〈研修會 敎材〉

Scientific Appreciation of Groundwater in the Hydrologic Cycle.

Some Experimental Results Concerning Rapid Water Table Response to Surface Phenomena.

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ABSTRACT

A review is made of transient phenomena relation to flow in the vadose zone. Reviewed topics include rapid water table response to rainfall, pulsating flow due to pressure perturbations in the vadoes zone, and the wave-like propagation of increased soil moisture caused by intermittent rainfall. As a basis of interpreting these phenomena, zoning of the vadose zone into a residual water zone, an unsaturated capillary zone, and a saturated capillary zone are proposed. Possible implications with respect to hydrological processes relating to theses phenomena are discussed.

INTRODUCTION

In recent years, many concepts relating to rainfall-runoff processes, such as Hortonian overland flow, variable source area-subsurface storm flow, partial area-overland flow, variable source area-overland flow, channel interception and groundwater flow, have been proposed. However, the mechanism of rainfall-runoff processes is still a controversial issue. General understanding baseflow is that response to rainfall is slow, runoff water is suppiled from preceeding rains(i.e., from pre-event water), flow is stable in time, and the runoff process can be hydraulically analyzed as saturated flow. In the case of so-called interflow, flow is rapid, the flow path is on or near ground surface, and water is supplied from the event water. However, isotope studies reveal that a large part of interflow is composed of pre-event water(Sklash and Far-

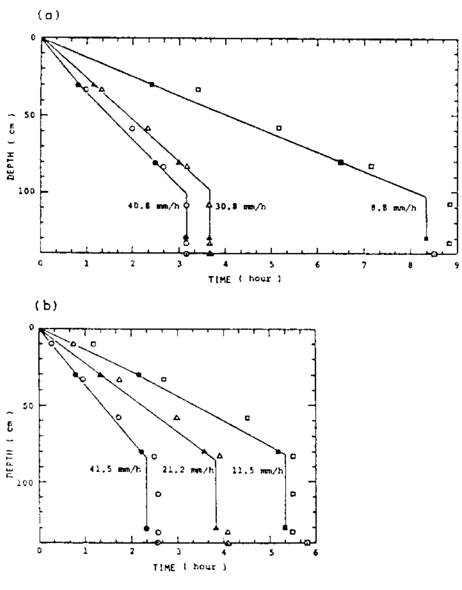

Fig.1. (a)Relation between lapse time required for the detection of soil water movement and depth below the soil surface under different rainfall conditions in the case of sand. Open marks show measured values by tensiometers, closed ones by microflowmeters and marks at the depth of 140cm by flowmeter(Sakura and Taniguchi, 1983). (b) Same as (a)but in the case of glass beads of 0.13mm diameter (Sakura and Taniguchi, 1983), Squares, triangles and circles correspond to different. rainfall intensities.

volden, 1979).

Other studies show the significant effect of pore-air in rainfall-runoff processes as will be discussed later. One must therefore re-examine the elemental processes relating to the behavior of subsurface water.

In this paper, field and laboratory evidence for instability of vadoes water are reviewed, and their possible implications with respect to various hydrological.

Regarding the movement of vadose water due to rain infiltration, an experimental study by Sakura and Taniguchi(1983) is worthy of note. Their experiments were carried out using a soil column(15cm × 15cm × 150cm)with the water table fixed at 140cm below the soil surface. Artificial steady rainfall was supplied to the top of the soil with a water content of field capacity. Groundwater discharge, profile of pressure potential, and soil water flux at three depths were continuously measured(Fig. 1). The experimental soils used were a sand with a median grain size of 0.17mm and two kinds of glass beads of 0.066 and 0.13mm diameter. The results and conclusion of this study are summarized as follows.

According to the equilibrium water content profiles of the experimented soil, the vadoes zone is divided into three zones such as the residual water zone(RWZ), unsaturated capillary zone(USCZ), and saturated capillary zone(SCZ). After rain started, a wetting front was formed and proceeded downward in RWZ with a constant velocity. The downward velocity of the wetting front depends on the rainfall intensity Then, No sooner had the wetting front reached the top of USCZ than the vadose water in USCZ and SCA started to move downward instantaneously, and groundwater dicharge through the water table was observed. The instantaneous response of vadose water in the capillary zone mentioned above is explained by the destruction or break of static equilibrium between an upward capillary force and a downward capillary zone(Sadura and Toniguchi, 1983).

RAPID WATER TABLE RESPONSE

The water table is defined as the plane where groundwater pressure is equal to atmospheric pressure. The water table may rise in response to rainfall of irrigation. However, the rise in the water table in frequently much greater than would be predicted on the basis of water balance calculations using fillable porosity and not groundwater recharge. Germann and Levy(1986) mentioned the following three possible explanations for this ; (1)the build-up of a pneumatic potential due to temporarily entrapped air ; (2)mass flow through porous media ; and (3)flow through macropores.

A special case of mass flow effect without the effect of air pressure was discussed by Gillham(1984)in detail, where the SCZ(tension saturated zone)extends from the water table to ground surface. In this situation, the effective specific yield is near zero, and application of a small amount of water results in a rapid and large rise in the water table. Gillham reported results of a field experiment in which the addition of 0.3cm of water caused the water table to rise 30cm in 0.25min. As the rise is caused by the change in the pressure potential in SCZ from negative to positive values due to the addition of a small amount of water, the water table returns very quickly to its original position with the loss of a small amount of water, either by downward drainage or by evapotranspiration. The effect is therefore highly transient.

In case where the top of USCZ does not extend to ground surface, the water table response due to mass flow through porous media would be recognized when the wetting front reached the top of USCZ as explained in the previous section. Sakura(1983)conducted an experimental study by using two 180cm deep monolith infiltration lysimeters. The lysimeters were packed homogeneoulsy with sand having a 0.38mm median grain diameter and volcanic ash soil called Kanto loam on a 20cm thick layer of gravel. Heights of capillary rise were about 45cm in the sand and over 125cm in the Kanto loam. The saturated hydraulic conductivities were 0.024cm s^{-1} for the sand and 0.0045cm s^{-1} for the Kanto loam. The water table was maintained at about 145cm below ground surface by drainage. Construction of lysimeters is shown in Fig. 2 The experiment continued for one year under natural precipitation. The main conclusion of this experiment was that the groundwater outflow from Kanto loam began to increase eariler than from the sand except for one case in which the surface soil layer was drier than field capacity. Observations using tensiometers and neutron soil moisture disclosed the mechanism of groundwater outflow as follows: although the saturated hydraulic conducivity is lower for the Kanto loam than the sand, the weting front reached the upper boundary of USCZ(i.e.,the top of capillary rise)earlier in the former than in the latter bacause the travel distance from ground surface was shorter for the former than the latter. The time when the wetting front reached to the upper boundary was ascertained by neutron soil moisture meter. This implies a process for piston-like flow in which the new rain water pushes old vadose water in the capillary zone downward.

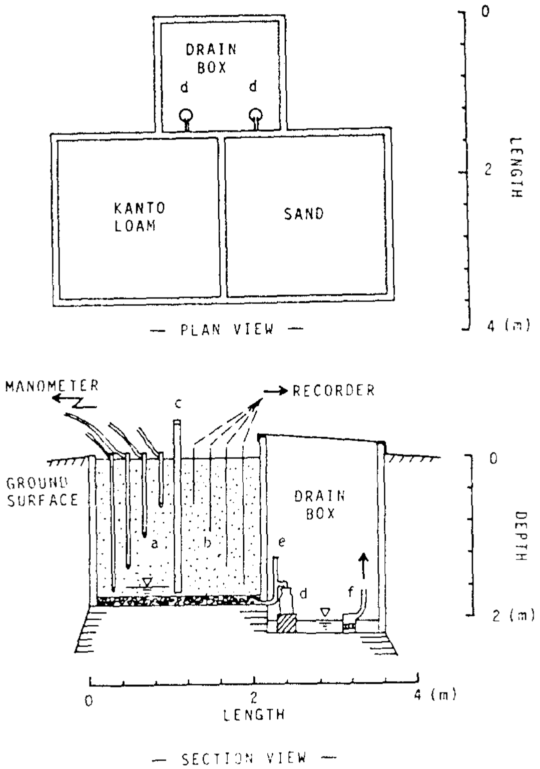

Fig.2. Construction of infiltration lysimeters(Sakura , 1983), a=tensiometer : b=thermocouple ; c=neutron access tube ; d=flow meter ; e=water table well : and f=pump.

If heavy rainfall of flooding causes water to infiltrate at a high rate into the soil, the build-up of a pneumatic potential due to entrapped air in the soil between the downward moving wetting front and the water table occurs. Observations by Miyazawa(1976)in a flat upland as shown in Fig.3 provide a clear evidence of the pnematic effect on the water table changes. Geology of the study area s characterized by alternations of sand, silt and silty sand layers covered with a Kanto loam formation of 2.5m thick. The water table was about 10m below ground surface. The total amount of vadose water was 5400-5700mm. Although no

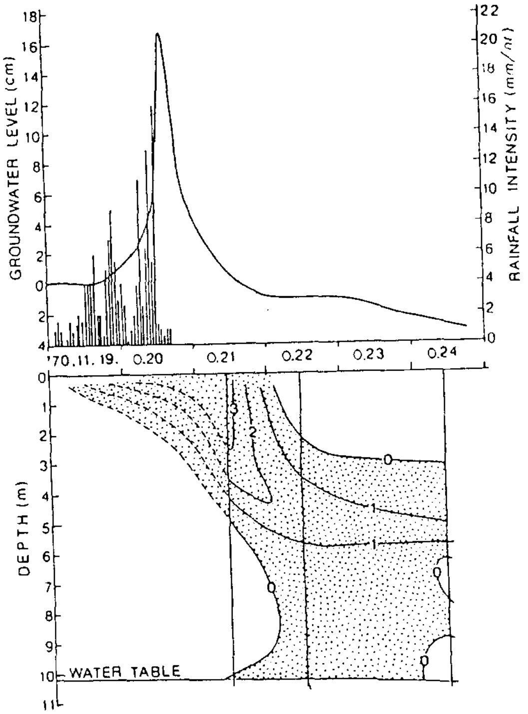

Fig.3. Changes in rainfall intensity and groundwater level(upper), and increase in soil moisture measured by neutron method(lower) for a storm on 19-20 November, 1970. Soil moisture changes are expressed by cm of water in a 100cm thick soil(Miyazawa.1976).

increase in soil mixture was observed in the deeper part of vadose zone, a 17cm increase in water level was observed in the observation well immediately after a heavy storm of 13.7cm.

In order to test the macropore effect, Shimada(1983)collected seepage water, through the Kanto loam formation at a depth of about 13m below ground surface.

The terrace surface over this cave is flat and used as vegetable field, therefore the surface runoff is negligible. A part of the obtained results is shown in Fig. 4. In general, the volume of these seepages corresponds not to a single rainfall but to several events during the season. As the ceiling of the cave was usually saturated, this would be due to the smoothing effect of a suspended capillary zone developed above the ceiling.

The tritium concentration of seepage water was measured whenever the collected volume reached the necessary amount for measurement. As shown in Fig. 4, the variation of the tritium concentration shows a gradually decreasing tendency.

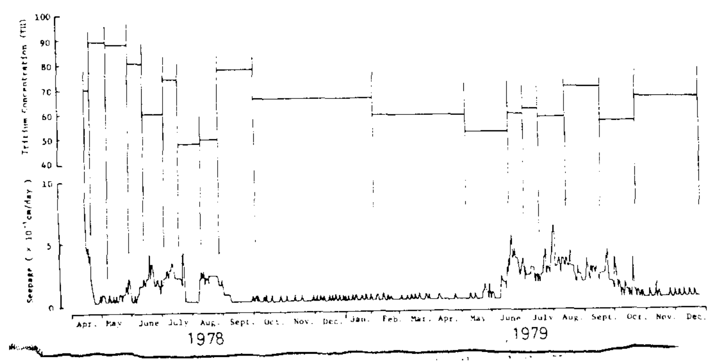

Fig.4. Variation of tritium concentration in seepage water through the Kanto loam formation(Shimada, 1983).

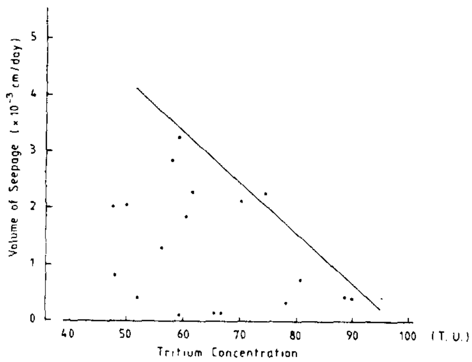

Fig.5 Relation between the volume of seepage and its tritium concentration(shimada, 1983).

The relation between the volume of water by individual sampling and its tritium concentration(Fig. 5)shows a clear distribution according to the amount of seepage. In case the seepage quantity is small the tritium concentration differs case by case, but in case of large quantity it shows lower concentration only. It is considered that in the formercase the seepage water originally should have high concentration nearly equal to that of water in SCZ, nevertheless indirect dilution due to percolation waters with lower tritium concentration occurs in some cases, but not in the other cases. Whereas, in the latter case, rain waters with low tritium concentration would directly dilute the seepaging waters because of the rapid percolation velocity.

As a conclusion of this section, it seems important to note that whatever the caused may be, if the rapid rise of water table occurs, then rapid increase in groundwater outflow will ensue.

PULSATING FLOW

Rapid infiltration causes build-up of peumatic potential below the wetting front. The increased pneumatic potential tends to alter the existing balance between forces acting on the vadose water. One of the resulting phenomena is pulsating flow. Serveral examples of pulsat-

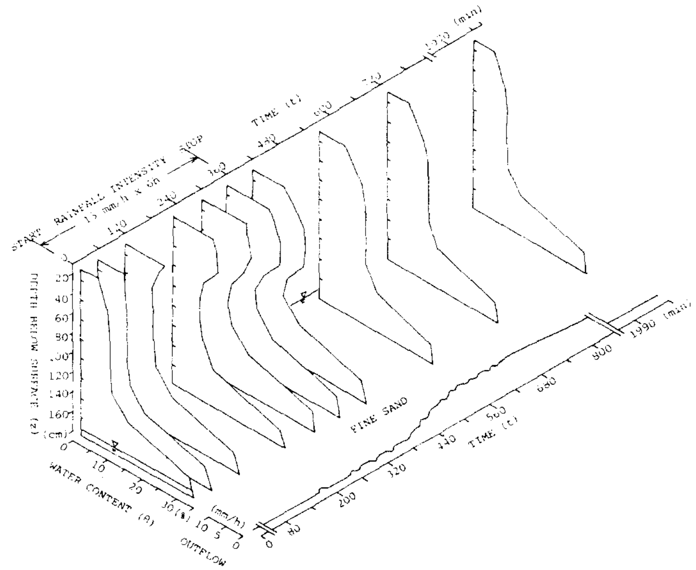

Fig.6. Water content profiles at different times and changes in outflow with time when rainfall with 15mm h^{-1} intensity was supplied for 6h(Kaihotsu, 1979)

ing flow observed in laboratory experiments are presented in this section.

Large-scale infiltration experiments were conducted using four cubic iron boxes with 2.4m sides(Kaihotsu, 1979). Artificial rainfall was supplied by a large-scale rainfall simulator at the National Research Center for Disaster Prevention, Tsukuba. figure 6 shows the changes in the water content profile and outflow from the box when a steady rainfall of 15mm h^{-1} intensity was suppiled for six hours. The physical properties of the experimental material of fine sand are : the saturated hydraulic conductivity is $1.43cms^{-1}$; diameter of soil particles 0.0-0.5mm ; and porosity 48.1%. An important feature in Fig.6. is the pulsations recorded on the rising limb of the hydrograph. The pulsation started earlier than the arrival of the wetting front at the top of USCZ at around 380min after the start of rain, and continued for about four hours after the stop of rainfall. The pulsations were also observed in an experiment with the same rainfall intensity using a coarse sand, but this time they were infrequent and did not occur after the rainfall stopped. The hydraulic conductivity of the coarse sand is 5.26cm s^{-1} and porosity is 47.2%. Though the results obtained are qualitative, it is reasonable to conclude that it is easier for the entrapped air to escape from the coarse sand than from the find sand.

The pulsations also occur during the drainage process. One example was shown by Alim(1986)using a 100cmL × 100cmH × 15cmW sand box packed with standard sand-(Fig. 7). Outlet and inlet chambers whose water levels are controlled by overflow tanks were attached to each side of the sand box. The distribution of hydraulic potential was measured by 54 tensiometers inserted from one side of the

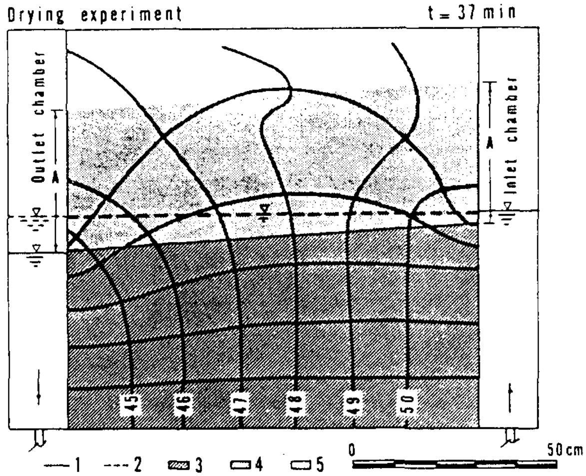

Fig.7. Hydraulic condition of the sand tank at 37 min of the drying experiment(Alim, 1986). A digit number is the hydraulic potential in cm H_2O and lines intersecting perpendiculary to potential line are flow lines. A corresponds to that of in Fig. 1. 1=water table position at water table position at initial condition ; 3=saturated zone ; 4=saturated capillary : 5=unsaturated caillary zone.

Fig. 8. Discharge hydrograph of the sand tank during the drying experiment(Alim, 1986).

sand box. The water table in the sand tank was adjusted at 54cm position from the base. When equilibrium was assured, the level of the overflow tank was lowered by 10cm, while the level of the inflow tank remained unchanged. the hydraulic condition of the sand tank at 37min after the start of experiment is shown in fig 7. Though slight changes in hydraulic potential were recorgnized, main flow patterns observed after 37-136min were nearly the same. The above observation shows that the flow within the SCZ develops the early stages of the experiment and the SCZ behaves as a pathway from the inlet to the outlet zones.

Figure 8 shows the changes in discharge from outlet chamber during the same experiment. By lowering the water level in the outlet chamber by 10cm, the outflow started immediately and reached the highest value within 4 min marking a high peak. A large pulsation occurred again at around 40 min after the start Figure 7 shows the flow pattern when the discharge rate is in a recovery condition from a considerable decrease during this pulsation. Since the soil air in the vadose zone is open to the atmosphere in this case, the cause of pulsation should be found within the capillary zone. However, the corresponding changes in pressure potential during the experiment could not be confirmed by tensiometer reading due to its low sensitivity.

The combination of discharge hydrographs for steady rainfall infiltration for CPAPand UCPAP experiments are shown in Fig. 9. Theses experiments were performed when the water table was located at 80cm below the sand surface.

In this case the upper boundary of the capillary zone reached a depth of 25cm below the sand surface. The difference in the discharge rates in the figure is due to the difference in rainfall intensities of the experiments.

This figure shows that in the case of CPAP experiment, after about 420min from the start, the discharge rate started to rise. After 475min, the discharge rate at first dropped rapidly but later solwly and continued with minor fluctuations till the end of the rainfall. When the pattern of the discharge rate was considered for the UCPAP experiment, it did not show great fluctuations, but there was a relatively large drop around 400min. This drop of the discharge rate continued for about one hour. Later it returned to a normal rate and continued with minor fluctuations until the end of the rainfall. The changes in the water table position during

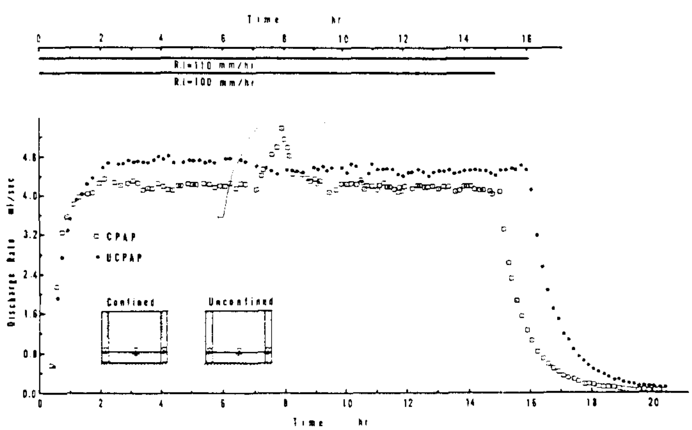

Fig.9. Comparison of discharge hydrographs under confined(CPAP)and unconfined(UCPAP) pore-air pressure conditions, under steady rain(Aim, 1986).

these experiments showed the same characteristics as in the discharge hydrograph for each experiment. During the CPAP experiment, the water table began to rise at about 420min and reached the highest value at around 480min. Within this transient period, the water table rose about 3.5cm higher than the position before 420min. But changes in the water table during the UCPAP experiments did not show greater flucuations.

From the results presented above, it is clear that the occurrence of pulsation is related to many physical and hydrological factors prevaliling at the site. The important hydrological factors are the depth to the depth to the water table below ground surface, rainfall intensity and rainfall duration. To elucidate the mechanism of pulsation,more precise experiments which include measurement of pore-air pressure will be necessary.

WAVE-LIKE PROPAGATION OF INCREASED SOIL MOISTURE.

Figure 10 shows the results obtained by more frequent soil moisture measurements by Maeda et. al.(1981)during a 221mm strom for the 6m thick Kanto loam formation overlying sand and gravel layers. The study site is a flat upland near Kiyose in Tokyo, where the water table is about 9m below ground surface. The ordinate of Fig.10 is the total water content within the 6m thick Kanto loam formation measured at 20cm interval by a neutron soil moisture meter. The measurements were repeated twelve times during and after the storms concerned. Figure 10 indicates that no increase in the total soil moisture storage occurred after the storm.

Next, a comparison of two successive soil moisture content profiles used in Fig. 10 is

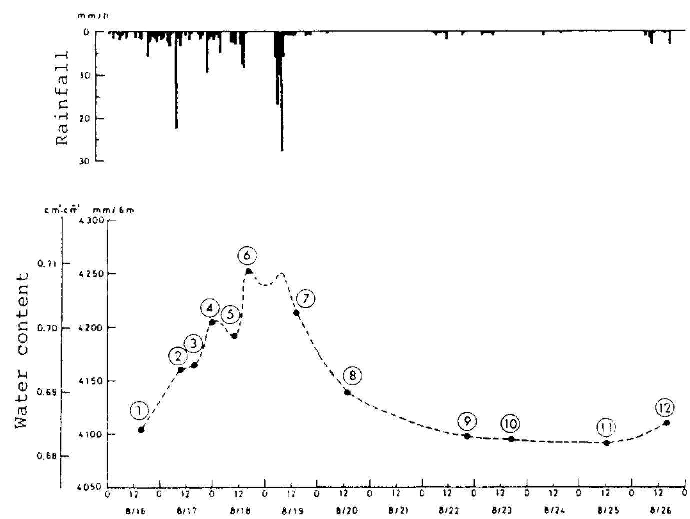

Fig.10. Time variation of total soil water content in a 6m thick Kanto loam formation during the 221mm storm of August, 1977(Maeda et al., 1986).

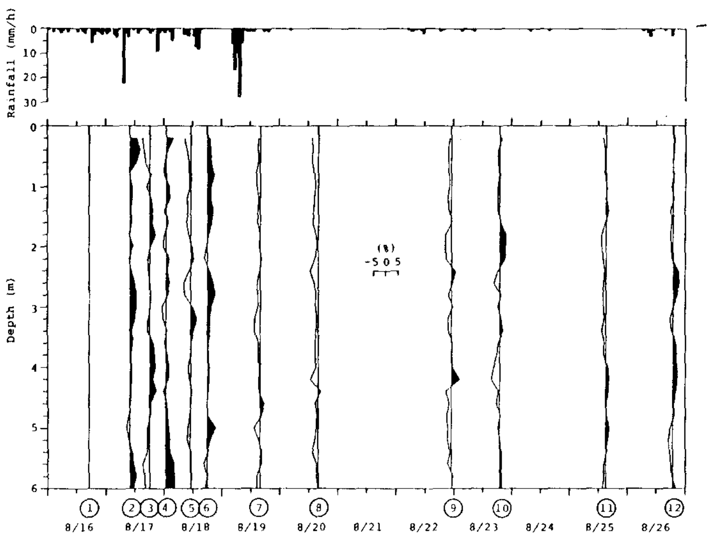

Fig. 11. Time variation of water content changes of two successive profiles (Maeda et al., 1986). Numbers in a circle correspond to those in Fig. 10. Soil moisture is increased in black parts, but decreased in white parts.

made. As shown in fig.11 the increased soil moisture zones appear to move downward with time.

The black and white areas in the figure indicate the increase and decrease in soil moisture content during the successive two time periods, respectively.

The first point to be noted in Fig.11 is the wave-like increase in soil moisture. However, as in the case by Andersen and Sevel(1974), the movement is apparent because the actual downward traveling velocity in the Kanto loam estimated by tritium profiles at the same site was about 1.3myr^{-1}(Kayane et al., 1980). The second point worthy of note is the alternate appearance of the increase and decrease in soil moisture with time at a given depth. The third point to be mentioned is that rainfall infiltration increases soil moisture not only in surface layers but also in deeper layers.

The fourth point is the appearance of the decreased zone immediately below the advancing front of the increased zone.

In the previous sections, we divided the vadose zone into three zones; the residual water zone(RWZ), unsaturated capillary zone(USCZ), and saturated capillary zone(SCZ).

Since the SCZ is quasi-saturated though the pressure is negative, if the SCZ extends from the water table to ground surface, addition of a small amount of water to the surface can change the pressure from negative to positive. The same effect may occur when the pressure of entrapped air above the SCZ is increased by the downward advance of the wetting front. This may cause an apparent rise of water level in piezometer.

The distinction of the USCZ from the SCZ is important because the former shows a limit of capillary rise. The vadose water within USCZ and SCZ is interconnected through the water-filled capillary pores. Therefore when the wetting front reaches the top of the USCZ, the upward capillary force is released, and the water in the capillary zone starts a downward movement.

The rapid apparent rise and fall of the water table after heavy rainfall or irrigation occur by the build-up of a pneumatic potential due to the infiltrating water.

The pulsating flows are observed either during infiltration process or drainage process. A large pulsation occurs even when a steady rain is supplied, if favorable hydrological condition are fulfilled. The pulsation is more pronounced under the confined pore-air pressure condition than the unconfined one.

Under wet climate, alternate occurrence of the increased and decreased zones of soil moisture are frequently observed in RWZ and USCZ during the process of infiltration and percolation responding to rainfall.

Since explanations concerning the movement of vadose water presented above are mostly qualitave, quantitative verification of these explanations will be necessary by applying a two-phase numerical model(i,e.,Morel-Seytoux and Billica, 1985)with air compression effect.

The above conclusions are solely based on the field and laboratory experiments conducted for the flat ground surface. A more general hydrological concern is the movement of vadose water in sloping terrains. The soils in sloping land are usually layered and inhomogeneous contrary to homogeneous materials used in the experiments. The irregularity of ground surface and pipes developed in soil give rise to irregular boundary conditions(Tanake et al., 1982). the amount of water stored in the vadose zone under wet climate is usually large than the amount of rain supplied by a normal storm. Under these circumstances, if we take into consideration the role of vadose water, it seems natural to observe a rapid runoff composed of pre-event water from a drainage basin as a response to a storm event, though the mechanism of rapid runoff would differ from place to place due to the differences in local hydrological conditions.

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288면으로 계속 →

넷째, 水資源開發을 擔當하는 關係 政府部處間의 計劃調整과 水資源開發의 强力한 推進을 目的으로 水資源綜合開發管理를 위한 政策審議機構을 설치하여 물行政을 一元化시켜야 하겠습니다. 지금까지 우리나라는 用水目的別 開發體制의 多元化로 用水需給計劃의 總括 調整이 안되고 있으므로, 이에 대한 改善方案으로서 복합적인 水資源關聯問題를 協議, 調整, 論議할 수 있는 機關의 設置가 시급합니다.

다섯째, 經濟成長과 生活水準의 向上에 따라 住民들에게 河川이 가장 친숙한 自然空間으로서의 그 기능이 要求되고 있으므로 舟運, 觀光, 休息 및 레크리에이션들을 包含하여 河川의 利用을 高度化시킬수 있는 河川綜合開發이 實現되어야 하겠습니다.

여섯째, 댐건설로 인한 水沒地域 移住民들의 補償과 移住對策에 관한 制度的 補完이 必要합니다. 事業施行에 가장 심각한 沮害 要因인 水沒民의 補償問題를 解決하려면 現行 補償評價方法 및 移住對策의 改善을 통하여 移住民에게 生計對策에 대한 충분한 配慮가 이루어질 수 있도록 制度的인 面에서 補完되어야 할 것 입니다.

일곱째, 향후 水資源의 最適開發및 運營을 위해서는 水文觀測增設의 擴充과 신뢰성 있는 水文資料의 蓄積이 이루어져야 하며, 장기적인 水資源開發計劃樹立과 補完을 위한 체계적이고 주기적인 水資源調査事業이 遂行되어야 하겠습니다.

끝으로, 물의 有限性과 水質保全의 重要性을 國民에게 알려서 물에 대한 節水 및 汚染防止認識을 鼓吹시키기 위한 적극적인 國民敎育과 弘報가 있어야 하겠습니다.

結　論

바야흐로 世界는 過去의 물 豊饒時代에서 물 不足時代로 변환됨에 따라 水資源 확보는 인류의 未來를 좌우하는 세계적인 共通課題로 등장하게 되었습니다.

우리나라의 現在 水資源利用量은 水資源總量의 22%에 불과한 實情에 있으므로 이를 더욱 擴大 利用될 수 있도록 하기 위해서 水資源開發管理는 長期的인 側面에서 가장 合理的이고 效率的인 方法으로 시행되어야 하며 良質의 물을 충분히 供給할 수 있도록 專門人들이 다같이 努力해야 할 것 입니다.

現在 建設部와 韓國水資源公社는 오는 '92年부터 시작될 "第3次 國土綜合開發計劃"과 연계하여 水資源의 合理的 開發과 效率的 管理를 도모할 目的으로 "水資源長期綜合計劃"(1991−2011)의 樹立을 推進中에 있어 本計劃이 원활히 추진될때에 國家 經濟 社會發展에 至大한 效果를 주리라고 믿습니다.

2000年代의 우리 後孫들에게 水資源을 통한 福祉社會, 즉 "물이 맑고 깨끗한 社會", "물이 多樣하고 豊足한 社會", "물이 災害로 부터 安全한 社會"인 WATOPIA의 所望을 實現키 위해서는 온 國民이 智慧를 모아서 물文化를 創造해 나가야 할 것입니다.

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