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STUDY ON THE GROUNDWATER FLOW SYSTEM BY ENVIRONMENTAL TRITIUM IN ICHIHARA REGION, CHIBA PREFECTURE *

By Akihiko KONDOH**

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ABSTRACT

This study was performed in order to elucidate the actual condition of a groundwater cycle both qualitatively and quantitatively in Ichihara region, Chiba Prefecture, Japan.

In this study, tritium (^3H) is used to clarify the three-dimensional flow pattern of groundwater. As the results of tritium analyses of 85 samples, it is made clear that groundwater is recharged at the upland regions and flows to the lowland regions. At the vicinity of drainage divides or the Yoro River, it becomes clear that the vertical components of groundwater flow are important.

Tritium concentrations in streams in the drainage basin dissecting uplands indicate the existence of the local flow systems, and their residence time are estimated to be below 30 years. On the contrary, the residence time of the intermediate flow system whose discharge area is the lowland of the Yoro River is over 30 years.

Although a certain degree of mixing occurs during groundwater movement, it is made clear that the general pattern of tritium concentration distribution in groundwater well reflects the history of the groundwater movement. These results support the availavility of the environmental tritium as a tracer, and it is clarified that it can be used to trace the regional groundwater movement.

The tritium analyses reveal the structure of the groundwater flow system, which is much influenced by topography. Then the three-dimensional mathematical model based on the obtained flow pattern is constructed in order to evaluate the dynamic flow through the groundwater basin and its sensitivity against the variation of the recharge.

On the basis of the water balance calculation on the ground surface, the recharge is estimated to be about 600 mm/year. It leads to the total amount of recharge to the basin about 150,000 m^3/day as the results of water balance simulation, but about 80% of the total recharged water discharges through the local or intermediate flow systems.

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** Adress from April 1, 1985 is the Environmental Research Center, the University of Tsukuba, Ibaraki 305 Japan.

The flow across the section along the coast of Tokyo Bay is estimated to be about 30,000 m^3/day. This flow, namely the one in the regional system, is relatively stable according to the sensitivity analysis of the dynamic flow. Flow in the local or intermediate flow systems is influenced by precipitation variation to much greater degree than the flow in the regional system is affected.

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LIST OF SYMBOLS

A	Cross sectional area
C	Concentration of material in solution
D	Discharge from the groundwater bain
D_L	Longitudinal dispersion coefficient
D_T	Transverse dispersion coefficient
D_{sl}	Longitudinal dispersivity
D_{st}	Transverse dispersivity
D_l	Discharge from the local flow system
D_i	Discharge from the intermediate flow system
D_r	Discharge from the regional flow system
Et	Evapotranspiration
K	Hydraulic conductivity
K_{xx}	Hydraulic conductivity in x direction
K_{yy}	Hydraulic conductivity in y direction
K_{zz}	Hydraulic conductivity in z direction
NBY	Natural basin yield
P	Precipitation
Q	Amount of pumping or natural groundwater flow
R	Recharge to the groundwater basin
R_l	Recharge to the local flow system
R_i	Recharge to the intermediate flow system
R_r	Recharge to the regional flow system
R_{max}	Maximum recharge
T	Transit time or mean residence time
TU	Tritium unit
V	Flow velocity
f	Direct runoff coefficient
h	Hydraulic head
i	Hydraulic gradient
t	Time
λ	Decay constant of tritium
φ	Direction of groundwater movement
ψ	Direction normal to groundwater movement
σ	Standard deviation of normal distribution

CHAPTER 1

INTRODUCTION

1.1 Previous studies

In the early stage of groundwater hydrology, the flow of groundwater had been dealt as an areal two-dimensional flow. Hubbert (1940) studied groundwater flow in a vertical cross section based on the potential theory, and found that the water table was not a flow line. His study was the first published account of the basin-wide flow of groundwater that considered the problem in exact mathematical terms as a steady state phenomenon.

However, Tóth (1962 and 1963) indicated incongruities of Hubbert's model, and solved analytically a steady-state groundwater flow equation, which is derived from Darcy's law and steady state equation of continuity, to get flow patterns of isotropic homogeneous aquifers in two-dimensional vertical cross section. Tóth accounted for local topographic relief by superposition of sinusoidal surface on the regional slope of the basin. He showed that flow region was bounded into several subregions, namely local, intermediate and regional systems of groundwater flow.

Freeze and Witherspoon (1966, 1967 and 1968) developed a numerical method for the analysis of nonhomogeneous (multilayer), anisotropic aquifers with general configurations of water table. They showed the effect of geology as well as the effect of topography.

These studies indicated that the main factors determining the structure of groundwater flow systems were the topography (as reflected on the water table configuration) and the geology, except for the climatic factor which influenced the recharge.

The existence of theoretically derived groundwater flow system has been confirmed by several researchers. Meyboom (1967) installed many piezometers in the Candadian Prairies, and clarified the three-dimensional flow of groundwater. Hitchon (1969a, b) described the effects of topography and geology on the groundwater flow system in the western Canada sedimentary basin. He showed that the potential distribution was strongly influenced by the topography and the Tóth's model was meaningful when applied to an actual sedimentary basin.

Tóth (1963) defined the groundwater flow system as "a set of flow lines in which any two flow lines adjacent at one point of the flow region remain adjacent through the whole region, and that can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction only". According to the above definition, the actual basin should be a composite basin consisting of many groundwater flow systems of different orders. Freeze and Witherspoon (1968) defined the groundwater basin as "a three-dimensional closed system which contains the entire flow paths followed by all water recharging the basin". It is the most fundamental unit in dealing with groundwater balance in that inter-basin flow does not exist. Therefore, clarifying the flow distribution in the groundwater basin is connected to the recognition of the actual conditions of groundwater flow.

The tracer method using environmental isotopes is available in a regional scale study both in time and space. Especially, environmental tritium is one of the most ideal tracers because it consists of water molecule.

Most studies on groundwater movement by environmental tritium are based on the flow models, for example, presented by Nir (1964) or Dincer et al. (1970), therefore, they did not always provide an understanding of the true situation of the groundwater movement. If the regional distribution pattern of tritium concentration can be obtained, the complicated model construction is not always necessary for the interpretation of groundwater movement or its residence time.

Haskell et al. (1966) measured the tritium concentration distribution in west side of the San Joaquin Valley in Western Fresno County, California, and estimated that groundwater had moved westward with average velocities of 2,440 – 2,895 m/year. However, Poland et al. (1975) sampled and tested the tritium concentrations of well waters along the same traverses as Haskell's, and they found that the average velocity was less than 460 m/year.

Rabinowitz et al. (1977b) performed random sampling of groundwater in the Roswell Basin, New Mexico. They confirmed the direction of groundwater movement and estimated the residence time of groundwater from the tritium concentration distributions.

These studies treated the groundwater movement as two-dimensional flow, however, the flow of groundwater occurred essentially in the three-dimensional space. If three-dimensional distribution of tritium concentrations can be made clear, three-dimensional flow distribution can also be clarified.

1.2 Objectives of the study

Groundwater flow system is a subsystem of the hydrologic cycle, and constitutes an open system connecting recharge areas and discharge areas. This system is a three-dimensional flow field of groundwater itself. As a long term average, the recharge to and the discharge from the system are in dynamic equilibrium in natural condition.

The recharge to the system can roughly be estimated from the water balance on the ground surface. Hence, by specifying the extent of the recharge areas in a groundwater basin, the total amount of recharge can be understood. This is equal to the dynamic flow through the groundwater basin and the total amount of discharge.

The groundwater basin is the most fundamental unit in dealing with the groundwater balance. The groundwater balance should be considered on the basis of the groundwater basin as a part of the hydrologic cycle. For that purpose, the spatial extent of the groundwater basin and the three-dimensional geometric distribution of groundwater movement in it must be determined.

The objective of present research is to understand the actual condition of the groundwater cycle both qualitatively and quantitatively. For that purpose, three-dimensional geometric distribution of the groundwater movement and the dynamic flow through the groundwater basin must be determined. Environmental tritium is used to determine the flow distribution in the groundwater basin, and the mathematical model is employed to quantify the dynamic flow through the groundwater basin and its spatial distribution.

1.3 Methods

Tritium is produced naturally in the upper atmosphere by interaction of cosmic-ray-produced neutrons with nitrogen. Natural level of tritium concentration in precipitation is estimated to be about 10 TU (TU: 1 tritium unit is equal to 1 T atom for 10^{18} H atoms), but thermonuclear tests started in the late 1952 increased the tritium level in precipitation to several thousands TU in

1960's. Therefore, tritium in groundwater is used to identify the water that entered the groundwater zone after 1953. The distribution of tritium in the groundwater flow system can be used to outline the direction of the groundwater movement and the transit time between the recharge and sampling.

On the basis of above account, firstly, spatial pattern of tritium concentration distribution in groundwater is investigated in order to clarify the flow pattern in the groundwater basin. Secondly, a three-dimensional mathematical model based on the flow pattern estimated by environmental tritium is constructed in order to quantify the dynamic flow through the groundwater basin.

Tritium analyses were made according to Shimada (1976) at the University of Tsukuba, Japan. Samples were concentrated by electrolytic enrichment method of two steps from 1,500 ml to about 5 ml, and then counted for β ray using a liquid scintillation spectrometer. Detailed explanation of the method is given in Shimada (1976 and 1977).

CHAPTER 2

DESCRIPTION OF THE STUDY AREA

The study area for this research is Ichihara region, Chiba Prefecture, Japan. The area is situated to the east of Tokyo Bay and covers an area of about 100 square kilometers. Figure 1 shows the location of the area.

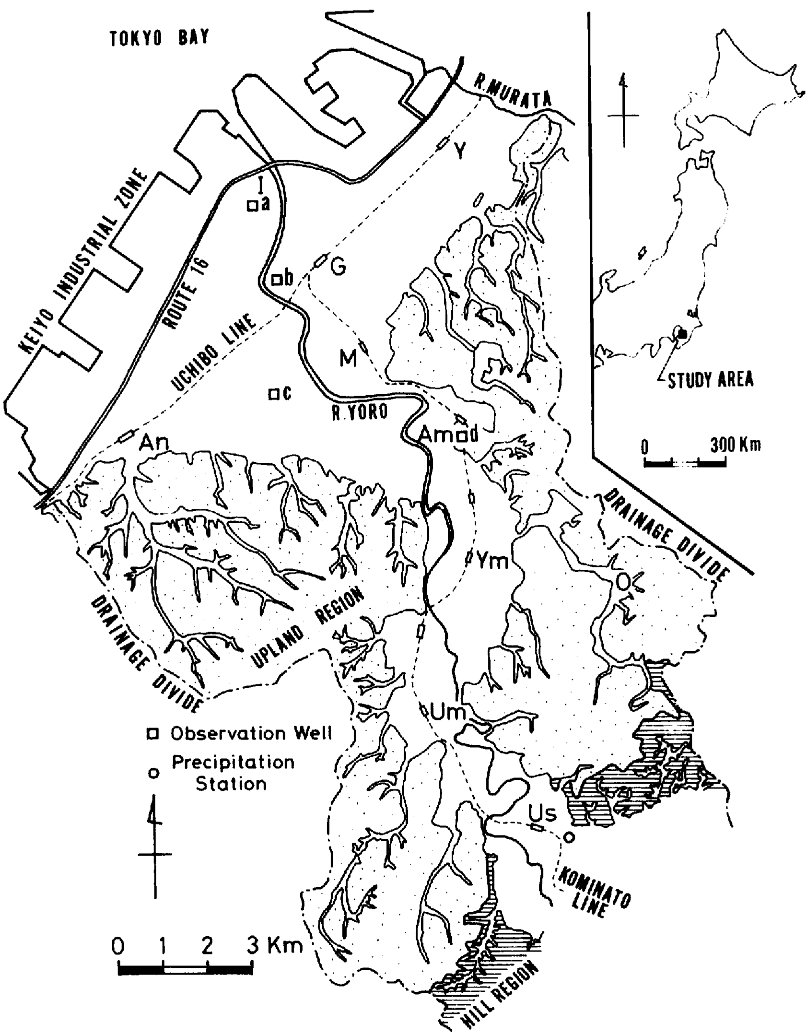


Figure 1 Location of the study area. (a) to (d) denote the location of the observation wells. I: Iwasaki, Y: Yamada, An : Anegasaki, G: Goi, M: Murakami, Am: Ama-ariki, Ym : Yamada, O: Ooke, Um: Umatate, and Us: Ushiku.

2.1 Topography

Topography of this area consists of diluvial uplands, river terraces, alluvial lowlands and reclaimed lands. The uplands are a part of the Shimosa upland and are widely distributed on both sides of the Yoro River. The Yoro River flows northward in the middle part of this area and empties into Tokyo Bay. The river terraces are widely distributed on both sides of the Yoro River and divided into many terrace surfaces. The alluvial lowlands are distributed along the Yoro River and along Tokyo Bay, and they become the delta near the mouth of the Yoro River. The coast was reclaimed and the Keiyo Industrial Zone was constructed.

The geomorphic surface of the upland regions is the Simosa Lower Terraces (Sugihara, 1970) and volcanic ashes above the Shimosueyoshi Formation, are distributed on the upland regions. The altitude of the upland regions is over 100 meters above sea level in the southeastern part and diminishes to about 40 meters in the northwestern part of this region.

The Yoro River forms valley plain about 1 to 3 kilometers wide, where many river terraces are distributed. These river terraces are divided into Ichihara surface, Nanso surface and Kururi surface (Sugihara et al., 1978; Kashima, 1982) according to the formative periods, and each surface is further divided into 2 to 5 subsurfaces.

The back marshes, natural levees, beach ridges and old channels are distributed in the alluvial plain. The relative height between alluvial plain and upland regions is about 40 meters in the northwestern part of the region, and increases to more than 100 meters near Ushiku.

The Kasamori Formation, the upper part of the Kazusa Group, is exposed in the south of Ushiku, and makes hilly countries with dense stream networks. It is composed of very muddy materials, accordingly, the erosion rate is high and the altitude of this area is lower than the southeast margin of the Shimosa upland.

2.2 Hydrogeology

The study area is entirely composed of the Quaternary systems, and can be explained as follows: the Shimosa Group and the Kanto Loam Formation which constitute the upland regions, and the alluvium which distributes along the rivers.

The Shimosa Group is widely distributed in the area of Shimosa Upland in the northern parts of the Boso Peninsula, and is composed of shallow marine sands and fresh- or brackish water mud. The mud beds interbedded by the sandy beds are mainly composed of silt or clay, and are locally accompanied by gravel beds of fresh water sediments forming channels.

The Shimosa Group shows cyclic sedimentation which starts from muds and ends with sands. Each mud bed is well continued and is used as boundaries for the classification of formations.

The study area is located in a southeastern part of the Kanto Tectonic Basin (Yabe et al., 1926). The Kanto Tectonic Basin forms basin structure which covers thick formations upper than Miocene series on the pre-Tertiary systems. In the Period when the Shimosa Group deposited, the Kanto Tectonic Basin was divided into some small subbasins (Uesugi et al., 1977). The study area is located in the southeastern part of a subbasin centered in the Tokyo Bay, and accordingly the Shimosa Group in the study area shows monoclinic structure dipping northwestward. According to the Chiba Research Institute for Environmental Pollution (1974), maximum depth of the Shimosa Group is minus 440 meters at Chigusa-Kaigan, Ichihara City. The depth of the top of the Kasamori Formation, which is the basement of Shimosa Group, diminishes southeastward as shown in Figure 2, and exposes ground surface at about 15 kilometers from the coast of Tokyo Bay.

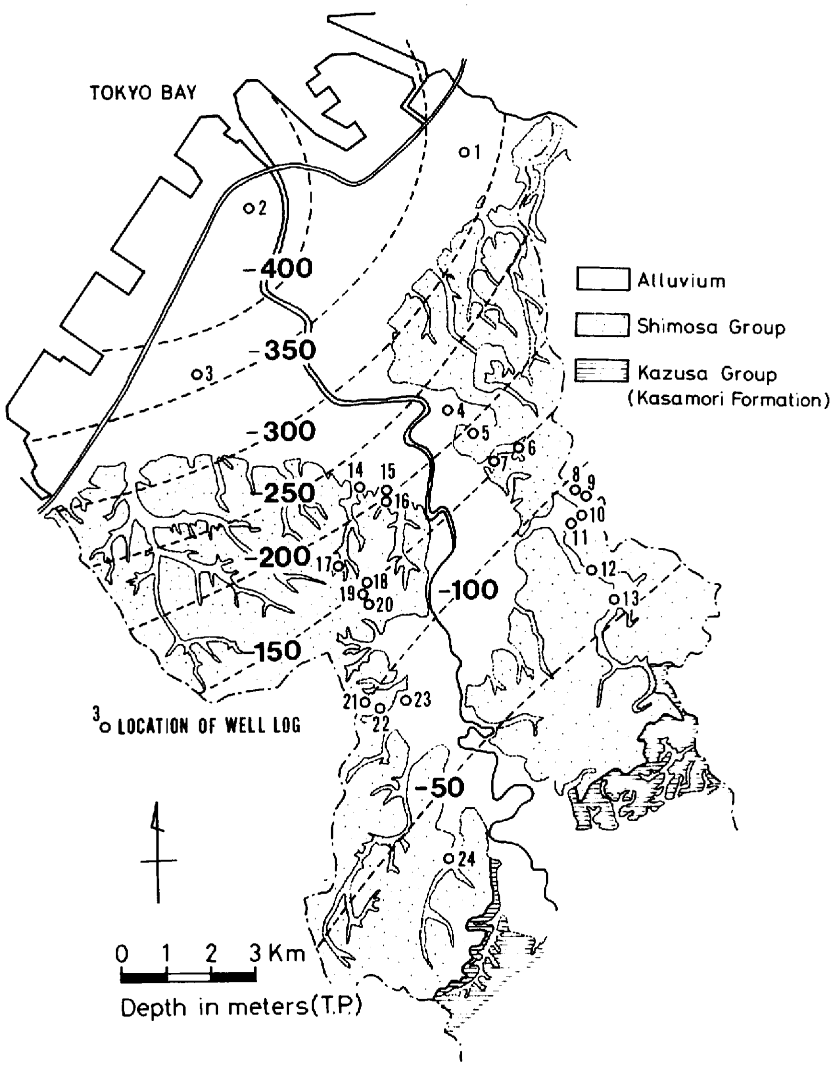


Figure 2 Generalized geologic map in the study area. Dashed lines indicate structural contour on top of the Kasamori Formation. Circles show the location of well logs.

Figure 3 shows geologic columns in the study area. The thickness of mud beds in the columns ranges from several meters to about 50 meters, but few pure clay or silt is presented, most of mud beds are sandy muds. At least four mud beds can be traced in the inland region, whose facies and thickness are changing at places, and muds disappear locally.

These muds can be observed as outcrops in the inland region. They are thinner than those of in the well logs, and generally thinner than about 10 meters. The facies of these mud beds are sandy mud or thin alternation of sand and mud with few portion of pure clay or silt.

The geology of this area shows the monoclinic structure with gentle slopes dipping northwest. Hence, the direction of groundwater movement tends to be considered that it flows to the direc-

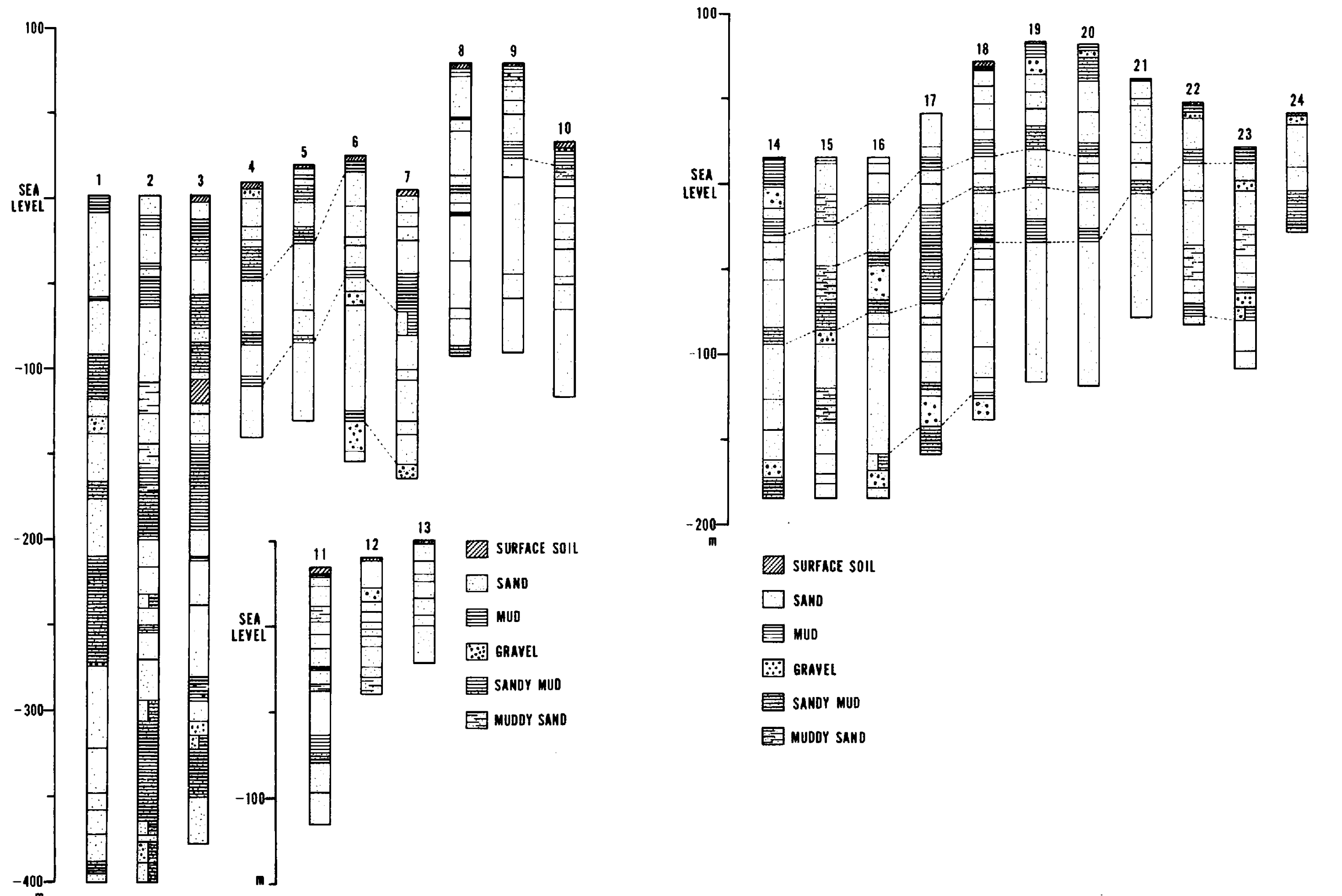


Figure 3 Well log cross sections. The locations are shown in Figure 2.

Table 1 Hydraulic conductivities obtained from aquifer tests. D: Domestic, O: Observation well, and A: Agriculture.

Location		Use	Screen (m)	*K* (cm/sec)
2.	Iwasaki	O	261.0 – 277.5	0.00006
3.	Aoyagi	O	327.0 – 360.0	0.00611
6.	Fukumasu	A	87.5 – 98.5	0.00250
			148.5 – 153.5	
			159.0 – 170.0	
8.	Sanwa	D	87.5 – 104.5	0.00067
			115.0 – 120.5	
			131.5 – 142.5	
9.	Sanwa	D	94.0 – 110.5	0.03400
			149.0 – 165.5	
10.	Takeshi	A	67.0 – 78.0	0.02010
			89.1 – 111.5	
11.	Takeshi	A	104.0 – 115.0	0.01300
			137.0 – 147.5	
			159.0 – 175.5	
	Chichu	A	23.0 – 40.0	0.00152
			72.0 – 100.0	
	Chichu	A	47.0 – 58.0	0.00760
			69.0 – 113.0	
12.	Ooke	A	11.0 – 55.0	0.00566
13.	Ooke	A	14.0 – 64.5	0.03100
16.	Unakami	D	90.0 – 107.0	0.03300
			145.0 – 162.0	
			183.0 – 195.0	
18.	Kofudai	D	126.0 – 131.5	0.00042
			137.0 – 153.5	
			170.0 – 181.0	
			197.5 – 203.0	
19.	Kofudai	D	125.0 – 137.0	0.23800
			143.0 – 150.5	
			161.0 – 179.0	
			185.0 – 191.0	
20.	Kofudai	D		0.02590
				Average: 0.028 cm/sec

Note) Location number corresponds to the one in Figure 2.
D: Domestic, O: Observation, A: Agriculture.

tion of dip along the strata. In the region consisting of the unconsolidated materials like Shimosa Group, mud beds are not completely impervious. Except for the region that thick mud beds are developed, the flow following the geologic structure only is hard to develop. Therefore, the flow pattern in the study area must be reexamined.

Table 1 shows hydraulic conductivities obtained from aquifer tests. These values are ranging from 10^{-1} to 10^{-5} cm/sec, and the average of 15 values is 0.028 cm/sec.

2.3 Precipitation and evapotranspiration

Long term record of precipitation for Ushiku, southern part of the study area, indicates the annual precipitation from 1954 to 1982 between 1,014 to 2,022 mm/year, with an average value of 1,627 mm/year. Precipitation in the area mainly occurs during rainy seasons of June and July, so called Bai-u, and during the typhoon season of late summer to autumn.

Evapotranspiration was calculated by Penman's method. The actual evapotranspiration from vegetated surface was estimated from the potential evapotranspiration from the surface of the water by multiplying the empirical constant. In this study, corrected reduction factor of Nakagawa (1983) was used to calculate the actual evapotranspiration. As for the empirical coefficients of short-wave and long-wave radiation in Penman's formula, those of Kobayashi (1977) and Nakagawa (1977) are used, respectively.

Meteorological data at Chiba City are used to calculate the evapotranspiration from 1966 to 1982. The data at Chiba City before 1965 are absent, and data at Tokyo before 1965 are used. As a result, annual evapotranspiration ranges from 643 to 779 mm/year and the average is 696 mm/year.

Figure 4 shows the variation of annual precipitation and evapotranspiration during 1954 to 1982. Annual evapotranspiration is relatively stable, however, precipitation shows large variation. Standard deviation of annual values from 1954 to 1982 is 38 mm/year for evapotranspiration, and 255 mm/year for precipitation. It means that annual recharge to groundwater may actually show a large variation.

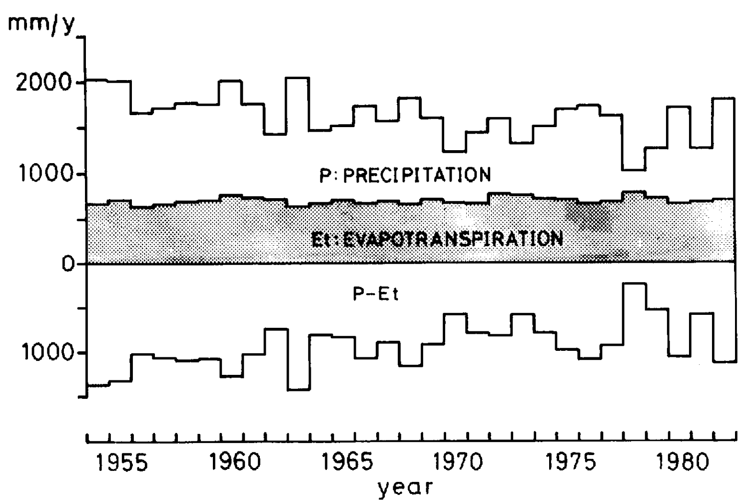


Figure 4 Annual precipitation and evapotranspiration at Ushiku during 1954 to 1982.

2.4 Groundwater Use

Groundwater from flowing wells or shallow wells was mainly used for domestic, irrigation or washing nori (laver) until late 1950's. Groundwater use of this region had changed in proportion as the development of the coastal industrial zone after 1960's

Figure 5 shows the changes in the pumping rate in Ichihara City after 1969 (Environmental Department of Chiba Prefecture, 1975–1982). No official statistics on groundwater use are available before 1969.

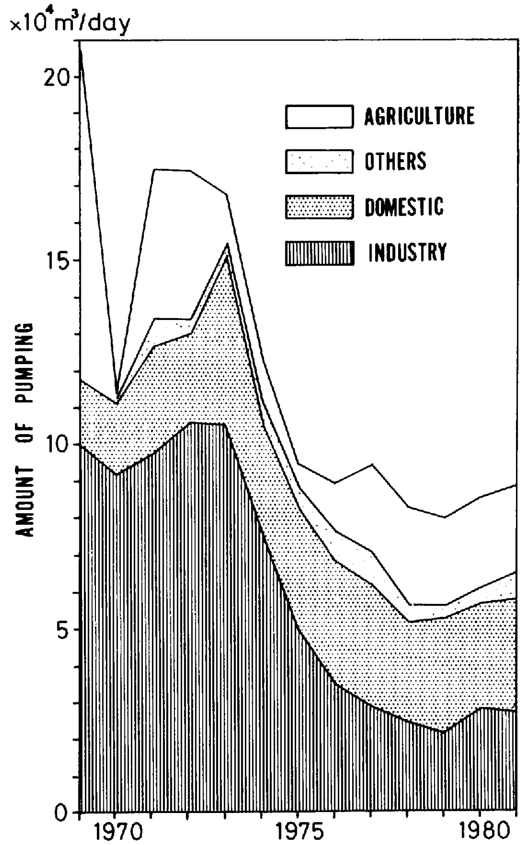


Figure 5 Changes in the amount of groundwater pumping for Ichihara City, 1969–1981.

Wells for agricultural uses are scattered in the alluvial lowlands and those for the domestic purposes are dug in the inland region which have a tendency to concentrate several wells at a site. On the contrary, almost all the wells for industrial use are in the coastal industrial zone, and the amount of pumping for industry in Figure 5 can be regarded as that in the coastal industrial zone.

The reclamation of the foreshore in the Ichihara region was started in 1957 and accomplished

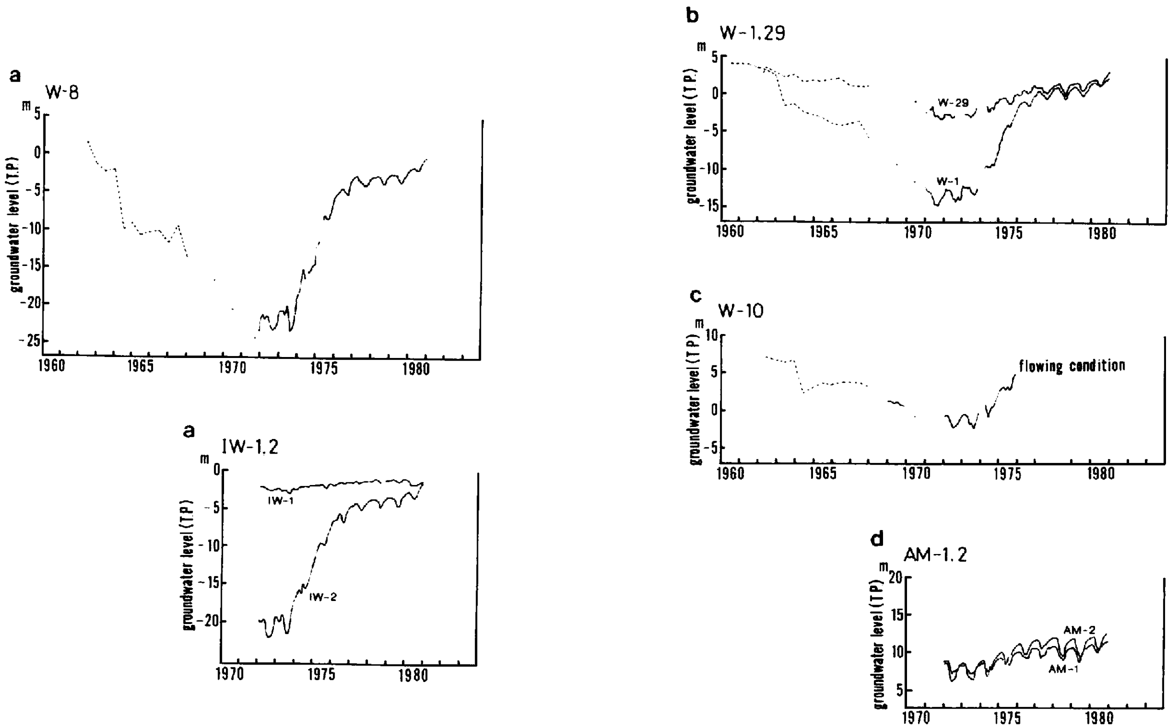


Figure 6 Changes in groundwater level for observation wells along the Yoro River. Locations of wells are shown in Figure 1.

in 1967. The abstraction of groundwater in the industrial zone began in 1959. In the early stage of groundwater development, there was no regulation for abstractions, partly because the groundwater resources were thought to be abundant in the region. According to the Hydrogeological Map of Chiba Prefecture prepared by Chiba Prefecture in 1961, the dynamic flow across the coast of Ichihara City of 20 kilometers long was estimated at least 150,000 m^3/day, and it was regarded as the possible amount of groundwater development.

The amount of pumping for industrial use was about 100,000 m^3/day and almost constant around early 1970's. In late 1960's, the undesirable effects such as the cessation of flowing wells and the land subsidence became a serious public concern. Accordingly, the regulations for groundwater pumping in Ichihara City was enacted by Chiba Prefecture in 1972. As a result, the amount of pumping for industrial use decreased rapidly after 1972 to about 20,000 to 30,000 m^3/day around 1980. As it will be stated later, the decrease of withdrawal for industrial use corresponds to the recovery of water levels in the coastal lowland.

2.5 Groundwater level fluctuations

Many observation wells are installed by Chiba Prefecture and Ichihara City in the study area. Figure 6 shows the changes in groundwater levels for observation wells along the Yoro River. The locations of observation wells are shown in Figure 1.

W-8, IW-1 and IW-2 at Iwasaki are located in the foremost part of the delta of the Yoro River. Depths of screens for these observation wells are from 258 to 272 meters in W-8, from 25 to 31 meters in IW-1, and from 261 to 278 meters in IW-2. The decline of water levels in W-8 until early 1970's reached 25 meters, and thereafter water levels have been rising steadily. Water level change of IW-2, whose screen is about the same depth with W-8, is similar to that of W-8. The depths of screens of wells in the coastal industrial zone are concentrated on the depth from 200 to 400 meters. The depletion of water pressure in this zone was influenced on the water level changes in W-8 and IW-2. The total fall of water levels in IW-1 is only about 2 meters. Therefore the vertical hydraulic gradient in early 1970's when the lowest water levels were recorded, attained about 1/10. The recovery of water levels of IW-2 is very rapid, and the water level in IW-2 is the almost same as that of IW-1 in 1980.

W-1 and W-29 are located at Goi about 2 kilometers from the coast of Tokyo Bay. Depths of screens in each well are from 245 to 257 meters and from 128 to 140 meters respectively. Water level of W-1 was higher than that of W-29 and they were at flowing condition around early 1960's. The fall of water levels was more rapid in W-1 than in W-29, and hydraulic gradient between the screens of each well reached about 1/10 in early 1970's. The recovery of water levels were more rapid in W-1 than in W-29, and the relation of water levels has been reversed in 1980.

The location of W-10 is about 3 kilometers from the coast of Tokyo Bay and the depth of screen is from 195 to 207 meters. The water level had fallen about 10 meters until early 1970's, and thereafter it has been recovered. W-10 has been at flowing condition since 1975.

AM-1 and AM-2 in Ama-ariki are located about 7 kilometers from the coast. The depths of screens in each well are from 76 to 95 meters and from 188 to 228 meters respectively. The water levels have been recovered since early 1970's. The water level in AM-2 was lower than in AM-2 in irrigation season of summer until 1974, and thereafter the relation is reversed.

Changes of these water levels are very similar to each other, and the pattern of changes are divided into following four distinctive periods. Each period corresponds to the changes of the amount of withdrawal in coastal industrial zone:

I	steady fall (–1970)	estimated to be larger than 100,000 m^3/day	
II	lowest level (1971–1973)	about 100,000 m^3/day	
III	rapid recovery (1974–1975)	rapid decrease from 100,000 to 50,000 m^3/day	
IV	steady recovery (1976–)	steady decrease from 50,000 to 20,000 m^3/day	

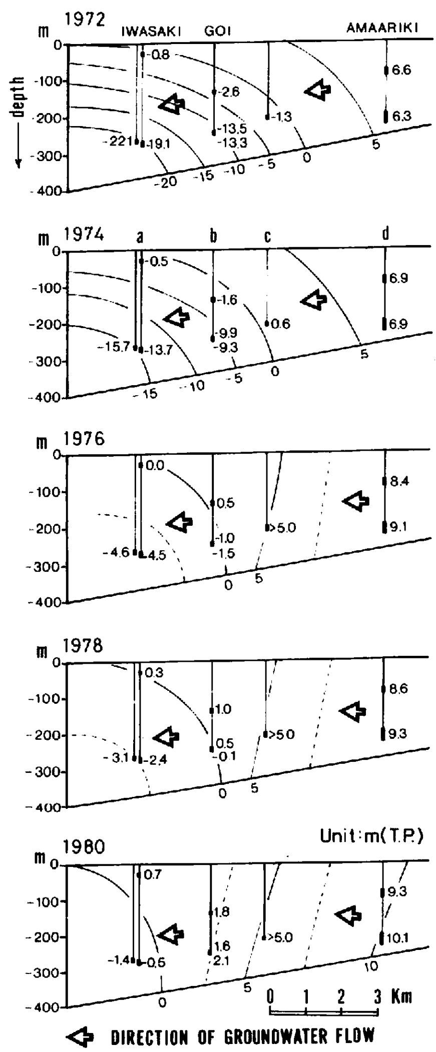


Figure 7 Changes in approximate hydraulic head distribution in a section along the Yoro River. Locations of wells are shown in Figure 1.

Groundwater levels were in a quasi-stationary condition in the period II with withdrawal amount of about 100,000 m^3/day, and they began to recover immediately after the amount of pumping for industrial use dropped from 100,000 m^3/day. It gives a clue to clarify the flow from upland regions toward the coast of Tokyo Bay.

Figure 7 shows the recovery of hydraulic heads along the Yoro River from Iwasaki to Ama-ariki. The hydraulic heads decreased downward in 1972 when the lowest water levels were recorded, therefore, the flow of groundwater had a downward component. The water levels have recovered from inland region after 1974. The relation of water levels between the two wells of different depth at Goi (W-1 and W-29) reversed in 1980, and hydraulic heads have increased in the direction of depth, namely the flow of groundwater has a upward component.

2.6 Flowing wells

The study area is famous for the flowing wells and many flowing wells were existed before 1960's. Figure 8 shows the distribution of flowing wells existed before 1971. These flowing wells gradually stopped flowing under the influences of withdrawal of groundwater at Keiyo Industrial Zone, and the flowing wells in the coastal area almost disappeared around 1970. Some of these wells restart flowing in proportion as the decreasing amount of pumping for the industries. Figure 8 also shows the wells under flowing condition as of 1982 in the study area.

The existence of flowing wells indicates that the hydraulic head increases downward. It is a characteristic in the discharge area in the Tóth's model (Tóth, 1963). Flowing wells are distributed in the lowlands along the Yoro River and major tributaries, and coastal lowlands. Accordingly, these areas are considered as discharge areas of the goundwater flow system.

As shown in Figure 7 or by the existence of flowing wells, groundwater heads change in vertical as well as in the horizontal directions. Therefore, the flow of groundwater should be clarified in a three-dimensional domain.

One of the factors which determine the flow in the coastal area is the water balance in the recharge area. Total amount of circulating groundwater can be estimated by considering the water balance of the groundwater basin containing recharge and discharge areas and the entire flow paths.

In the following chapters, the author attempts to clarify three-dimensional groundwater movement from recharge to discharge areas consistently.

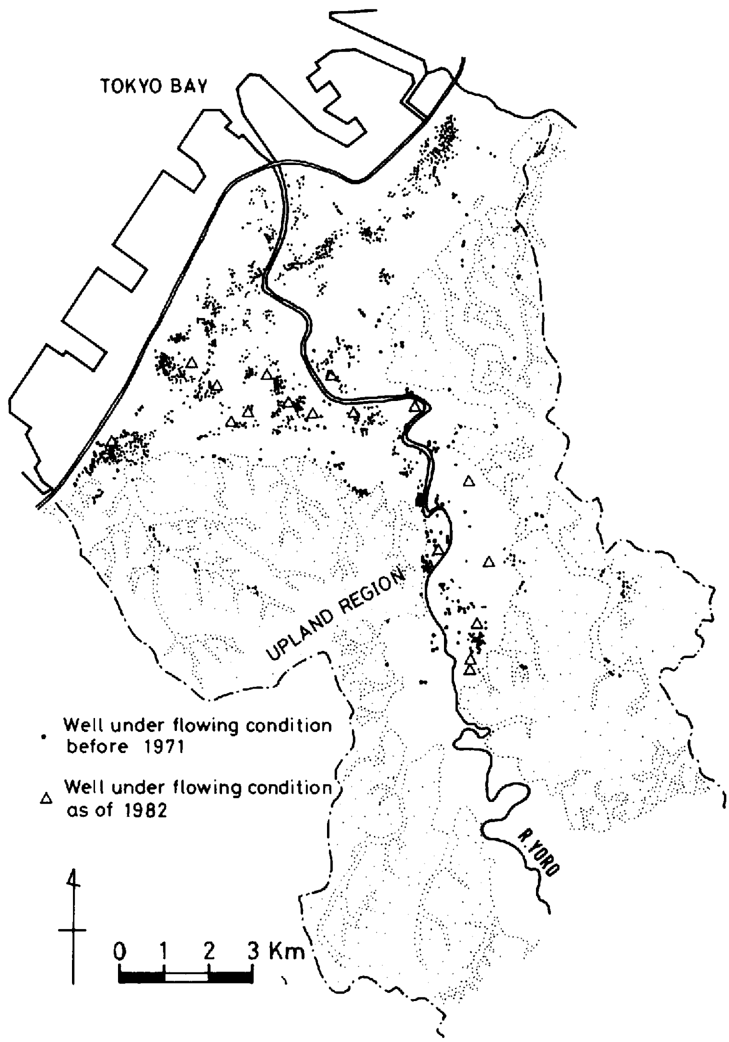


Figure 8 Distribution of wells under flowing condition before 1971. Triangles indicate the wells under flowing conditions as of 1982.

CHAPTER 3

GROUNDWATER FLOW SYSTEM REVEALED BY ENVIRONMENTAL TRITIUM

According to the definition given by Tóth (1963) for a groundwater flow system and to his classification of the flow system depending on the local topography such as local, intermediate and regional systems, an actual groundwater basin should be composite one consisting of groundwater flow systems of different orders.

Methods to clarify the groundwater flow system in a field involve direct measurement of hydraulic head and tracer method, but the method using environmental tritium as a tracer is the one that can clarity the flow distribution of groundwater directly. In this chapter, the clarification of the groundwater flow system is attempted using environmental tritium as a tracer.

3.1 Tritium concentration in Precipitation

Tritium concentration in precipitation has been measured in world networks in cooperation with IAEA and WMO. In Japan, data measured in Tokyo after March 1961 are published by IAEA (1969, 1970, 1971, 1973 and 1974). It has been also measured monthly at Tokyo University of Education in Tokyo from August 1972 to December 1976 and at the University of Tsukuba, Ibaraki Prefecture, since January 1977.

The changes of tritium concentration in precipitation with time at any places in the world have a very similar tendency. Accordingly, Shimada (1976) estimated the tritium concentration in Tokyo before 1960 using data from Ottawa, Canada (IAEA, 1969) where tritium analysis of precipitation was first started.

Figure 9 shows the temporal variation of the tritium concentration in precipitation in Tokyo and Tsukuba. Dashed line indicates the corrected value for radioactive decay in April 1982.

Although the natural level of the tritium concentration is estimated about 10 TU, thermonuclear tests started in late 1952 produced artificial tritium and it was distributed throughout

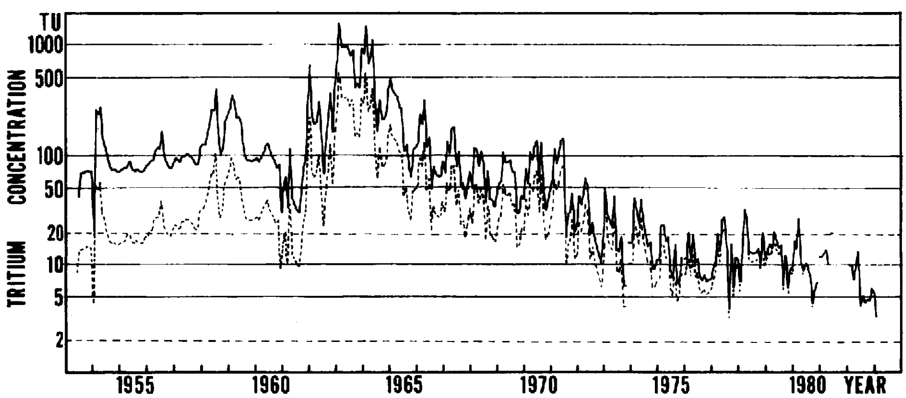


Figure 9 Secular variation of tritium concentration in precipitation in Central Japan. Dashed line indicates the corrected value for radioactive decay with April 1982 as a standard.

the hydrologic cycle by natural process. Consequently, tritium levels in atmospheric water have been risen by as much as three orders in magnitude over those in the pre-nuclear era after 1953. Its peak was observed in 1963, and since then, it has been decreasing steadily.

Because the source of the tritium is in the atmosphere, the supply of tritium is eliminated after precipitation infiltrates into the ground, and its concentration decreases according to its half-life. Therefore, as far as the groundwater flow is in steady state, the variation of tritium concentration in precipitation should be preserved in the direction of groundwater movement.

Based on the above accounts, tritium concentrations of the groundwater are measured in order to clarify the directions of the groundwater movements and their ages.

3.2 Distribution pattern of tritium concentration in groundwater

Figure 10 shows the location of wells sampled for tritium analyses as well as the tritium concentrations of well waters. It is considered that groundwater of less than 2 TU is pre-bomb origin and transit time is more than 30 years. It has a great possibility to consider that the groundwater of over 20 TU was recharged in 1960's because the greater parts of over 20 TU in corrected values in Figure 9 occupies 1960's.

Tritium concentrations of well waters vary from 0.0 to 40.7 TU. The number of samples which shows larger than 20 TU is nine. These high level samples are taken in upland regions. On the contrary, almost all groundwater showing less than 2 TU are distributed near the Yoro River. Therefore groundwater whose transit time is relatively short is distributed in the upland regions, and that of relatively long transit time is distributed in the alluvial lowland near the Yoro River. This distribution pattern of tritium concentration in groundwater suggests that groundwater is recharged in the upland regions and flows to the direction of the Yoro River.

Figure 12 shows the vertical distribution of tritium concentration along five traverses shown in Figure 11. The tritium concentrations are plotted for the maximum and the minimum values during 1981 to 1983.

The central part of the profile A is the alluvial lowland of the Yoro River and each side is the upland region. Tritium concentrations of groundwater are relatively high in the upland regions and are low near the Yoro River. Tritium concentrations decrease with increasing depth at the lowland of the Yoro River, but it increases downward in upland region on the left bank of the Yoro River. The shallow groundwater in the upland region is known to be recharged recently by comparing their tritium concentrations with that of precipitation. The groundwater with 31.7 TU, i.e. the maximum tritium concentration observed here is assumed to be recharged around 1960's when tritium concentration of precipitation was very high. Therefore, the transit time of groundwater increases downward in the upland region.

Tritium concentration of groundwater decreases toward the Yoro River from the upland regions and it becomes less than 2 TU near the Yoro River. Hence, the transit time of the groundwater increases from the uplands to the Yoro River and it exceeds 30 years near the Yoro River.

In the profiles B and C, the left edge is the lowland of the Yoro River and the right-hand side is a drainage basin of the Ooke River which is one of tributaries of the Yoro River. The tritium concentrations decrease in the direction from upland region between the Yoro River and the Ooke River toward the Yoro River, and reach below 2 TU near the Yoro River. Hence, the transit time of the groundwater increases toward the Yoro River and it exceeds 30 years near the Yoro River.

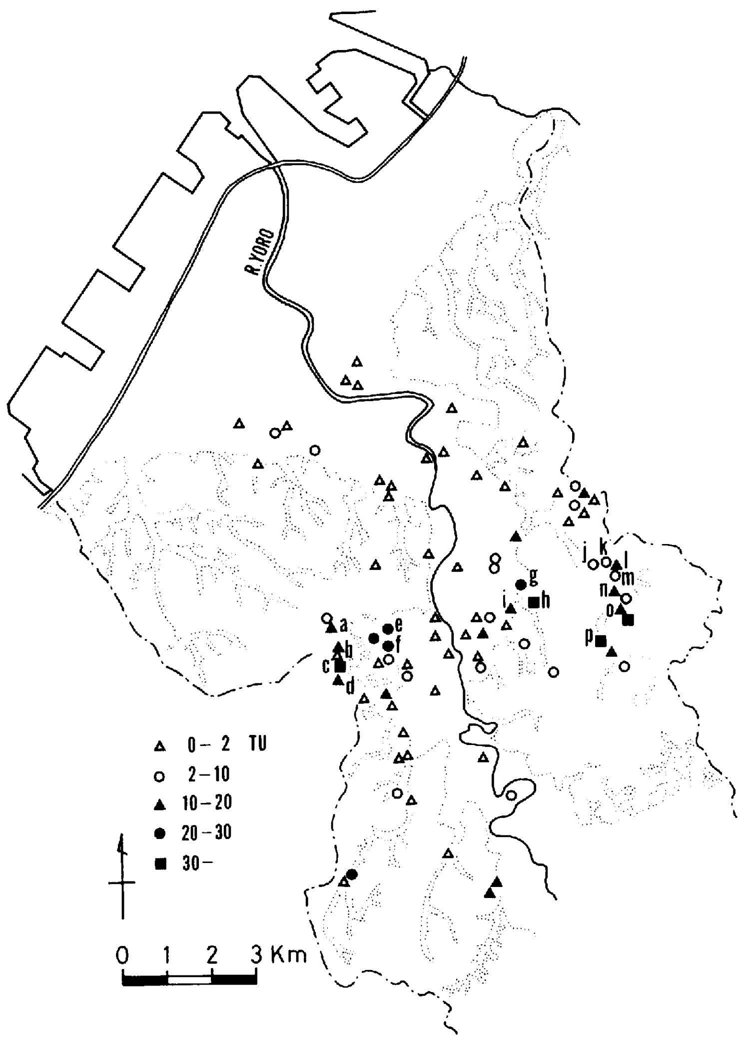


Figure 10 Locations of wells sampled for tritium analyses and classified concentrations of well waters. (a) to (p) denote the wells for long term observation of tritium concentration.

The left-hand side of the profile D is the alluvial lowland countinuing to Tokyo Bay. In the drainage basin of the Ooke River in the right hand side, the tritium concentrations of the groundwater are fairly high. This indicates that the groundwater was recharged after 1953. The tritium concentrations of the groundwater in the upland region between the coastal lowland and the Ooke River is relatively high though the depths of the screens are relatively deep. On the contrary, the tritium concentrations of relatively shallow groundwater are very low in the coastal lowland indicating that the transit times are over 30 years.

Profile E shows the tritium concentrations of groundwater along the Yoro River. The tritium concentrations are very low except for one sample, and indicate that the transit times here is also over 30 years.

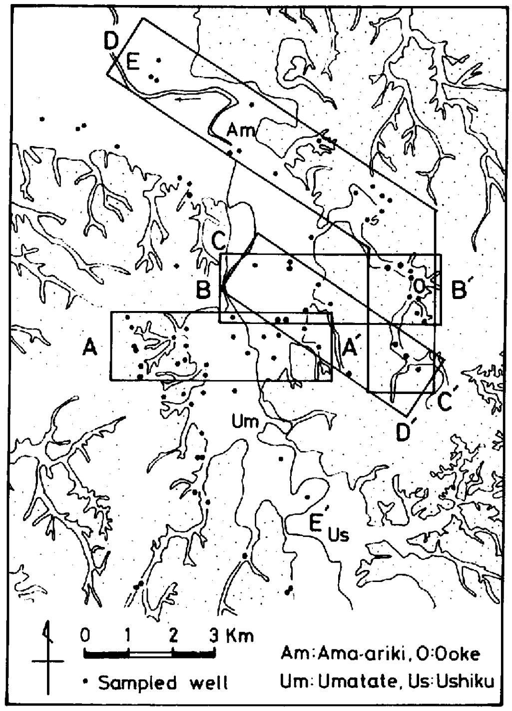


Figure 11 Wells sampled for tritium analyses and lines of sections shown in Figure 12.

These distribution pattern of tritium concentration of groundwater can be explained by considering the flow from upland regions to the lowlands. Figure 13 shows the directions of groundwater flow estimated from tritium concentration distributions of profiles A to D in Figure 12. Groundwater is estimated to be recharged in the upland regions flowing toward the lowland regions as a whole. At the upland regions, groundwater flow is considered to have significantly large downward component because the tritium concentrations increases downward. The reason why tritium concentrations are very low near the Yoro River is that the upward component of groundwater flow exists and recent infiltrated water cannot enter into deep portion of the groundwater flow system.

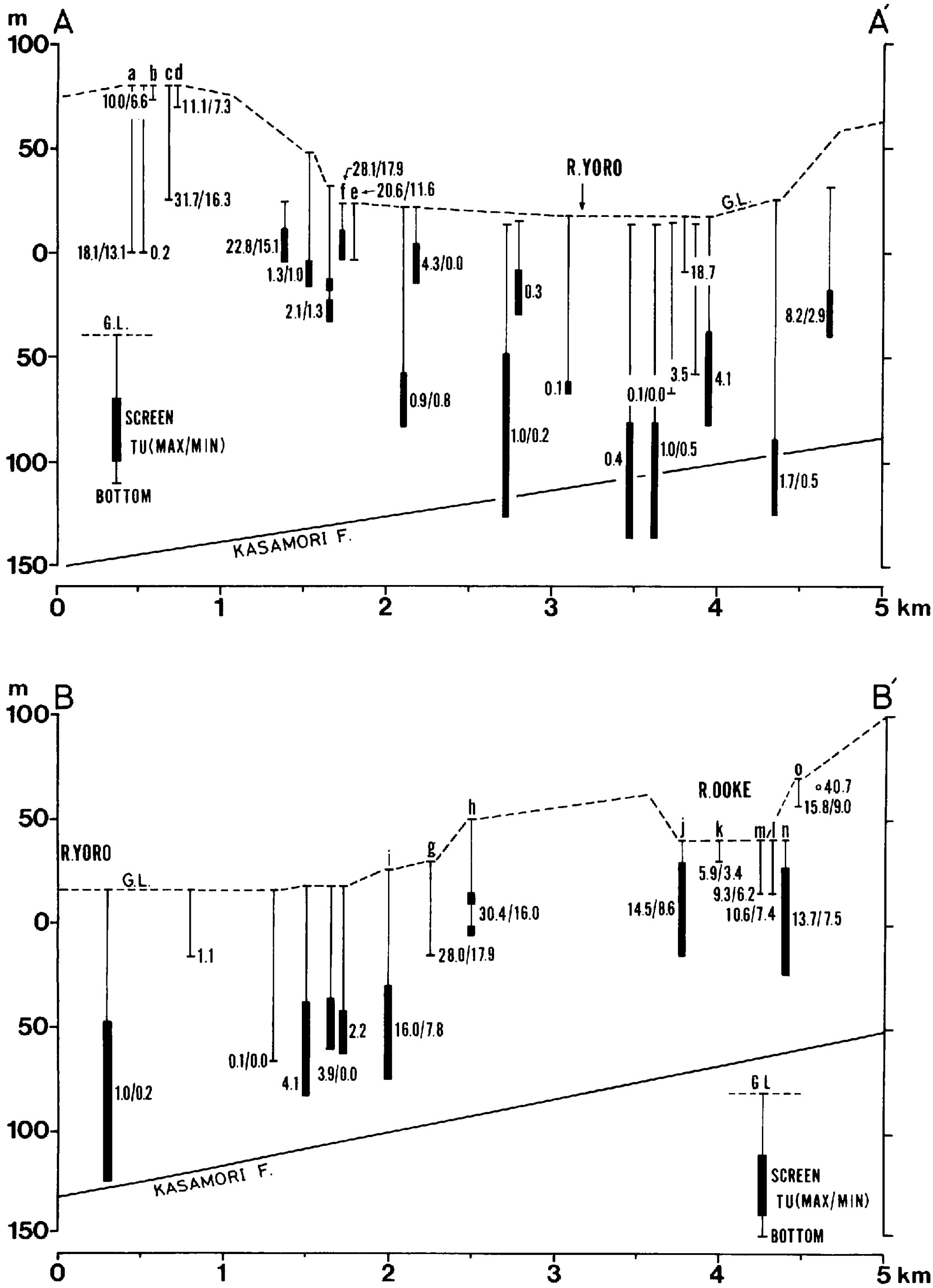
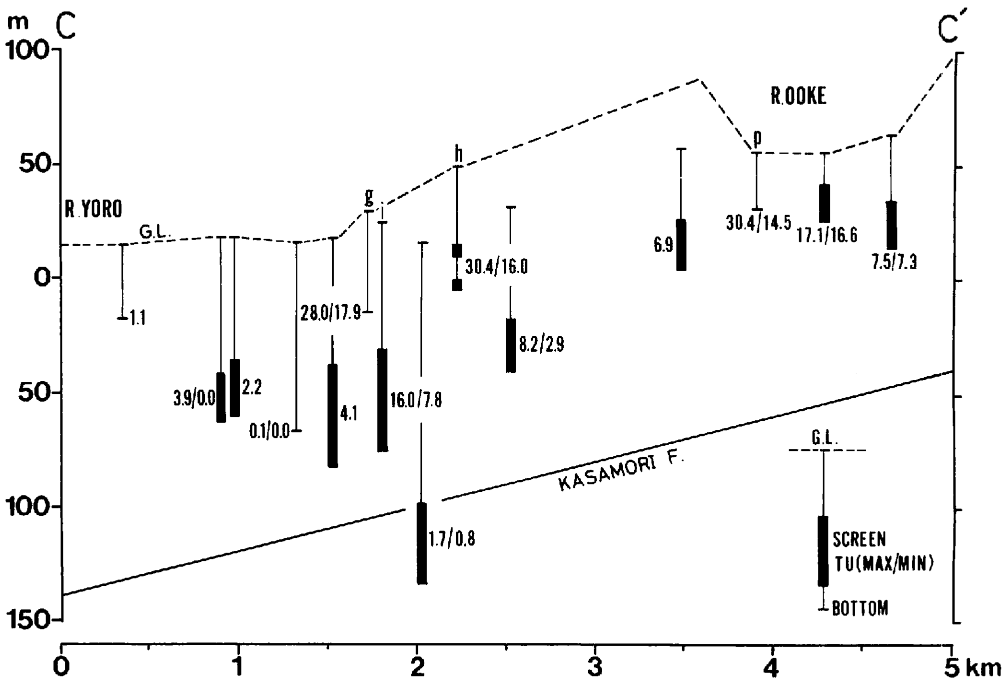


Figure 12 (1) Tritium concentrations of well waters along sections shown in Figure 11.



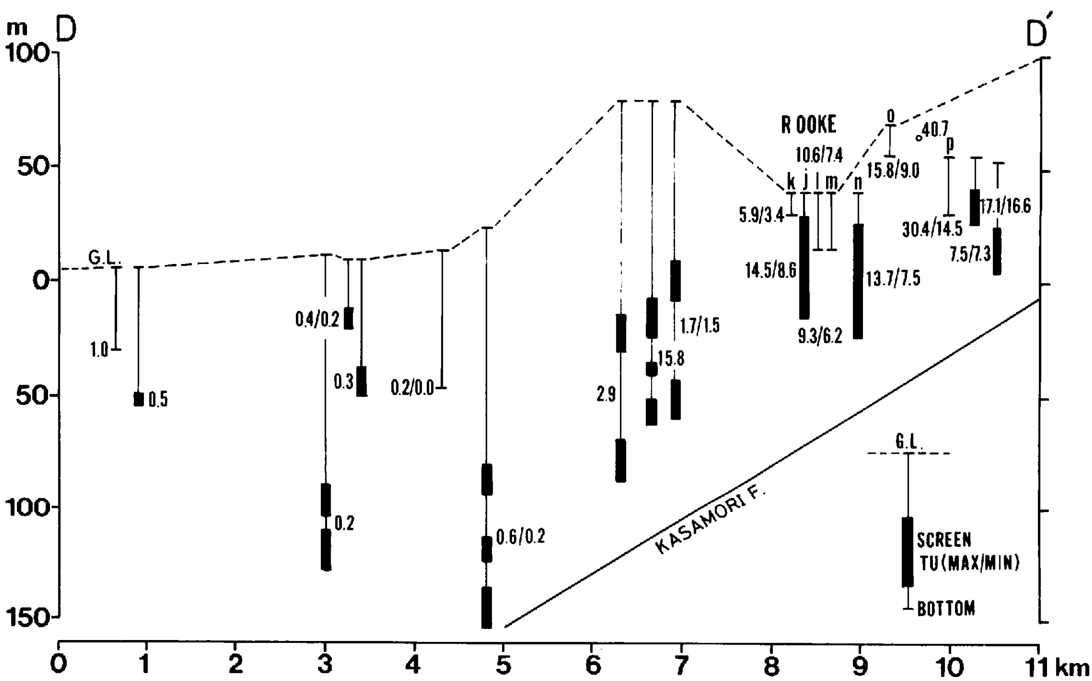


Figure 12 (2) Tritium concentrations of well waters along sections shown in Figure 11.

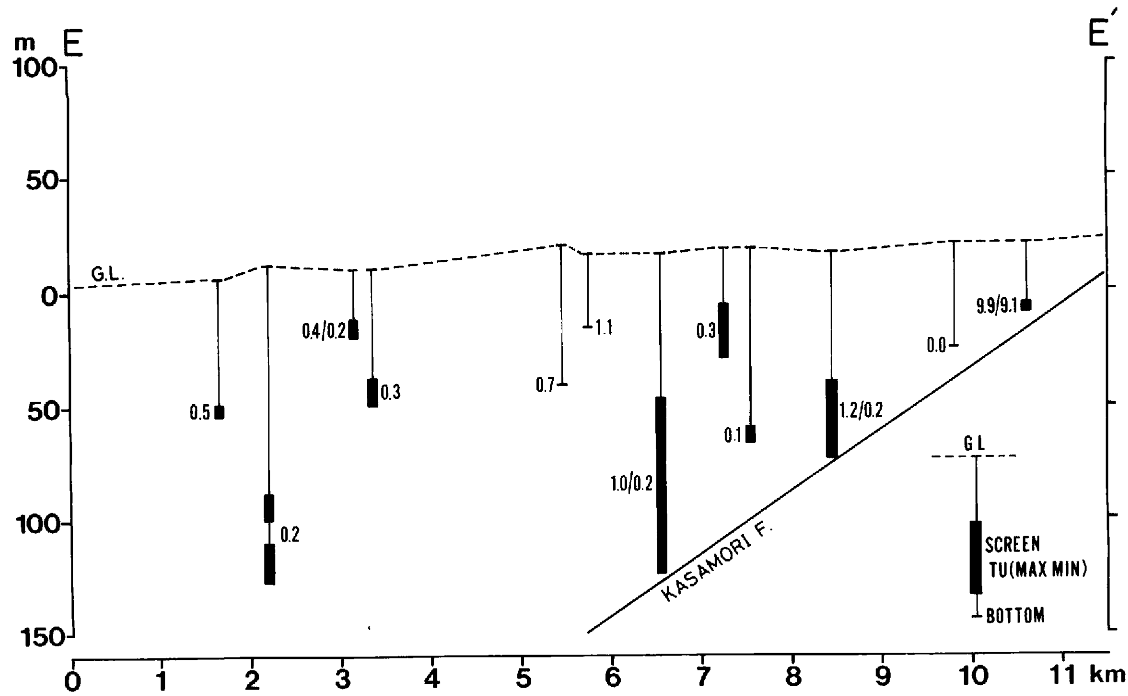


Figure 12 (3) Tritium concentrations of well waters along sections shown in Figure 11.

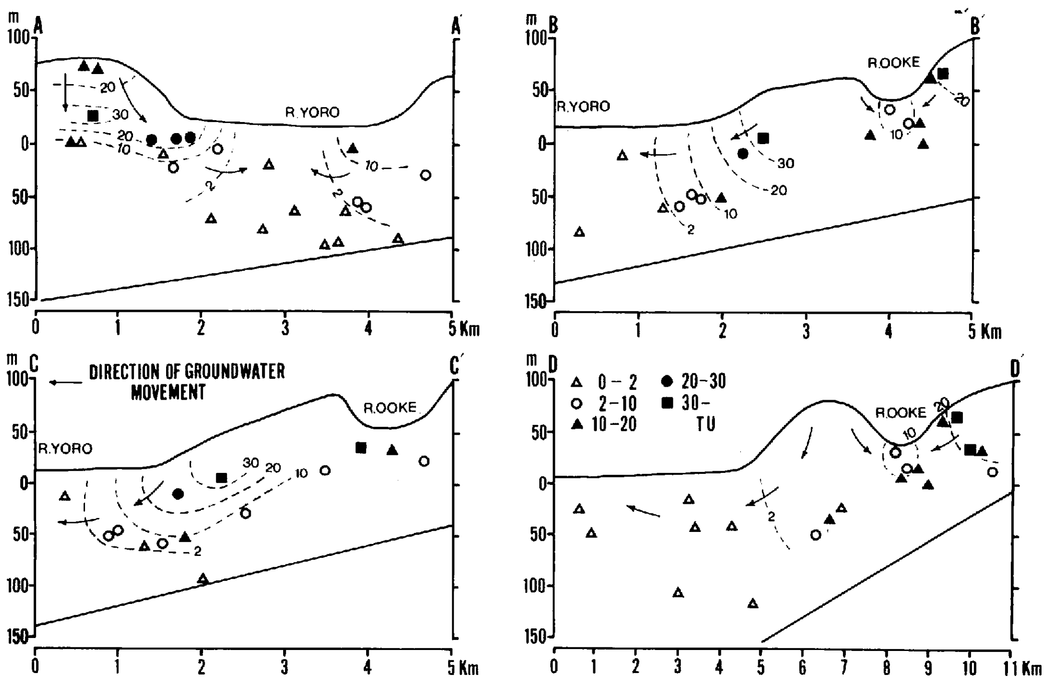


Figure 13 Estimated directions of groundwater movement based on Figure 12.

3.3 Tritium concentrations in streams

Most drainage basins that dissect uplands have permanent stream flows. If streams are maintained by groundwater, it is possible to estimate the existence of a groundwater flow system in a small scale because streams can be considered as the discharge area of groundwater. Accordingly, tritium concentrations of stream waters in the dry season were measured during winter of 1982–1983. Then 18 small drainage basins, where housing sites are not well distributed, were selected, and water samples were collected for tritium analyses. Figure 14 and Table 2 show the results of tritium analyses of stream waters. The obtained values are considered to be those of baseflow.

Tritium concentrations of precipitation after late 1982 show about 5 TU. If rain water discharges immediately after precipitation, tritium concentration of stream waters should be the same level as of the precipitation. Tritium concentrations of stream waters are rather high in compari-

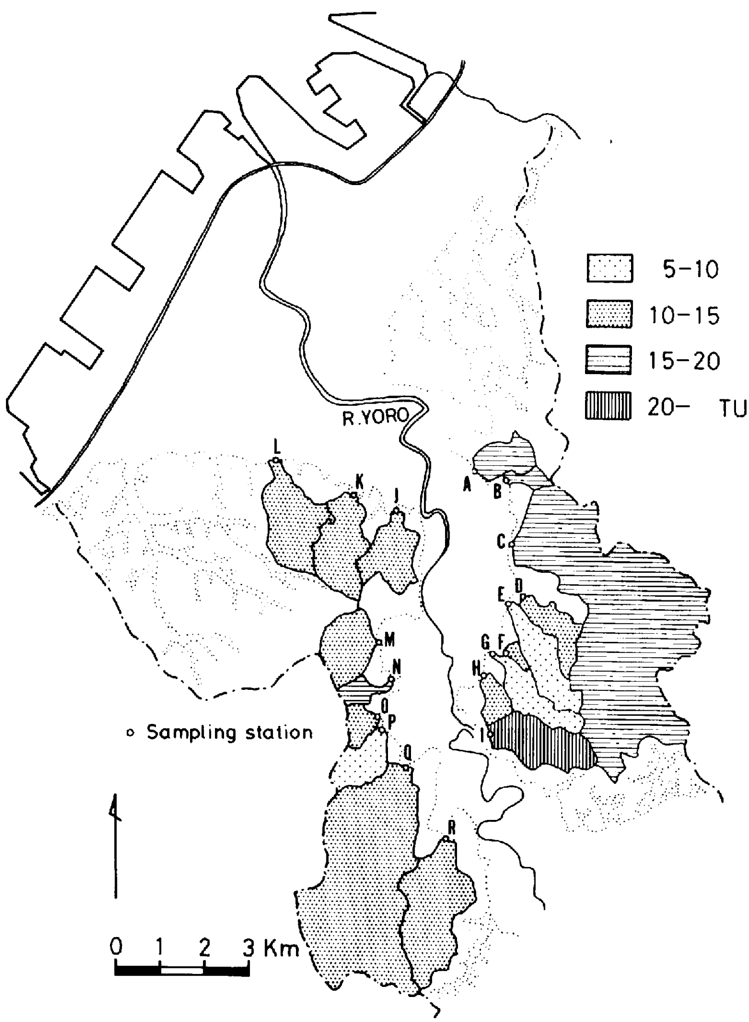


Figure 14 Tritium concentrations of stream waters in dry season in 1982–1983.

Table 2 Tritium concentrations of stream waters in dry season. A to R denote the drainage basins shown in Figure 14.
NF: no flow, and NM: not measured.

	Nov. 1982	Jan. 1983
A	11.9	16.8
B	10.4	17.3
C	16.8	14.8
D	10.4	5.6
E	9.5	NF
F	11.2	9.6
G	7.8	8.5
H	9.0	12.1
I	22.6	21.8
J	12.5	14.7
K	9.3	13.4
L	NM	12.2
M	13.9	9.9
N	19.6	14.6
O	12.6	13.6
P	7.5	6.1
Q	13.1	12.1
R	13.4	NM

(Unit: TU)

son with that of precipitation at the same periods. Therefore, waters in these streams are known to be retained in the drainage basin as groundwater for a certain time.

Figure 15 shows the variation of the tritium concentrations of stream waters in the drainage basins (C) and (M).

In the drainage basin (C), tritium levels of stream waters are in the order of 10 TU till point (iii), and is over 20 TU after point (iv). Meanwhile, groundwater of relatively high tritium concentration exists between points (iii) and (iv). Accordingly, the variation of tritium concentration of stream water coincides with the distribution pattern of tritium concentration in groundwater in the drainage basin (C). In drainage basin (M), tritium levels of stream waters are about 10 TU, and are higher than those of precipitation.

Consequently, tritium concentrations of stream water in the drainage basins dissecting uplands are higher than those of precipitations in the same period, and it is made clear that the origin of base flow is groundwater. This indicates that a flow of groundwater toward the stream exists. Therefore, a small scale groundwater flow system can be estimated to exist in the drainage basin having permanent streamflows.

The residence times of these flow systems are estimated to be within 30 years because of the high tritium concentrations of stream waters.

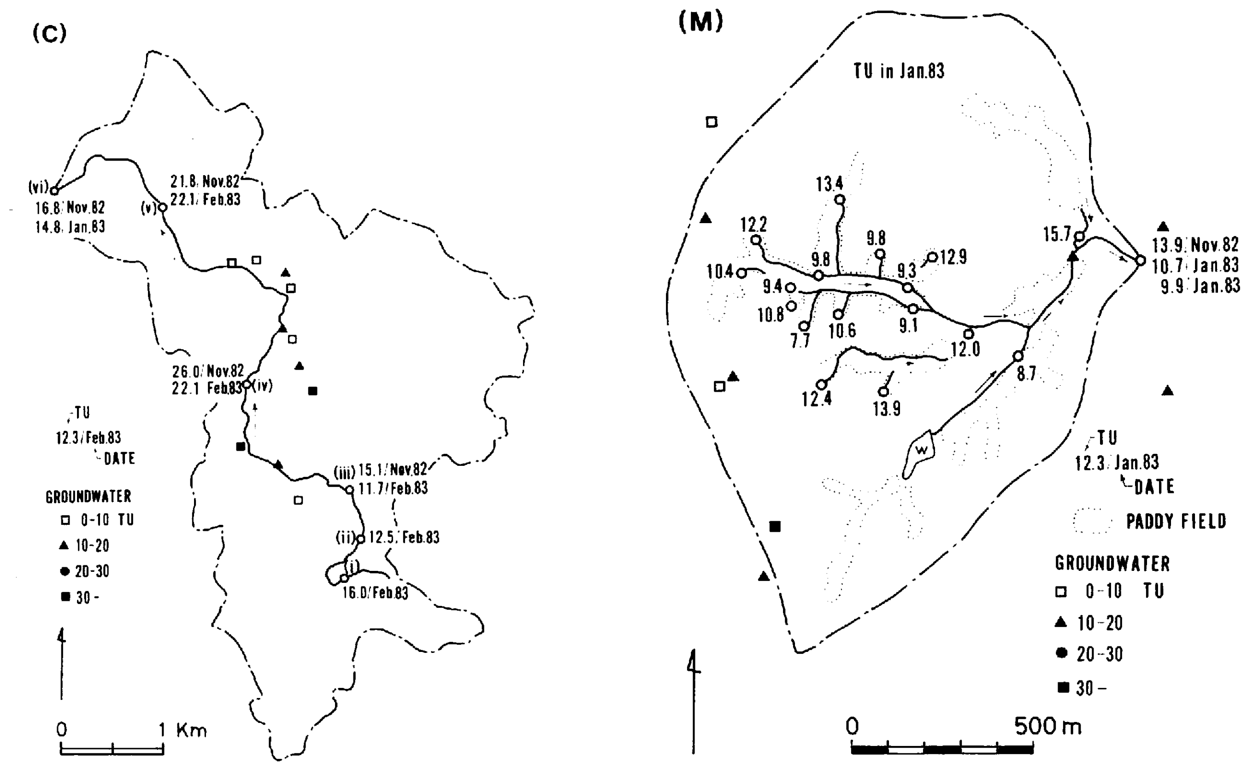


Figure 15 Tritium concentrations of stream waters sampled in the drainage basins (C) and (M) in Figure 14.

3.4 The estimation of the groundwater age

The most fundamental structure of groundwater flow system was revealed by the spatial distribution pattern of tritium concentration in groundwater. Namely, groundwater in the area is recharged at the uplands and flows to the lowland of the Yoro River as a whole, although local flow systems are estimated to be developed in the small drainage basins dissecting the uplands. In this section, the groundwater ages of 16 stations (**a** to **p** in Figures 10 and 12) are estimated by the convolution integral method (Dincer et al., 1970).

Groundwater age can be obtained if the tritium concentrations of recharging and sampling water are specified, because the half-life of tritium is known. It is necessary, however, to take time series of tritium concentration in groundwater for a certain periods because the variation of tritium concentration in precipitation is large.

Assuming the groundwater mixes in a constant mode as it flows, time series of tritium concentration are calculated by the following equation.

$$f_O(t) = \int_0^{\infty} f_i(t-T) f_R(T) \exp(-\lambda T) dT \qquad (3-1)$$

where $f_O(t)$ is the theoretical tritium output function, $f_i(t)$ is the input function which is the time series of tritium concentration in precipitation, $f_R(T)$ is the transit time distribution function or the system function, λ is the decay constant of tritium, T is the transit time between the recharge and sampling, and t is the time. By comparing the output function of equation (3–1) with the observed values, the groundwater age can be estimated. Equation (3–1) assumes a constant flow velocity and a constant recharge.

A function formula of f_R must approximate the mode of mixing of groundwater. The normal distribution function can approximate the dispersive mixing of groundwater. Therefore it is used for the system function. Then, f_R is expressed as follows.

$$f_R(T) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(t-T)^2}{2\sigma^2}\right] \qquad (3-2)$$

where T is the mean residence time, σ is the standard deviation, π is the ratio of the circumference to its diameter and t is the time. The shapes of the system function are shown in Figure 16.

Table 3 shows the results of calculations, and Figure 17 shows the output functions and measured tritium concentrations. Error is the average residual from the output functions. Figure 18 shows the age distributions in groundwater along sections shown in Figure 11. The locations of wells are shown in Figures 10 and 12.

Samples (a) to (d) are obtained from the upland region about 80 meters above sea level in the left bank of the Yoro River near the divide. The groundwater ages of (b) and (d), which were sampled from the shallow wells on the upland, are 1.6 years and 2.3 years, respectively, and indicate the recent recharge. Samples (a) and (c), which are sampled in the vicinity of (b) and (d), shows relatively old ages, 28.9 years and 26.1 years, respectively. Therefore transit time of groundwater increases downward. Because groundwaters of (a) and (c) are assumed to be recharged at immediately upper surface, the average flow velocities can be obtained by dividing the bottom depth by groundwater age, and are 2.8 and 2.1 m/year respectively.

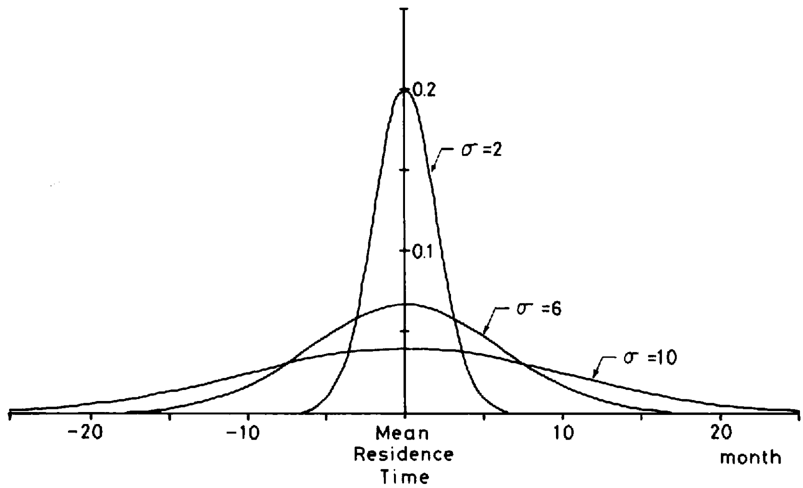


Figure 16 Shapes of system functions.

Table 3 Groundwater ages estimated from convolution integral method. σ is standard deviation of normal distribution. Error is average residual from the output functions. Locations of (a) to (p) are shown in Figures 10 and 12.

Well	Ground level	Screen or Bottom	Residence Time	σ	Error
(a)	82	B: 80	28.9	10	2.35
(b)	80	B: 7.74	1.6	1	0.89
(c)	85	B: 54	26.1	4	3.94
(d)	85	B: 10.8	2.3	2	0.35
(e)	25	B: 27	28.4	10	3.42
(f)	25	S: 14–27	13.5	1	1.00
(g)	25	B: 45	26.3	1	3.23
(h)	50	S: 35–40, 51–55	10.0	10	2.51
(i)	25	S: 56–100	2.9	2	0.55
(j)	38	S: 11–55	5.2	2	0.96
(k)	38	B: 10	6.9	1	3.67
(l)	40	B: 25	6.4	4	0.29
(m)	40	B: 25	5.6	2	1.25
(n)	45	S: 14.0–64.5	5.3	1	1.60
(o)	65	B: 14	3.3	2	0.66
(p)	55	B: 25	9.8	9	1.51
	(m)	(m)	(year)	(month)	(TU)

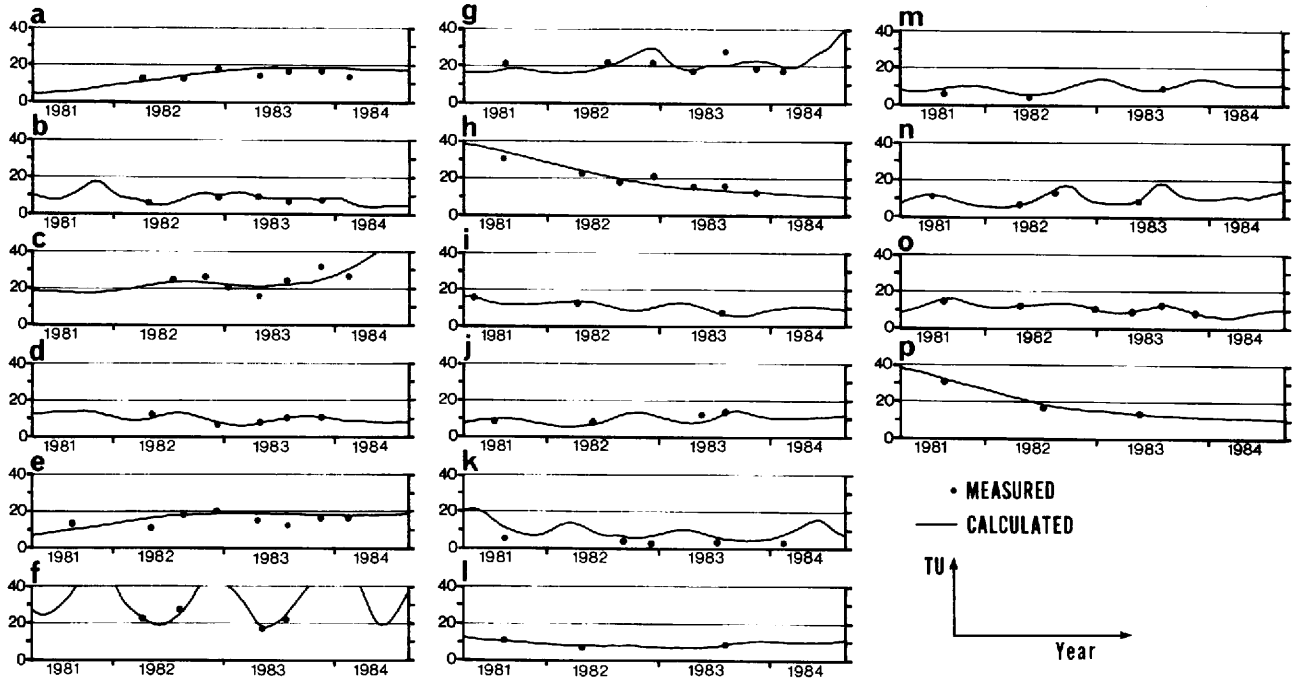


Figure 17 Tritium-time profiles of sixteen long-record wells and output functions of convolution integral.

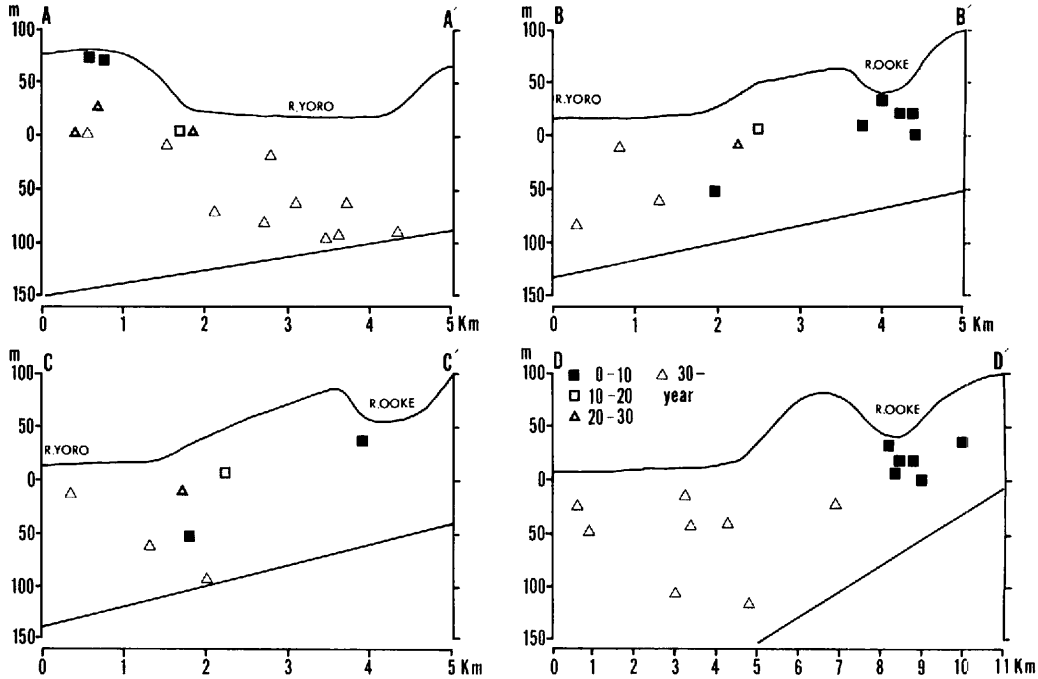


Figure 18 Groundwater age distributions along sections shown in Figure 11.

Samples (e) and (f) are obtained from the alluvial lowland near the upland region on the left bank of the Yoro River. The groundwater age of (f) is 13.5 years, and that of (e), which is nearer to the Yoro River than (f), is older than that of (f), and is 28.4 years.

Sample (h) is from a terrace surface of 50 meters above sea level, and its age is 10 years. The age of sample (g), which is located at the alluvial lowland closer to the Yoro River than (h), increases to 26.3 years.

These groundwater ages can correlate to the groundwater flow pattern estimated from the spatial pattern of the tritium concentrations. The ages of groundwater from the shallow wells on the upland region indicate recent recharge, and the ages increase toward the Yoro River. The ages of groundwater exceed 20 years near the boundary between the uplands and the alluvial lowland of the Yoro River, and are more than 30 years near the Yoro River. On the upland, the age of the groundwater flowing downward, exceed 20 years at the depth of about 50 to 80 meters.

Meanwhile, samples (j) to (p), which are obtained in the drainage basin dissecting the upland region, are younger than 10 years. These wells are located in the alluvial lowlands along the stream. Accordingly, it seems that the groundwater that was recharged at least more than 10 years ago had already discharged. In the previous section, it is revealed that the streams in the drainage basin dissecting uplands discharge groundwater as baseflow in dry season. Therefore these groundwaters do not correlate to the flow system that groundwater flows from upland regions to the lowland of the Yoro River, and the existence of a small scale flow system of groundwater can be estimated in the small basin dissecting uplands.

3.5 Theoretical distribution of tritium concentration by advection-dispersion model

In this section, tritium concentration distribution is calculated theoretically by using a advection-dispersion model, and it is examined whether the measured tritium patterns can be explained theoretically by the assumed flow pattern.

The basic equations are as follows (Bear, 1972):

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y}) = 0 \qquad (3-3)$$

$$\frac{\partial}{\partial \varphi}(D_L\frac{\partial C}{\partial \varphi}) + \frac{\partial}{\partial \psi}(D_T\frac{\partial C}{\partial \psi}) - V\frac{\partial C}{\partial \varphi} = \frac{\partial C}{\partial t} \qquad (3-4)$$

where h is the hydraulic head, K_{xx} and K_{yy} are the hydraulic conductivities of x and y directions, C is the concentration of material in solution, V is the flow velocity, φ and ψ are the directions of the stream lines and the normals to those lines, respectively. The coefficients D_L and D_T are the longitudinal and lateral dispersion coefficient, respectively, defined by

$$D_L = D_{sl} \cdot V$$
$$D_T = D_{st} \cdot V \qquad (3-5)$$

where D_{sl} is the longitudinal dispersivity in the direction of flow and D_{st} is the transverse dispersivity normal to the direction of flow in an isotropic porous medium. Dispersivity is a second-rank tensor, and its principal axes are set to coincide with the direction of flow and normal to the direction of flow in this model.

The Galerkin technique is used to determined approximate solutions to the equations (3–3) and (3–4) under appropriate boundary conditions. The cross-sectional representation of the saturated flow system is divided into an equivalent system of subregions. In this study, triangular elements are employed. Detailed explanation of the method is given in Pickens et al. (1976).

The calculated areas are representatives of the right bank and the left bank of the Yoro River in the A, and B, C profiles in Figure 12. The upper boundary is the water table, and is assumed to be at the same altitude of river bed in this study. The boundaries on both sides are imaginary vertical impermeable ones representing groundwater divide as well as the Yoro River. The calculated areas are bounded on the bottom by sloping impermeable basement which represents the top of the Kasamori Formation.

The hydraulic conductivity in the horizontal direction is assigned to be 0.01 cm/sec, which is equal to the average of the results of aquifer tests as an order. The vertical hydraulic conductivity is 1/100 of the horizontal one, and effective porosity is assumed to be 0.3.

Figure 19 shows the head distributions as solutions to the equation (3–3). These flow patterns are mainly formed under the influence of topography. Flow vectors are calculated from the head distribution in each element, and the equation (3–4) is solved under above mentioned boundary conditions. The radioactive decay of tritium is corrected in each time step. Figures 20 and 21 show the results of calculations.

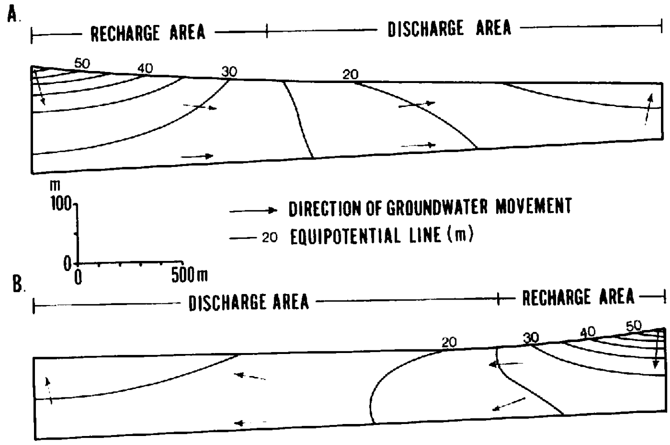


Figure 19 The steady-state hydraulic head distributions with flow directions.

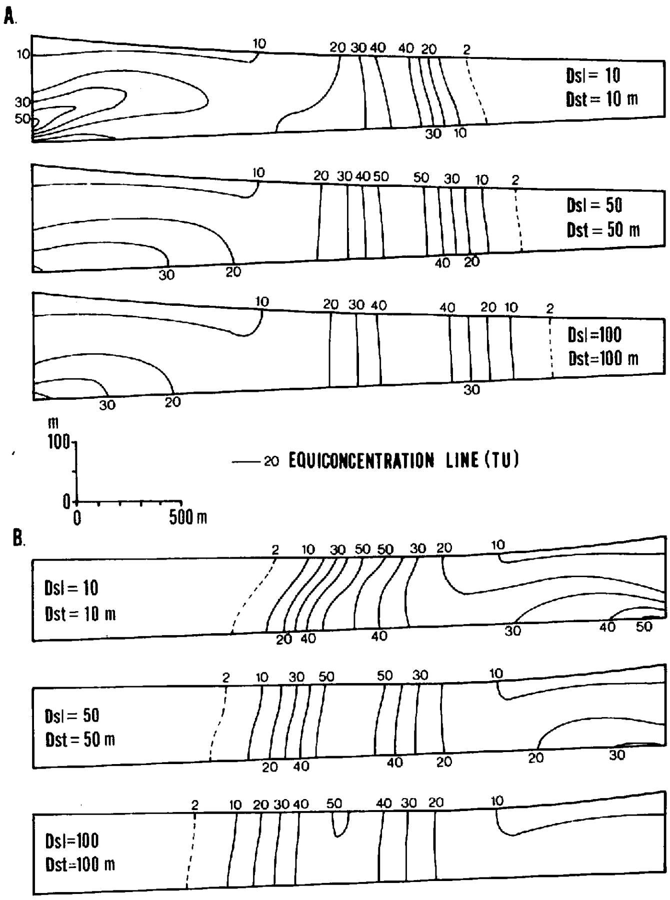


Figure 20 The effect of dispersivity on tritium conventration distributions in April 1982.
D_{sl}: longitudinal dispersivity, D_{st}: transverse dispersivity.

The highest tritium concentration of sampled waters in observation period is 40.7 TU. The number of samples higher than 30 TU is five. In order to dilute precipitation, which was higher than 1,000 TU in early 1960's, to such a level, the value of dispersivity should be about 100 meters or more in this model.

In the isotropic case shown in Figure 20, the vertical gradient of tritium concentration is small in comparison with the measured one. Generally, the longitudinal dispersivity is larger than the transverse one. The ratio of D_{sl}/D_{st} takes about 1 to 10 according to the review of Anderson (1979), most of which are obtained from areal models. Robson (1978) noted that the dispersivity values used in the areal model differed from those needed to calibrate the profile model. In his areal model, the ratio was 3.3, but it was needed to be increased to 330 in his profile model.

Figure 21 shows the effect of dispersivity ratio on tritium concentrations. The vertical gradient of tritium concentration become large as the ratio increases. By comparing the calculated pattern with the observed pattern in the case of D_{sl}/D_{st} = 100 on Figure 21, it can be seen

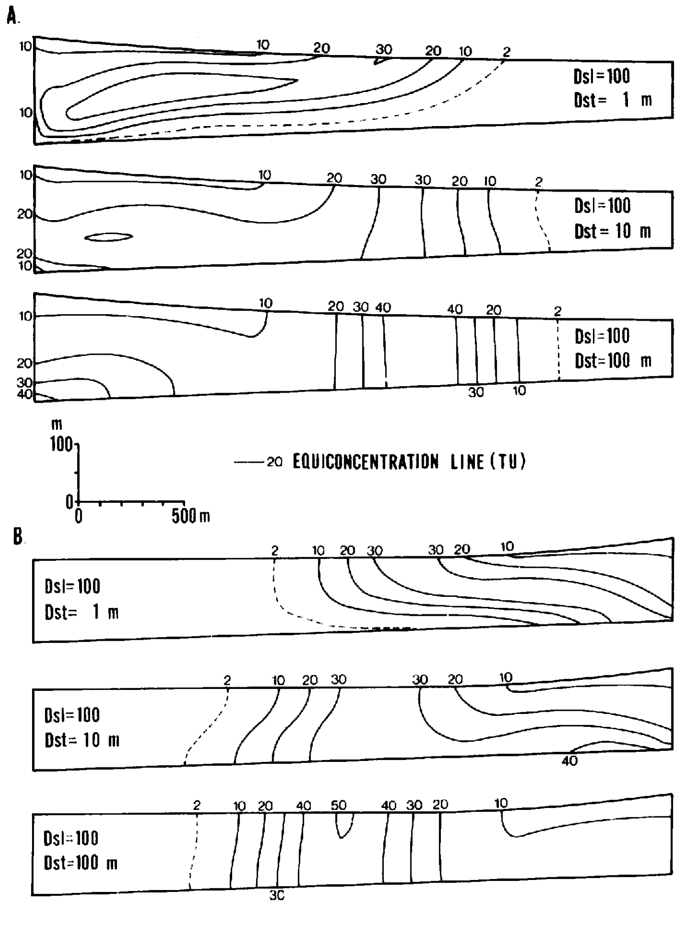


Figure 21 The effect of dispersivity ratio on tritium concentration distributions in April 1982. D_{sl}: longitudinal dispersivity, D_{st}: transverse dispersivity.

that the general patterns have close similarities. Namely, the upper part of upland regions are occupied by groundwater less than 10 TU, and the tritium levels increase downward. The tritium front shown by 2 TU lines does not reach the Yoro River, and tritium levels decrease downward in the lowland regions.

The reason for the large anisotropy of dispersivity is seems to be related to the structure of aquifers. The geology of the area is alternation of sands and muds, and they are nearly flat. Hence, the horizontal and vertical permeability differ each other. It is considered to be influenced on the anisotropy of dispersivity.

As shown in Figure 9, groundwater recharged in 1960's when tritium concentration in precipitation was very high, could be over 100 TU as of 1982 when the dilution by mixing was negligible. According to the observed distribution pattern, the peak concentration in groundwater, however, is considered to be about 30 TU around 1982. Therefore it can be considered that a certain degree of mixing occurs during the groundwater movement.

Although strict discussion on the absolute value of the dispersivity is difficult because the dispersivities used in the model partly depend on the size of each element, the dispersivity of 100 meters is equal to the dispersion coefficient of about 10^{-4} to $10^{-6} m^2/sec$ in the model. This value is far larger than the self-diffusion coefficient of water, i.e., $2.22 \times 10^{-9} m^2/sec$ (Eisenberg et al., 1969). Therefore, it is considered that the mixing process is not by diffusion, but macro-dispersion derived from the velocity difference at each point in the strata due to the heterogeneity of the geologic materials. It indicates that the actual flow of groundwater in the basin is not so much uniform. This is of great importance for the investigation of a contaminant transport in the groundwater flow system.

Although a certain degree of mixing occurs during the groundwater movement, general pattern of tritium concentration distribution in groundwater well reflects the history of groundwater movement. This supports the availability of the environmental tritium as a tracer, and it is made clear that it can be used to trace the regional groundwater movement.

It is also shown that the horizontal hydraulic conductivity with the magnitude of 10^{-2} cm/sec can explain the migration of thermo-nuclear tritium from uplands to the lowlands. It is used in the water balance simulation in the following chapter.

CHAPTER 4

WATER BALANCE OF THE GROUNDWATER BASIN

The most fundamental unit in dealing with the water balance of groundwater is the groundwater basin. Total amount of circulating groundwater can be determined by considering the water balance of groundwater basin, and is used as a measure of the safe yield of the basin.

The three-dimensional geometric distribution of groundwater movement was clarified in previous chapter. In this chapter, quantitative understanding of the groundwater cycle is attempted. A water balance simulation based on the obtained flow pattern is performed in order to estimate the quantity of dymanic groundwater flow and its spatial distribution.

4.1 Water Balance Equations

On the basis of the steady-state assumption, the recharge to the groundwater basin is equal to the discharge from it, and this is the dynamic flow through the groundwater basin. This quantity is defined by Freeze and Witherspoon (1968) as the natural basin yied (*NBY*).

The "average annual" water balance equations are as follows;

$$R = (1 - f)P - Et \qquad (4-1)$$

$$R = R_l + R_i + R_r \qquad (4-2)$$

$$D = D_l + D_i + D_r \qquad (4-3)$$

$$R = D = NBY \qquad (4-4)$$

where P is the precipitation, Et is the evapotranspiration, f is the direct runoff coefficient, R is the recharge and D is the discharge. Suffixes l, i and r mean the local, intermediate, and regional flow systems respectively. This water balance calculation gives the long term average of the basin-wide water balance under natural conditions.

4.2 Evaluation of the Recharge

Recharge, R, can be obtained if f is known because P and Et are known in equation (4 – 1). According to the previous studies on direct runoff coefficient in the drainage basins whose geological conditions are similar to the study area, direct runoff coefficient is assumed to be relatively small. Kotoda (1968) investigated rainfall-runoff relations in a small basin of Tama, Western district of Tokyo. As a result, his first order direct runoff coefficient was only 11.4% as a average of 13 observations, and even total runoff coefficient was 21.4%. Miyake (1978) obtained direct runoff coefficients in three small basins in Osaka, which were 21, 25 and 17%.

Hirata (1966) describes that the reason for the difference of direct runoff coefficients on the same precipitation event in different basins was caused by the difference of infiltration capacity near the surface. In the investigated area in this study, planation surfaces which are covered with volcanic ashes (so called Kanto Loam) distribute widely, therefore a large amount of precipitation is expected to infiltrate into the ground, and the direct runoff coefficient in the study area would be small. Referring to previous studies, it will be proper to assume the average direct runoff coefficient as 20%. By substituting the P = 1627 mm/year, Et = 696 mm/year (see 2.3) and f = 20% into equation (4–1), then R reaches to 606 mm/year. Hence, the average annual recharge in the area is estimated to be about 600 mm/year.

4.3 Evaluation of the Natural Basin Yield

In order to incorporate the structure of the groundwater flow system revealed in the previous chapter into the model, it is necessary to satisfy the following conditions.

(1) Energy required to move groundwater is given in proportion to the topographic height.

(2) The model must be a three-dimensional one.

The steady-state three-dimensional groundwater flow model that can satisfy the above conditions is used to evaluate the dynamic flow through the groundwater basin, namely, the natural basin yield.

The basic equation is as follows, which is developed from Darcy's law and the steady-state equation of continuity:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=0 \qquad (4-5)$$

where K_{xx}, K_{yy} and K_{zz} are the components of the permeability tensor in the x, y and z directions whose principal axes are coinciding with the coordinate axes, and h is the hydraulic head. Equation (4–5) is solved numerically under the appropriate boundary conditions according to the method described by Freeze and Witherspoon (1966).

In the Freeze-Witherspoon model, it is difficult to specify suitable recharge except for the case that the accurate water table configuration and the permeability distribution are known, because the elevation of water table is fixed.

In this study, the condition that the configuration of the water table is determined by the topographic configuration, permeability distribution and the amount of recharge, is added to the model in order to assign suitable recharge. Namely, the configration of the water table is corrected until the recharge at each node on the water table falls below the given recharge.

Figures 22 and 23 show the calculated area and boundary conditions. The boundary conditions are determined on the assumption that the groundwater basin is bounded on the bottom by the Kasamori Formation which is considered as relative impermeable basement, on the top by the water table, and all sides by imaginary impermeable boundaries which simulate the groundwater divides.

The solid lines in the Figure 23 are river level, which is an isopleth of the minimum level in the 500 meters mesh, and is used to the first approximation of the water table. It is the maximum level of the water table. The dashed lines indicate the structural contours on top of the Kasamori Formation.

Horizontal hydraulic conductivity is assigned to 0.01 cm/sec, which is the average of the results of aquifer tests and can explain the velocity of the tritium movement (see 3.5). The ratio of horizontal to vertical hydraulic conductivity is set 100.

The average annual recharge in this region is estimated about 600 mm/year, then the calculation is performed with maximum recharge (R_{max}) of 600 mm/year.

Figure 24 shows the hydraulic head distributions in cross sections. The regions with high hydraulic head are upland regions. The hydraulic heads are comparatively low in the lowland of

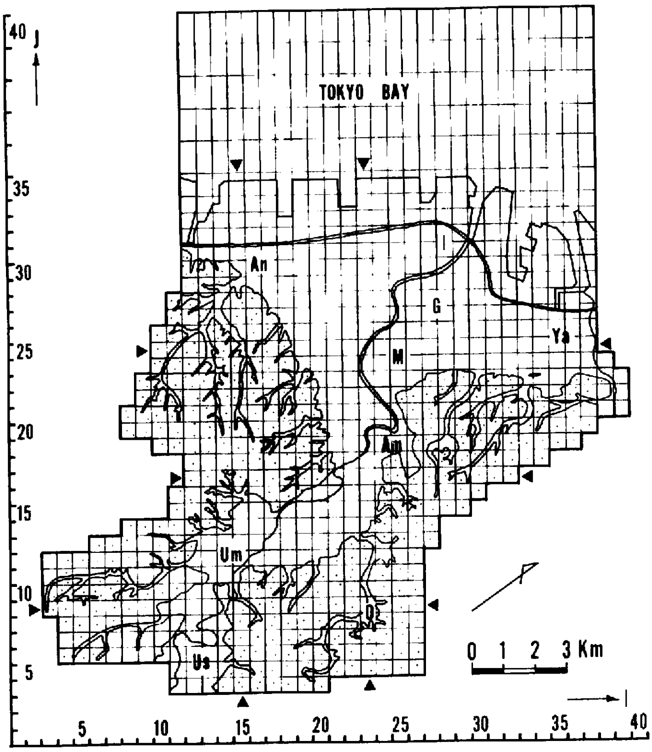


Figure 22 Calculated area. I: Iwasaki, An: Anegasaki, G: Goi, Ya: Yawata, M: Murakami, Am: Ama-ariki, O: Ooke, Um: Umatate, Us: Ushiku

- - - - - structural contour on top of the Kasamori Formation

——— river level with 500 meters mesh

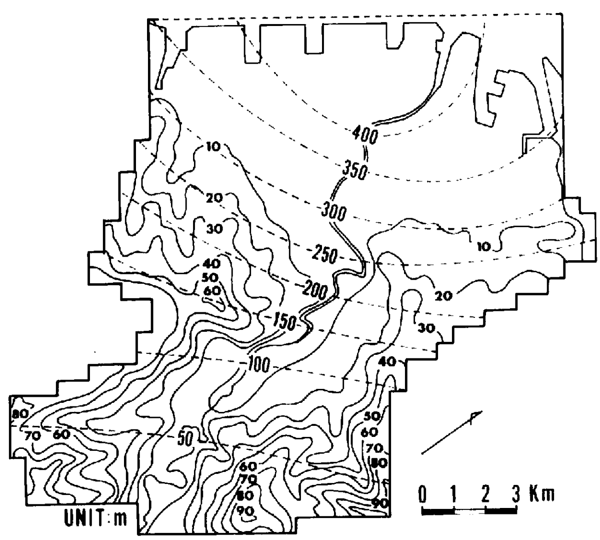


Figure 23 Boundary conditions. Solid lines are river level contoured by using 500 meters mesh. Dashed lines indicate the structural contours on top of the Kasamori Formation.

the Yoro River and the coast. The heads decreases downward in the upland regions and increases in the lowland regions. Actually, the existence of the flowing wells (see 2.6) indicates that the heads are increased downward in the lowland regions. Groundwater is recharged at the upland regions and flows to the lowland regions under these head distributions. This flow pattern agrees with the one estimated from the distribution pattern of tritium concentration in groundwater.

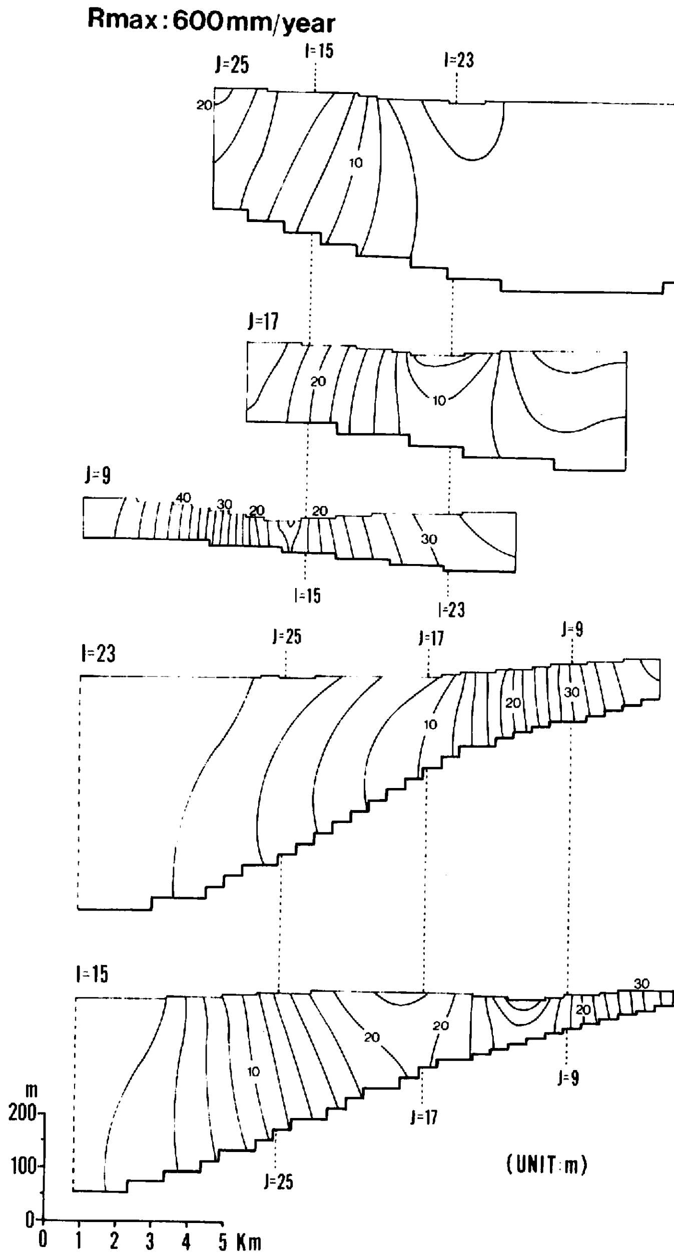


Figure 24 Hydraulic head distributions in the case of R_{max}=600 mm/year. Locations of sections are shown in Figure 22.

Recharge (or discharge) in each node on water table can be obtained from Darcy's law:

$$Q(i, j) = K_{zz} \cdot \Delta h \cdot \Delta x \cdot \Delta y \qquad (4-6)$$

where $Q(i, j)$ is the recharge or discharge in node (i, j), K_{zz} is the vertical hydraulic conductivity, Δh is the hydraulic gradient near water table, Δx and Δy are the intervals of nodes in i and j directions, respectively. Total recharge (or discharge) can be obtained by summing up the recharge (or discharge) in each node which belongs to the recharge (or discharge) area.

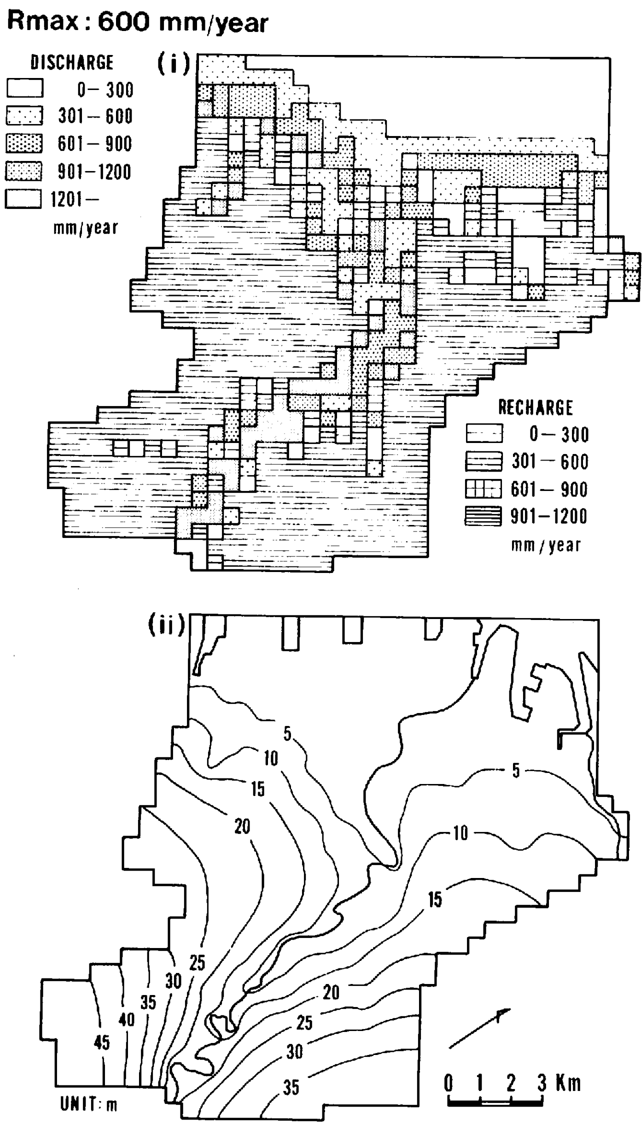


Figure 25 Recharge-discharge map (i) and water table configuration (ii) in the case of R_{max} =600 mm/year

Figure 25 shows the recharge-discharge map and the configuration of the water table. Recharge areas almost correspond with the upland regions, while the discharge areas appear along the Yoro River and its major tributaries, and the coastal lowlands. The rate of discharge is high in the lowland of the Yoro River and the coastal plain near the uplands, and it becomes low with the distance from the uplands.

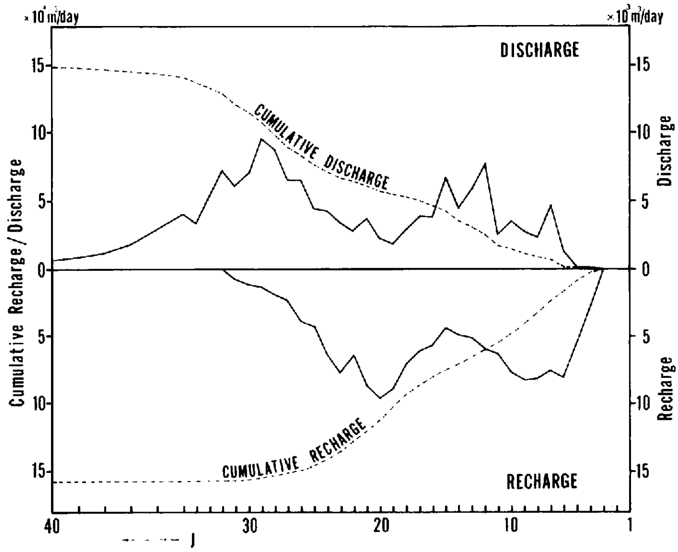


Figure 26 Water balance of the groundwater basin.

Figure 26 shows the amount of recharge and discharge, and cumulative recharge and discharge in the J direction. Total recharge (= total discharge) is about 150,000 m^3/day, that is, the dynamic flow through the groundwater basin is also about 150,000 m^3/day.

The amount of discharge has a minimum value at J=19, where the width of the valley floor becomes narrow. Discharge of the interior part from J=19 is considered as the one from the groundwater flow system formed by the lowland of the Yoro River and the upland regions. Cumulative discharge until J=19 is about 55,000 m^3/day, which is 37% of the total recharge.

Cumulative discharge reaches 50% of the total recharge at J=25 (Murakami), and attains 80% at J=31, in the southern margin of the coastal industrial zone. Most recharged water in the upland regions discharges until it reaches the coast of Tokyo Bay.

4.4 Sensitivity of the dynamic flow

As stated before, annual precipitation shows large variations. The maximum annual precipitation is about twice as much as the minimum one. Therefore annual recharge to the groundwater may actually show a large variation. The response of the groundwater flow system to the varying recharge is evaluated in the followings by using the previous method.

Figures 27 to 30 show the results of calculations in the case that the maximum recharge (R_{max}) are set 300 and 1,200 mm/year as the extremities.

In both cases, the coastal plain and the lowland of the Yoro River are discharge areas and upland regions are the recharge areas. Along the major tributaries of the Yoro River, discharge areas appear in the case of 1,200 mm/year. The configuration of water table is very smooth for R_{max}=300 mm/year. The water table rises as a whole in the case of 1,200 mm/year, but the upturn is restricted at the valleys, and therefore the undulation of water table increases.

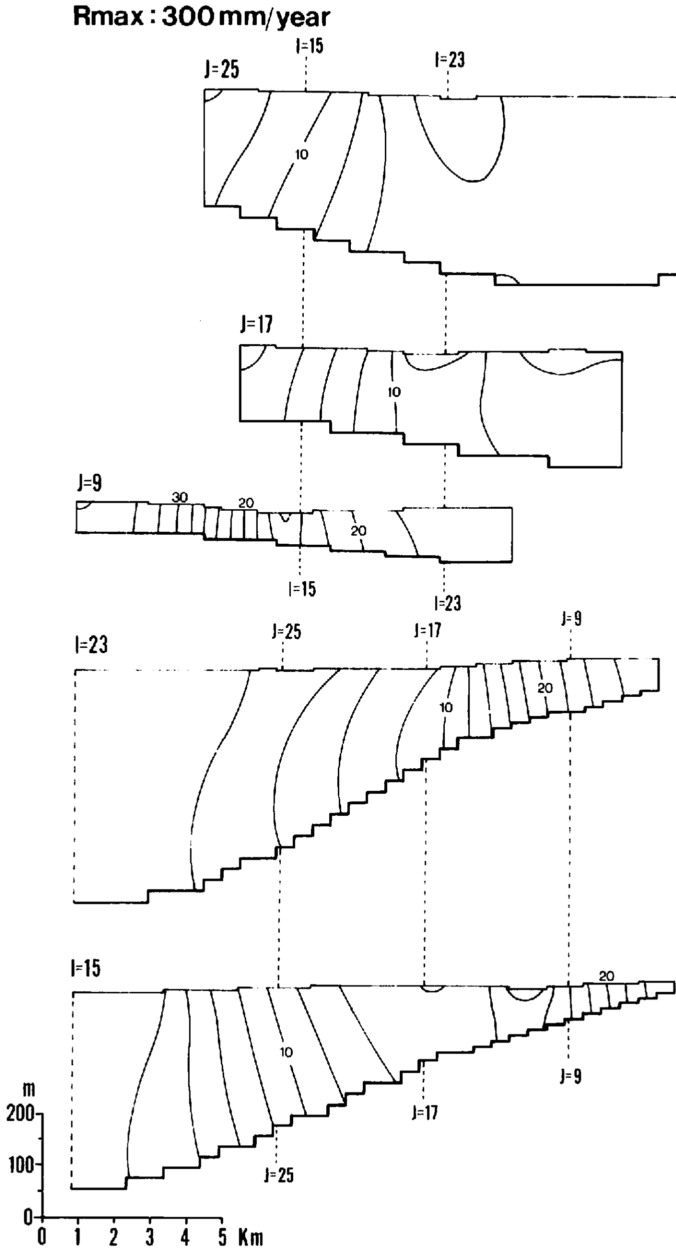


Figure 27 Hydraulic head distributions in the case of R_{max}=300 mm/year. Locations of sections are shown in Figure 22.

Figure 31 shows the discharge in J direction for the three cases. The increases of discharge with the increases of recharge are larger at the interior part, especially at the lowland of the Yoro River, than at the coastal plain. This is because the discharge from small scale flow systems, *i.e.* local or intermediate systems, increases with the increase of the recharge. The reason why the discharge from small scale system increases is that the topography controls the relief of water table increase and makes the small scale groundwater flow systems to become active.

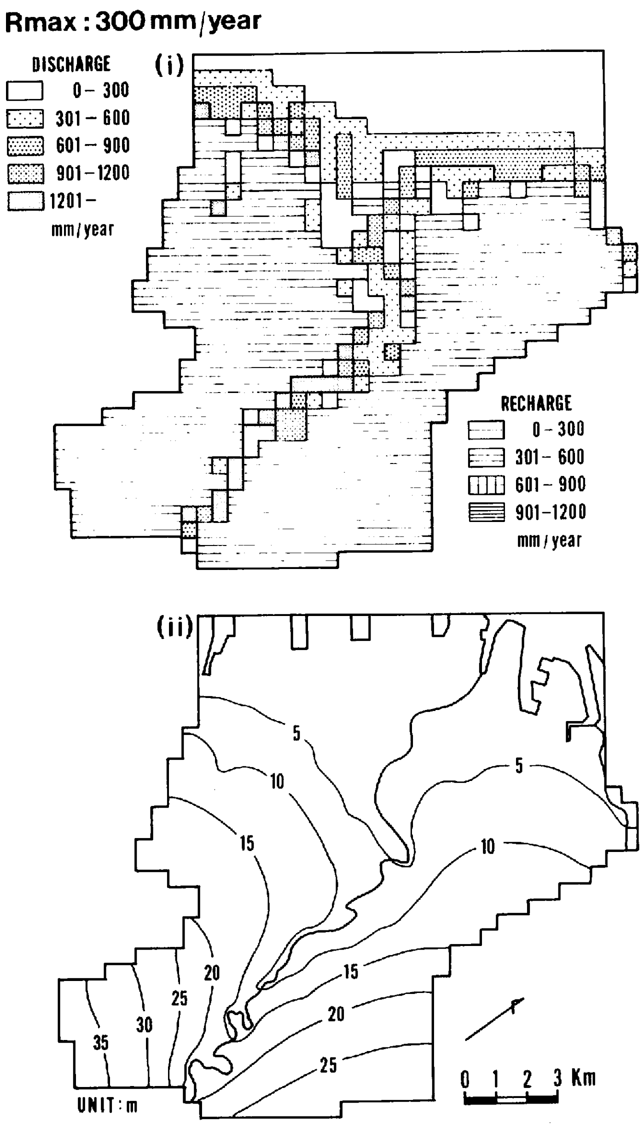


Figure 28 Recharge-discharge map (i) and water table configuration (ii) in the case of R_{max}=300 mm/year.

The discharge, hence the dynamic flow, of the regional system is relatively stable, and is determined by the large scale topography, extent of the basin and the permeability of geologic formations in the area. On the contrary, flow in the small scale systems is influenced by precipitation variation to much greater degree than the flow in the regional systems are affected.

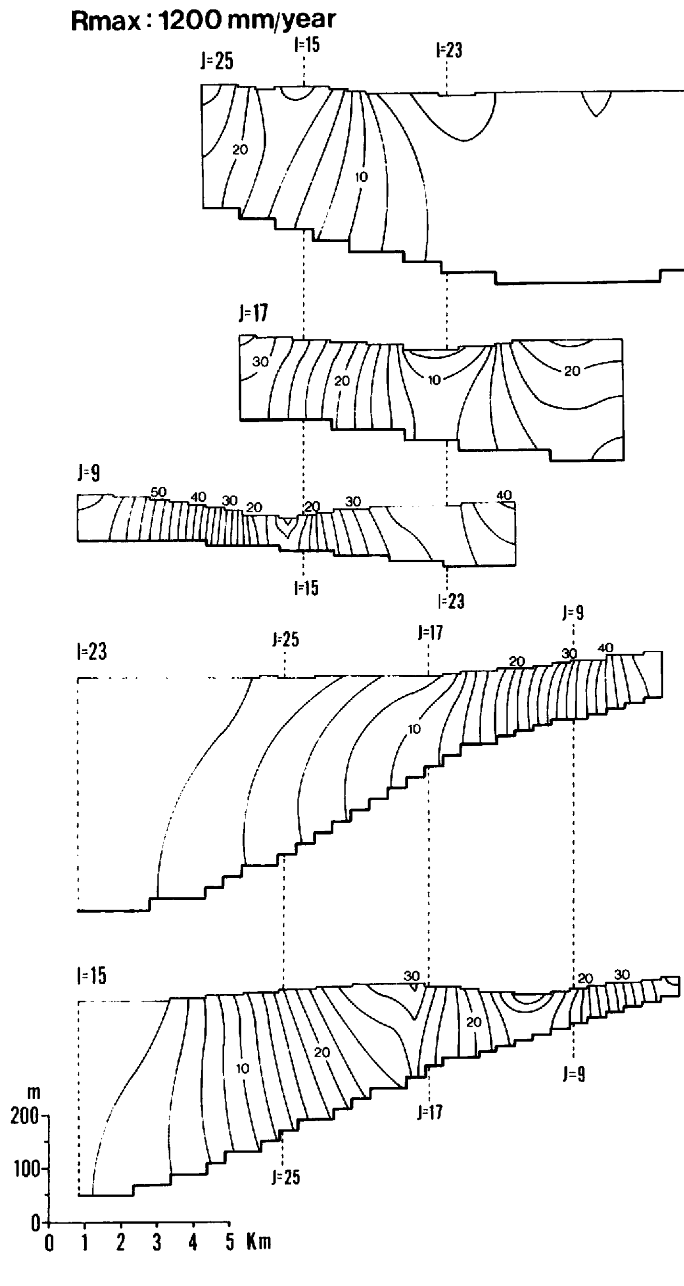


Figure 29 Hydraulic head distributions in the case of R_{max}=1,200 mm/year. Locations of sections are shown in Figure 22.

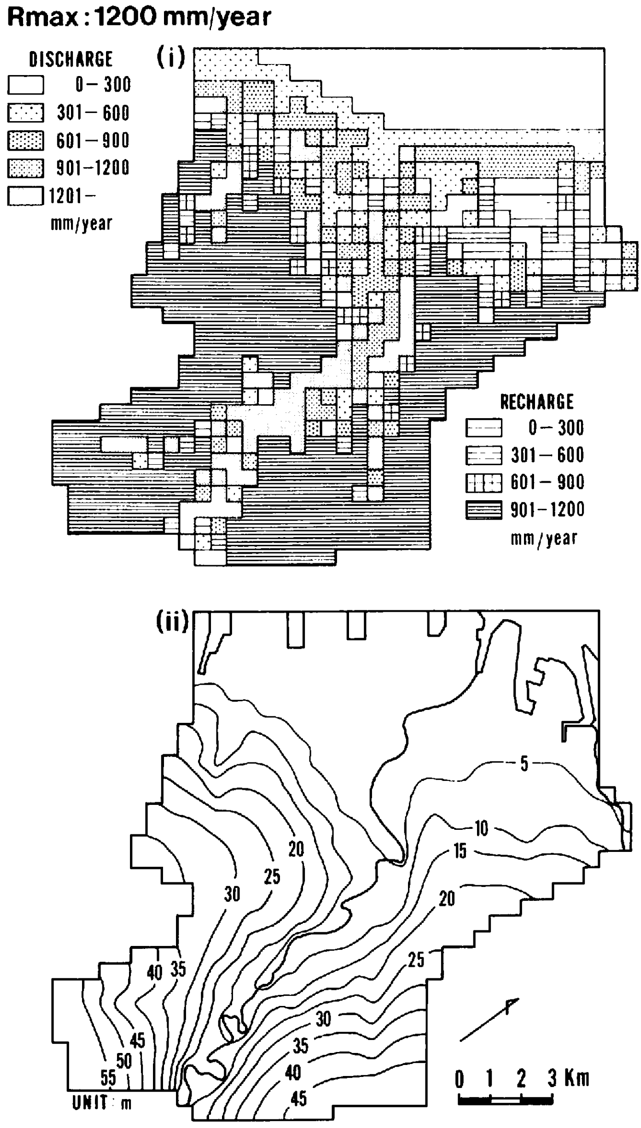


Figure 30 Recharge-discharge map (i) and water table configuration (ii) in the case of R_{max}=1,200 mm/year.

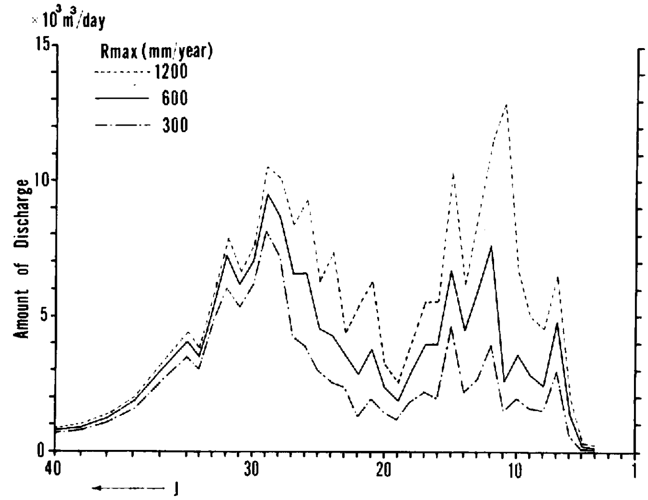


Figure 31 Changes in the amount of discharges for the different recharge.

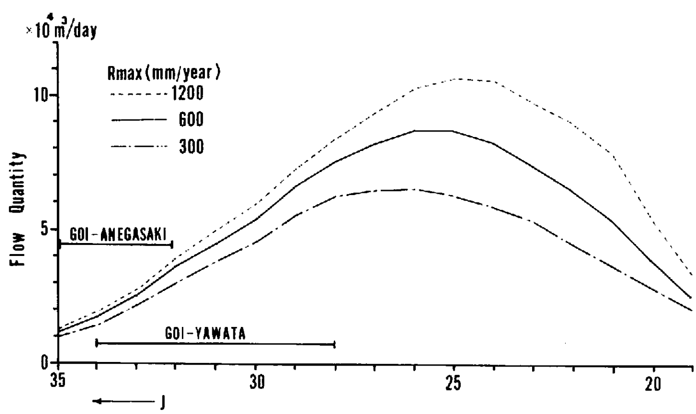


Figure 32 Flow quantities across sections along the coast of Tokyo Bay.

CHAPTER 5

DISCUSSION

From the distribution pattern of tritium concentration in groundwater, it is revealed that the groundwater is recharged at the uplands and flows toward the lowlands as a whole. At the vicinity of drainage divides or the Yoro River, it becomes clear that the vertical components of groundwater flow are important.

The tritium concentrations of stream waters in dry season suggest that the origin of base flows is groundwater. Therefore it is assumed that a small scale or a low order groundwater flow system exists in a small drainage basin dissecting the upland region. This flow system corresponds to the local flow system of Tóth's definition of the groundwater flow systems (Tóth, 1963) because the recharge areas are uplands adjacent to the lowland.

Tritium concentrations of base flow indicate that the residence time of the local flow system is less than 30 years. On the contrary, the residence time of the groundwater flow system whose discharge area is the lowland of the Yoro River is over 30 years. This flow system underlies the local flow systems, so it corresponds to the intermediate flow system.

Consequently, two groundwater flow systems of different orders, namely, the local and the intermediate, are clarified by means of environmental tritium. According to Tóth (1963), the regional system is the one whose recharge area occupies water divide and its discharge area lies at the bottom of the basin. Therefore the regional system in the study area corresponds to the flow from uplands toward the lowlands along Tokyo Bay.

The estimated flow pattern suggests the existence of the groundwater flow system theoretically derived by Hubbert (1940) and Tóth (1962, 1963), and it is known that the groundwater flow system in the study area is formed basically under the influence of topography rather than geology. Namely, as the water table is high in the uplands and low in the lowlands, the groundwater flows to the direction that the potential difference disappears. This is also confirmed by the numerical simulation including the topotraphic and geologic conditions in the area (Kondoh, 1982).

These results indicate that groundwater flows through the mud beds, namely, the mud beds can not influence on the flow system enough to alter the flow pattern formed under the influence of topography. When only the geologic structure in the study area is emphasized, the flow toward Tokyo Bay along the strata is estimated, which is the one considered so far. The results of tritium analyses, however, do not support the existence of such a flow.

These results of tritium analyses approve the availability of environmental tritium as a tracer, and clarify that it can be used to investigate the regional groundwater flow.

In order to quantify the dynamic flow through the groundwater basin by the mathematical model, the model should reflect the flow pattern as stated above. Hence, related to the results of tritium analyses, Freeze-Witherspoon model is known to be most suitable method for the water balance simulation.

About 600 mm/year of recharge can be expected from the water balance on the ground surface. According to the water balance simulation, total amount of recharge is about 150,000 m^3/day, but about 80% of recharged water is discharged at inner parts than Keiyo Industrial Zone, and therefore the flow across the profile along coast is estimated to be about 30,000 m^3/day.

The amount of groundwater flowing from uplands toward the coast of Tokyo Bay can roughly be estimated by means of the relation between the amount of pumping and water level fluctuations in observation wells.

In Figure 7, average hydraulic gradient between Iwasaki and Ama-ariki, i, was 0.0036 in 1972 when the water levels were at minimum level, and was 0.0015 in 1980 when the water levels have been recovered fair degree. Total amount of pumping at coastal industrial zone in 1972 was about 100,000 m^3/day, and the water levels were in a quasi-steady state. Assuming that the amount of pumping and the flow of groundwater were in equilibrium in 1972, the Darcy's law, $Q=AKi$, holds true, where Q is the amount of pumping or flow of groundwater, A is a cross-sectional area, and K is the permeability. Then the value of AK can be obtained as a proportional constant between Q and i.

In 1980, the hydraulic gradient between Iwasaki and Ama-ariki was 0.0015, so about 40,000 m^3/day of groundwater flow was expected from the proportionality between Q and i, but the total amount of pumping in the coastal industrial zone was about 30,000 m^3/day, accordingly water levels were recovering in 1980. On the basis of the topographic configuration, hydraulic gradient between Iwasaki and Ama-ariki is estimated to be about 0.0001, therefore it can be considered that about 28,000 m^3/day of groundwater flows from upland regions toward the coast in natural condition.

Figure 32 shows the flow quantities for different recharges as the results of calculations. The flow quantities across the sections from J=32 to 35, which are corresponding to the coastal industrial zone, range from 12,000 to 36,000 m^3/day, and they agree well to the above estimated value. Hence, it regarded that groundwater of about 30,000 m^3/day flows through the section along the coastal industrial zone. This quantity can be regarded as a flow of regional groundwater flow system.

Compared with the one estimated so far, it is fairly small. This is considered to be caused by the difference of the way of recognition about the groundwater flow system. In the former way of thinking about the groundwater movement in the study area, it seems to be regarded that all the groundwater recharged in the inland regions flows toward Tokyo Bay. In the groundwater flow system which the energy required for the groundwater movement originates from the potential difference made by the topography, however, all recharged water in the uplands does not flow toward the coast, but almost it discharges through the local or intermediate flow systems in the inland regions.

The flow across the profile along the coast is only 20% of the total recharge, and almost recharged water discharges at inland region. The flow of regional system, however, is relatively stable and is less sensitive to the change of the recharge due to the climatic variation.

The amount of pumping in the coastal industrial zone is about 20,000 to 30,000 m^3/day around 1980, therefore, it is considered to be in equilibrium with the natural regional groundwater flow.

CHAPTER 6

CONCLUSIONS

In order to clarify the actual condition of groundwater cycle, namely, the recharge, movement and discharge of groundwater, the investigation was performed in the Ichihara region, Chiba Prefecture.

Firstly, environmental tritium is used as a tracer to analyze the three-dimensional geometric distribution of groundwater movement. As the results, it is clarified that the tritium concentration distribution in groundwater well reflects the groundwater movement, and the three-dimensional flow pattern of groundwater can be made clear. It is also clarified that environmental tritium can be used to trace the regional flow of groundwater.

Secondaly, the mathematical model based on the flow pattern revealed by environmental tritium is constructed, and spatial distributions of recharge, discharge, and dynamic flow are evaluated.

The results are summarized as follows:

(1) Distribution pattern of tritium concentration in groundwater indicates that recharge areas of groundwater are uplands and the discharge areas are the lowlands, and groundwater flows from uplands to lowlands as a whole. It is also suggested that the vertical components of groundwater flow are important near the drainage divides or the Yoro River.

(2) Tritium concentrations in streams indicate that the baseflow is maintained by groundwater, and the existence of local groundwater flow systems are estimated in the drainage basins dissecting uplands.

(3) The residence time of the local flow systems is estimated to be below 30 years because tritium concentrations of baseflows are rather high in comparison with that of precipitation in the same period. In the intermediate system whose discharge area is the lowland of the Yoro River, the residence time exceeds 30 years because thermonuclear tritium has not reached the Yoro River.

(4) Tritium concentration in groundwater indicates that a certain degree of mixing occurs during the groundwater movement. It cannot be explained by the molecular diffusion, and it is considered that mixing process is macro-dispersion caused by heterogeneity of geologic materials.

(5) General pattern of tritium concentration distribution can be explained by the advection-dispersion model despite a certain degree of mixing. This serves the availability of environmental tritium as a tracer for the study on the regional groundwater flow.

(6) The average annual precipitation in the study area is 1627 mm, and average annual evapotranspiration is 696 mm. When considering the direct runoff component in the water balance equations, the average annual groundwater recharge is estimated to be about 600 mm. It leads to the total amount of recharge (=discharge) about 150,000 m^3/day, which is equal to the dynamic flow through the groundwater basin.

(7) About 80% of total recharged water discharges through the local or the intermediate flow systems at the lowlands of the Yoro River or the lowlands along the coast. The flow across

the section along the coast is estimated to be about 30,000 m^3/day, which is almost equal to the amount of pumping in the coastal industrial zone around 1980. Therefore the recent amount of groundwater use in the coastal industrial zone is considered to be in equilibrium with the natural flow of groundwater.

(8) The flow of regional flow system is relatively stable, and less sensitive to the change of recharge due to precipitation variation.

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編集・発行者　筑波大学水理実験センター

〒305 茨城県新治郡桜村天王台1－1－1

TEL 0298(53)2532

印刷　　株式会社　三　協　社

〒164 東京都中野区中央4－8－9