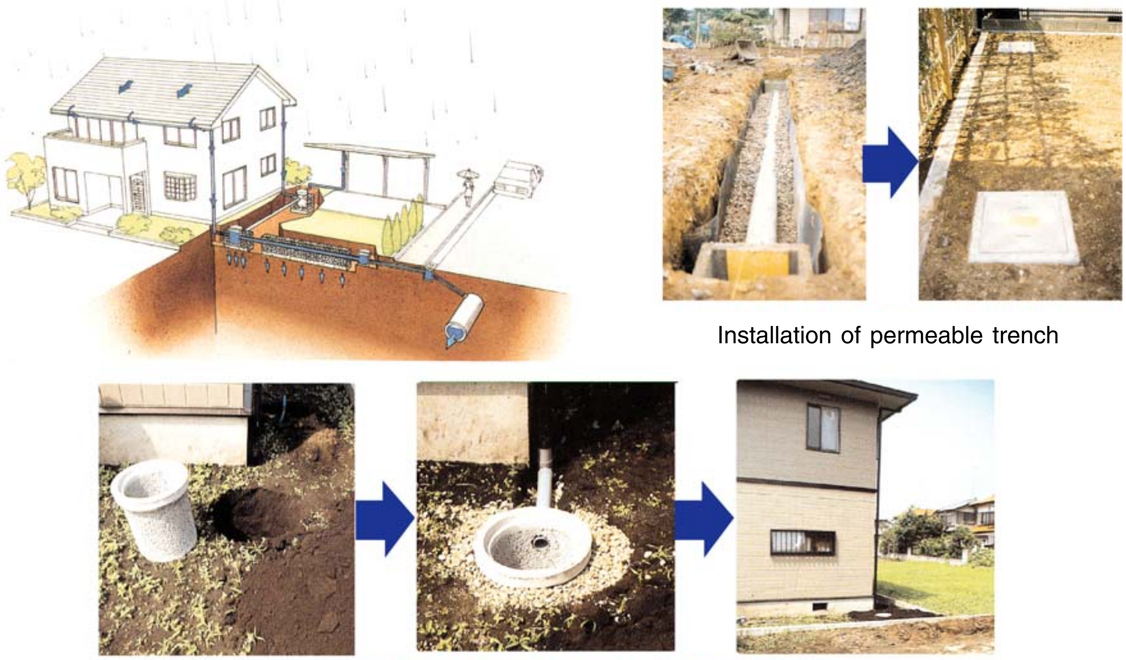
Let us take a typical example of infiltration facilities for an individual house (Figure 7). Assuming the site area to be 120 m^2 for a unit house and its roof area to be 60 m^2, the size of a permeable box and permeable trench is determined in such a way that the rainfall on the roof could be infiltrated in the same volume as the rainfall on the bare land of 60 m^2. As a result, two permeable boxes (diameter 1 m, depth 1 m) and an 8 m length of permeable trench (width 1m, depth 1 m) were concluded to be necessary. In another case, 34,000 houses have to introduce such infiltration facilities until the year of 2030.

The effectiveness for flood control was calculated using the design hyetograph of centralized rainfall pattern based on the rainfall intensity formula of return period of 3 years (equivalent to 50 mm/hr) which was applied for the improvement plan of Azuma river carried by Saitama Prefecture.

The total volume of effectiveness in 2 hours in the vicinity of peak discharge time on the storage volume is equivalent to 76 to 623 of swimming pool (25 m length). It is very difficult to construct a reservoir to control such a large volume since land acquisition is difficult in this crowded city area.

Daily average flow discharges throughout the year were calculated in order to estimate the effect of rainwater infiltration facilities. Calculated daily average flow discharges of 365 days at the downstream end show a sort of index for the characteristics of flow discharge throughout a year.

Figure 7: Typical example of infiltration facilities for an individual house



Installation of permeable trench

Installation of permeable box

The increased value is very small, but if accumulated becomes a valuable 2600 m^3/day, which is natural and sustainable.

Predictions of groundwater levels in 2030 are based on an assumed decrease of rainwater infiltration due to the development of residential areas. However, by introducing a permeable connection box and a permeable trench for drainage in each individual house, the groundwater level can be recovered substantially or even completely.

Green areas, water surfaces and agricultural land will reduce and be covered by pavements and roofs due to urbanization. This will cause a reduction of evapotranspiration and bring what we call heat island phenomenon where the temperature slightly rises up.

Rainwater infiltration facilities are meant to improve the water content in soil. After rainfall, the water in the soil evaporates and this accelerates evapotranspiration. A comparison of the annual water balance between today and 2030 needs to be evaluated so that any factors to be improved can be rectified.

Calculations show that annual infiltration and evapotranspiration are reduced and the surface runoff is decreased due to the effect of such infiltration facilities. Artificial flows such as water supply and wastewater will increase due to the expected increases in population in the future. It is remarkable that the treated water from Tokorozawa treatment plant (804 mm/year) being discharged into the Azuma river at present will be zero in the future after the improvement of the basin-wide treatment plant.

Conclusion

The concept of a well balanced hydrological system is important for urban river basin management. The hydrological system should be balanced between flood control, water resources and water environment.

The preservation of green areas and agricultural areas and the promotion of rainwater storage and infiltration facilities hold the key to such a balance. A partnership between government and citizens is important and engineers have to explain the effectiveness of such measures so that government and citizens cooperate in this social movement.

References

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