Journal of Nepal Geological Society, 2011, Vol. 43, (Special Issue), pp. 267–276

Hydrogeology of shallow and deep aquifers in Nara Basin, West Japan

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ABSTRACT

Among the various factors responsible for the potentiality of an aquifer, the surface and subsurface geology, drainage density and amount of groundwater recharge are considered to playing significant role. A combined analysis of pumping test data, subsurface distribution of aquifer materials, borehole resistivity logs and active fault lineaments has been carried out in order to assess the hydrogeological conditions of Nara Basin, West Japan. Basically, groundwater in the area is available in unconsolidated sedimentary aquifer and in underlying fractured aquifers in granitic basement. The study has outlined the promising areas of higher groundwater potential in both the unconsolidated sediments and basement rocks and tried to find out the most effective controlling factor for the groundwater potentiality in the area. The average electrical resistivity values of water bearing formations in sedimentary sequence is 56 N.m while it is 638 Ω.m for the fractured basement aquifer. The general flow of shallow and deep groundwater is found to be towards the western part of Yamato River, which is flowing almost through the central part of the Basin. The optimal yield and specific capacity of wells as well as hydraulic conductivity of aquifers are higher in the northeastern part of the study area, which is having a higher density of active fault lineaments. The drainage density is comparatively higher in the southern part of the study area. However, the distribution of permeable sediment is higher around the Yamato River and in northeast, southernmost and western part of the study area. Thus the combined effect of relatively high percentage of permeable material and the higher density of the active fault lineaments in the northern part has resulted the northeastern part as a promising area of groundwater potential.

Keywords: groundwater potential, specific capacity, hydraulic conductivity, active fault lineament, Nara Basin

Recieved: 14 November 2010 **revision accepted:** 10 January 2011

INTRODUCTION

Alluvial basins are the major sources of groundwater resources in many parts of the world. However, groundwater resources development in fractured-rocks is also commonly practiced in many parts of the world. In alluvium, groundwater occurs mainly in granular formation because of primary porosity. While, high production areas in hard rock aquifers are associated either with weathered or hydraulically conductive fracture zones (fissaures/joints) as secondary porosity. Though identification of these highly permeable zones is difficult, detailed structural analysis and understanding of the tectonic evolution of the area can provide useful information to locate such zones.

Nara Basin is located on west Japan. The basin is a valley surrounded by mountainous terrain and is about 770 km2 in areal extent. There are many streams reaching the valley from the surrounding mountains to form Yamato River. Yamato River flows almost through the central part of the Nara Basin towards west (Fig. 1). The average elevation of the Nara Basin is around 60 m above sea level (asl), while the height of the surrounding mountain ranges from 470 m to 900 m, the highest peak lies in southern part of the study area. The mean annual precipitation in the area is around 1325 mm.

The shallow wells in the unconsolidated sediments are drilled to meet the drinking water demand in the area. However, most of the deep wells are drilled to exploit the thermal water from the fractured granites for commercial purpose. The objective of the present study is to understand the groundwater condition in the unconsolidated sediments and fractured rocks utilizing well data and geological structures in the area, particularly faults. The hydrogeological information has been obtained from well log, pumping test, and electrical logging data.

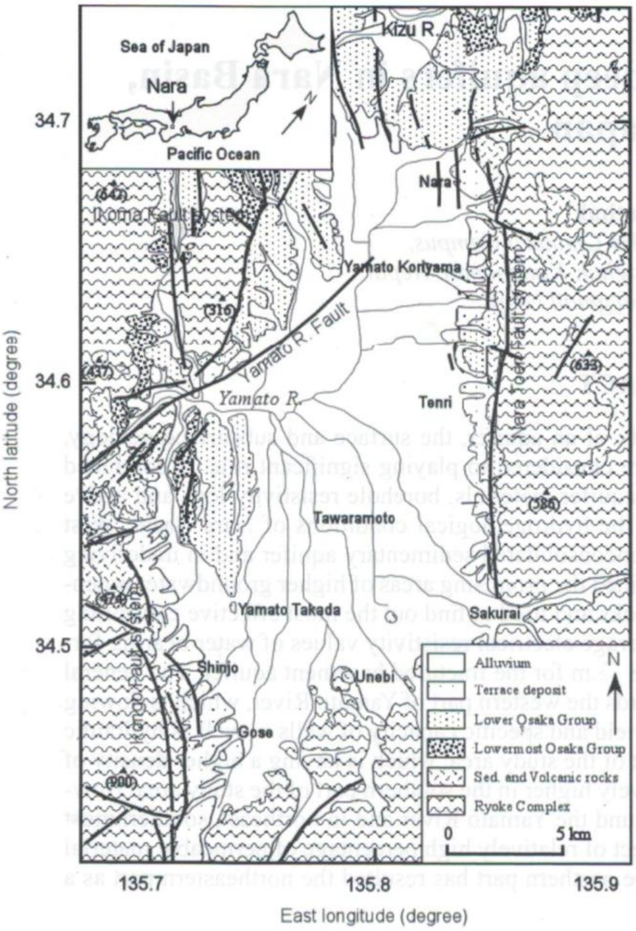

Fig. 1: Geological Map of the Nara Basin

GEOLOGICAL SETTING OF THE AREA

The geology of Nara Basin can be broadly subdivided from top to bottom into the Alluvium (Holocene), Terrace deposits (Upper Pleistocene), Osaka Group (Late Pliocene-Upper Pleistocene) and the Cretaceous granitic basement of Ryoke complex (Ikebe and Takenaka, 1969). Alluvial deposits consists chiefly of unconsolidated clay, sand and sandy gravels attaining the maximum thickness of 5 m. Whereas the terraces (maximum thickness 20 m) are consisting of alternating beds of marine clay with sand and non-marine sandy gravel, sand, and clay (Fig. 1). The Osaka Group is further subdivided into the Upper-, Lower- and Lowermost parts (Huzita and Kasama, 1983). The upper and Lower parts consist of alternating beds of marine clay with sand and gravel and non-marine sandy gravel, sand, and clay. The Lowermost part is consisting of non-marine clay, sand, and gravel. The different marine beds occurring at different depths are considered to be the marker beds and are considered to demarcate the geological boundaries of above mentioned units (Itihara, 1961; Yoshikawa et al., 1987). The maximum thickness of the Osaka Group is around 600 m. The deep drillings in the northern part of the basin evidences that the maximum thickness of the whole sequence above the Ryoke complex is around 646 m.

The surface of Nara Basin is mostly covered by alluvial deposits. The terrace deposits are exposed along the terraces lying between the hills and the Plain area. Likewise, the Osaka Group sediments can be observed along the foothill, and the Miocene beds (volcanic and sedimentary rocks) are sporadically exposed in some localities. The upper part of Osaka Group is not exposed in the study area (Itihara et al., 1991). In the higher elevation areas, the granitic basement is well exposed, mostly forming higher hills surrounding the basin.

Table 1: Description of the wells in fractured rocks basement in the study area

Well No.	Well Depth (m)	Altitude (m)	Geology of Screened zone	Sp. Cap. (Q/s) m^3/day/m	Screen location (m bgl)	Screen length (m)	Water level (m. asl)
HS5	*800*	*62.5*	*Sediment+Granite*	*28.07*	*580-788*	*99.0*	*37.0*
HS43	*625*	*54*	*Sediment*	*70.30*	*400-581*	*118.5*	*13.3*
HS53	*1101*	*86*	*Granite*	*1.05*	*826-1085*	*115.0*	*54.0*
HS54	*650*	*38*	*Granite*	*0.84*	*505-644*	*124.0*	*21.1*
HS60	*801*	*111*	*Granite*	*2.25*	*698-801.4*	*103.4*	*77.5*
HS104	*1100*	*62.5*	*Sediment+Granite*	*0.65*	*477-1094*	*243.5*	*-3.0*
HS123	*1100*	*273*	*Granite*	*1.01*	*1028-1094*	*66.0*	*272.9*
HS128	*1500*	*70*	*Granite*	*1.21*	*751-1015*	*102.0*	*63.2*
D14	*202*	*282*	*Granite*	*541.44*	*165-198*	*33.0*	*300.0*
D18	*101*	*230*	*Granite*	*0.41*	*6-93*	*40.0*	*194.6*

The basement structure in the basin as estimated from the analysis of gravity data shows that the altitude of basement topography is the lowest in the northeastern part of the basin and the rocks form a NE–SW trending subsurface ridge south of the Yamato River (Pathak, 2006). The study reveals that thick alluvial deposits are overlying the basement rocks in the northeastern part of the basin.

Most of the faults in the basin and surrounding mountainous part have approximate north-south trend, whereas some faults trending in NE-SW direction also exist. The major faults in the area are north-south running Nara-Toen fault system in the north east of the basin and Kongo fault system in the south west of the basin. These fault systems have been delineated by the Seismic reflection survey carried out by Geological Survey of Japan (Okumura et al., 1997a, 1997b).

HYDROGEOLOGIC PARAMTERS

The hydrogeology of the basin has been described in several studies (Murakami, 1951; Takahashi and Ikeda, 1965; Taniguchi, 1994; Inagaki, N., Taniguchi, M., 1994). All these studies are dealing with the shallow groundwater in the overlying sedimentary cover. These studies neither present detailed information on the aquifer properties nor describe the distribution of aquifer materials throughout the basin. Furthermore, none of these studies are dealing with the deep aquifer and the fractured rock aquifer as well. The study of the vertical groundwater flow to the deeper part through the analysis of the temperature measurement data from several wells shows that the groundwater is flowing vertically downward at the majority of sites (Pathak, 2003), suggesting that the overlying unconsolidated aquifers are recharging the fractured basement aquifers. However, the upward flow at some locations was noticed suggesting that the pressure distribution is basically controlled by the distribution of fractures in the basement. Likewise, the three-dimensional groundwater flow model of the basin shows that groundwater is flowing towards the central part of the basin from the surrounding areas and the flux is high in the northern part of the basin (Pathak 2002). The discharge of groundwater outside the basin takes place through the Yamato River.

The wells considered in the study are drilled both in crystalline basement (granite) and overlying sedimentary cover. The shallow wells are reaching up to depth of 250 m, while the deep wells are as deep as 1500 m. The altitude of the locations of shallow and deep wells ranges from 34-288 m and 38-273 m asl, respectively. The water level in shallow and deep wells vary from –0.5 to 285.25 m, and from –3.0 to 300 m, respectively above sea level. The groundwater in the unconsolidated sedimentary formation is flowing from the surrounding areas towards the Yamato River, in the midwestern part of the valley. Like shallow groundwater, the deep aquifer also shows general trend of groundwater flow towards Yamato River in the western part of the basin (Fig 2).

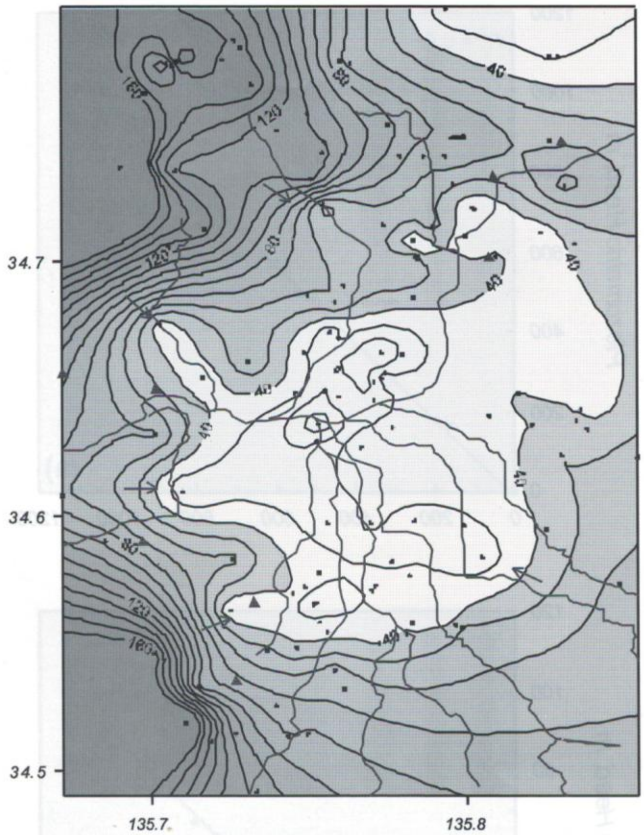

Fig 2: Locations of wells and water table (msl) for unconsolidated aquifer in the basin.

Another hydraulic parameter to indicate the well yield is specific capacity (volumetric flow/drawdown, i.e. Q/s), which basically represents the performance of a well. Though it also depends upon the efficiency of well construction, it basically reflects the hydraulic characteristics of the aquifer. Thus the specific capacity is an effective means to estimate the potentiality of wells.

In both deep and shallow aquifers, very high correlation coefficients (0.99 and 0.82) have been obtained between the piezometric head (height of water table above the top of screen) and the depth of the top screened aquifer (Fig. 3). This correlation indicates that the rise in water table in the wells is related to the confining pressure.

YIELD OF THE WELLS

For the proper management of groundwater basin, it is very important to define the groundwater yield from wells. Hata (1998) has summarized and described the use of different types of yields in order to explain the extractable groundwater yield from a groundwater basin. In community water supply project, the Optimal yield concept (critical pumpage capacity for individual well) can be applied (Hata, 1999).

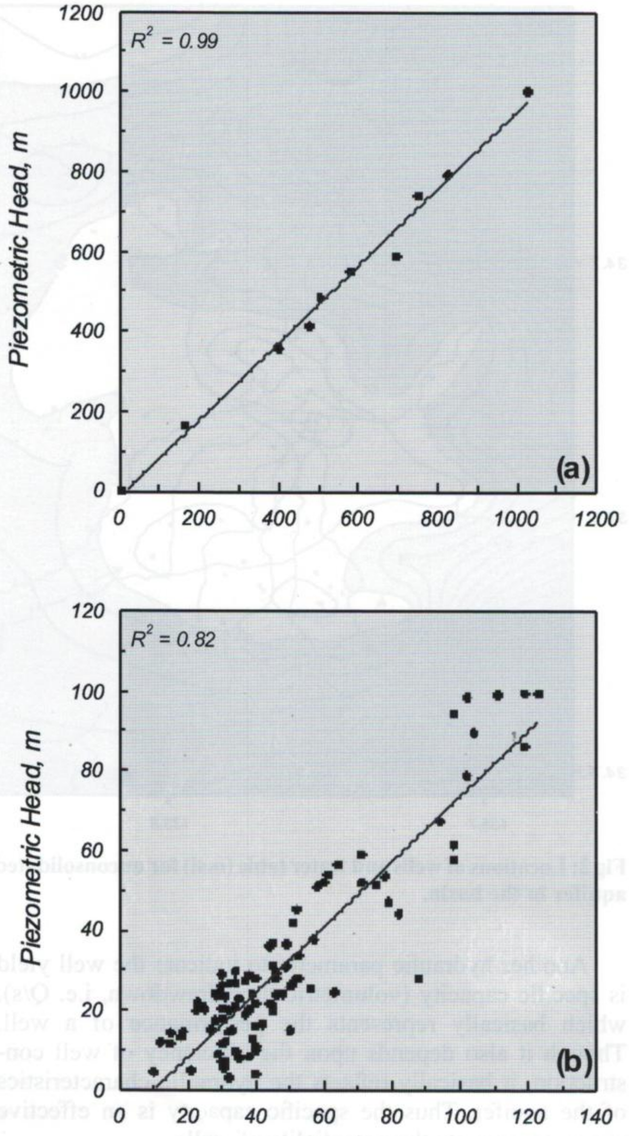

Fig. 3: Graph showing the relationship between the piezometric head and the top of screen for (a) basement and very deep aquifer, and (b) shallow aquifer in sediments.

The discharge versus drawdown that is obtained from step drawdown pumping test for some of the representative wells in the study area are plotted to understand the potentiality of the single well (Fig. 4). The slope of the straight line is an indicative of either laminar or turbulent flow (Murashita, 1962). Laminar flow exists if the angle of inclination is less than 45o, while the inclination exceeding more than 45o will be turbulent flow. The inflection point from which the flow changes from laminar to turbulent is defined as critical discharge. The discharge below the critical discharge is defined as optimal yield of a single well. It can be seen that the optimal yield for most of the deep wells lies below 200 m3/day. All these wells are screened completely in the basement rocks. The wells HS5 and HS43 have optimal discharge value more than 500 m3/day. The well HS5 is screened both in sediment and basement rocks, while HS43 is screened in deep sediment. Likewise, laminar flow condition can be seen up to the discharge as high as 2600 m3/day in well D2 (250 m deep) drilled in sediment. This suggests that the unconsolidated sedimentary aquifer is more productive than the fractured aquifer of the basement rocks. Further, all these highly productive wells lie in the northern part of the basin.

SPECIFIC CAPACITY OF WELLS

In this connection, the specific capacity of 10 wells drilled either in sediment or in basement (depth > 250 m) and 117 wells (depth up to 250 m) drilled in overlying unconsolidated sedimentary sequences has been considered to describe the groundwater potential in the study area.

The specific capacity of the shallow wells in unconsolidated sediments ranges from 1 to 755 m3/day/m (average: 127 m3/day/m). It is to be noted that this value is found to be independent to the depth of aquifer. Likewise, the specific capacity of very deep wells screened either in deep sediment or basement ranges from 0.645 to 70.30 m3/day/m (Table 1). The shallow well drilled in basement near the Yamato River has very high value (541.44 m3/day/m), while well at southern part has very low value. The box plot of specific capacity for both the shallow and deep wells shows that most of the values lie between 50 and 250 m3/day/m for shallow wells while it is too low for deep wells and wells in basement (Fig. 5). The highest values reported from the wells lying in the northern part. A contour map has been drawn for the distribution of specific capacity of shallow wells (Fig. 6). It is clear that the wells drilled in northern part of the basin (north of Yamato River) has higher specific capacity in both the shallow as well as deep wells, while it is lower in the area lying south of Yamato River.

HYDRAULIC CONDUCTIVITY OF AQUIFER

The hydraulic conductivity of the alluvial and fractured aquifers in the area has been calculated by analyzing the pumping test data of the wells (Tables 1 and 2). The hydraulic conductivity of wells in sedimentary aquifer ranges from 1 x10-2 to 583 x10-2 m/day. The high conductivity values lies to the north of Yamato River while low values (less than 10 x10-2 m/day) lie in the southern part of the study area (Fig. 7). The hydraulic conductivity of the very deep aquifer, mostly in basement, is very low (average 1.23 x10-2 m/day). However, wells in the northeastern part of the valley have higher hydraulic conductivity values reaching up to 80.5 x10-2 m/day. The shallow well (D14) drilled in the basement, near the exit of Yamato River, has very high hydraulic conductivity (606 x10-2 m/day), however the hydraulic conductivity of the shallow well (D18) in the southern part of the study area is too low. This can be attributed to the fact that this shallow well is receiving direct recharge through tributary of Yamato River that is flowing in N-S direction through east of the well location.

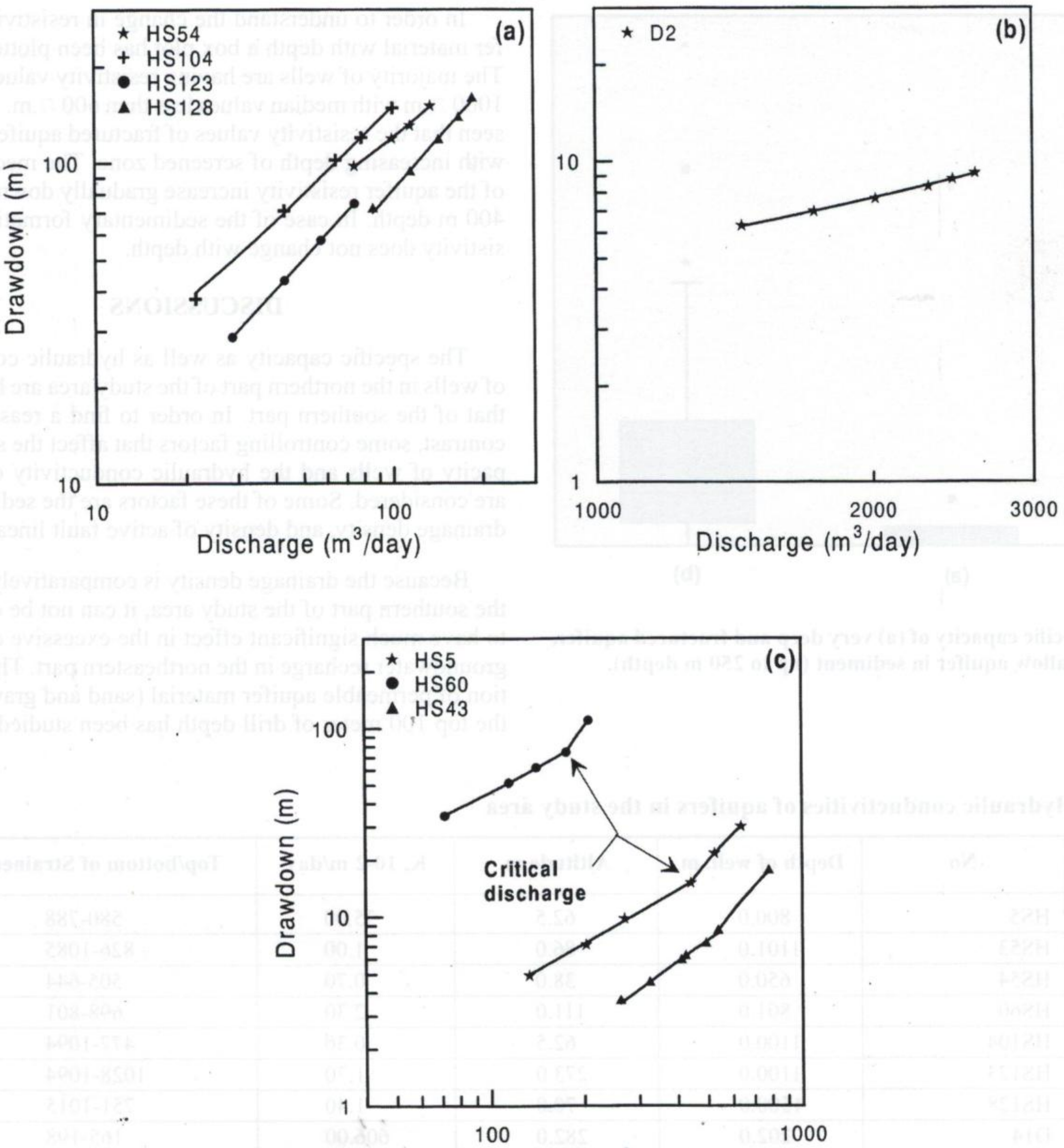

Fig. 4: Discharge versus drawdown showing laminar flow in (a) deep fractured aquifer and (b) shallow aquifer. The turbulent flow above the critical discharge in deep aquifer is shown in (c).

ELECTRICAL CHARACTERISTICS OF AQUIFER

The electrical characteristics of different aquifers have been described based on the resistivity logging in the wells, which has revealed the subsurface resistivity values. The resistivity of basement ranges from and 19 to 7140 Ω.m while that of the sediments ranges from 2 to 433 Ω.m. The average resistivity of basement and overlying sedimentary layers are 770 and 67 Ω.m, respectively showing a sharp distinction in electrical resistivity in basement.

In order to estimate the resistivity of the fractured aquifer as well as of very deep aquifers, the resistivity values as measured across the screened zone at different depth in each wells has been obtained for 50 cm interval. The mean resistivity value of the fractured aquifer is 492 Ω.m. The box plot of the resistivity values is very useful to evaluate the data statistically so that the representative data can be easily identified. The resistivity value of less than 500 Ω.m has the highest frequency among all the wells. The median resistivity value is 321.0 Ω.m. Likewise, the average resistivity of shallow aquifer of sedimentary formation is 54 Ω.m where the majority of the values are less than 50 Ω.m.

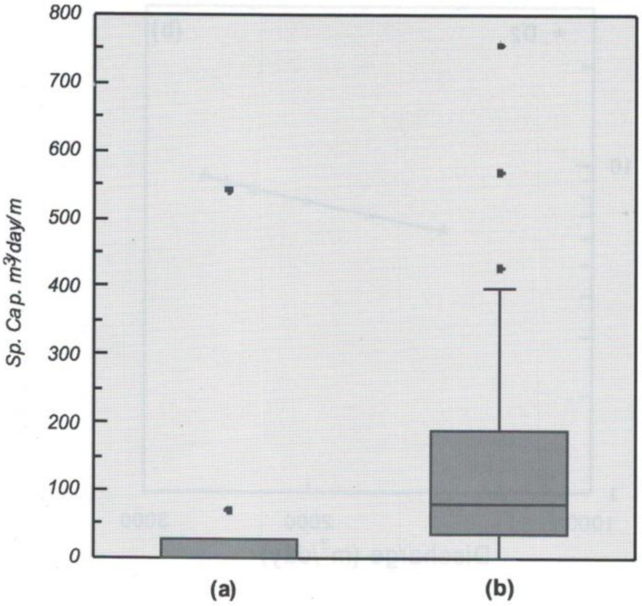

Fig. 5: Specific capacity of (a) very deep and fractured aquifer, and (b) shallow aquifer in sediment (up to 250 m depth).

In order to understand the change in resistivity of aquifer material with depth a box plot has been plotted (Fig. 8). The majority of wells are having resistivity values less than 1000 Ω.m with median values less than 600 Ω.m. It is clearly seen that the resistivity values of fractured aquifer increases with increasing depth of screened zone. The median values of the aquifer resistivity increase gradually downward from 400 m depth. In case of the sedimentary formation, the resistivity does not change with depth.

DISCUSSIONS

The specific capacity as well as hydraulic conductivity of wells in the northern part of the study area are higher than that of the southern part. In order to find a reason for this contrast, some controlling factors that affect the specific capacity of wells and the hydraulic conductivity of aquifers are considered. Some of these factors are the sediment size, drainage density, and density of active fault lineament.

Because the drainage density is comparatively higher in the southern part of the study area, it can not be considered to have much significant effect in the excessive quantity of groundwater recharge in the northeastern part. The distribution of permeable aquifer material (sand and gravel) within the top 100 meter of drill depth has been studied by means

Table 2. Hydraulic conductivities of aquifers in the study area

	No	Depth of well, m	Altitude m	K, 10-2 m/day	Top/bottom of Strainer, m bgl
Basements	HS5	800.0	62.5	35.00	580-788
	HS53	1101.0	86.0	1.00	826-1085
	HS54	650.0	38.0	0.70	505-644
	HS60	801.0	111.0	2.30	698-801
	HS104	1100.0	62.5	0.30	477-1094
	HS123	1100.0	273.0	1.70	1028-1094
	HS128	1500.0	70.0	1.40	751-1015
	D14	202.0	282.0	606.00	165-198
	D18	101.0	230.0	1.10	6-93
Unconsolidated sediments	HS43	625.0	54.0	81.00	400-581
	D2	251.0	54.0	470.00	119-234.5
	D15	81.0	36.0	176.00	14-76
	SA	20.4	55.4	530.00	3.15-19.3
	SB	20.4	46.6	583.00	4.9-20.4
	S15	11.0	62.8	33.00	3.7-10.6
	S18	12.0	67.7	1.00	2.0-12.0
	S21	6.0	65.9	8.00	2.5-6
	S24	17.0	45.4	5.00	10-16.5
	S1	30.5	55.9	492	Aquifer samples from these wells were analyzed to calculate K. The values represents in average for the aquifers within drilled depths.
	S2	30.6	73.3	173	
	S3	30.3	72.4	570	
	S4	45.3	77.0	138	
	S5	45.6	52.5	155	
	S6	30.3	66.7	518	
	S7	30.5	54.3	213	

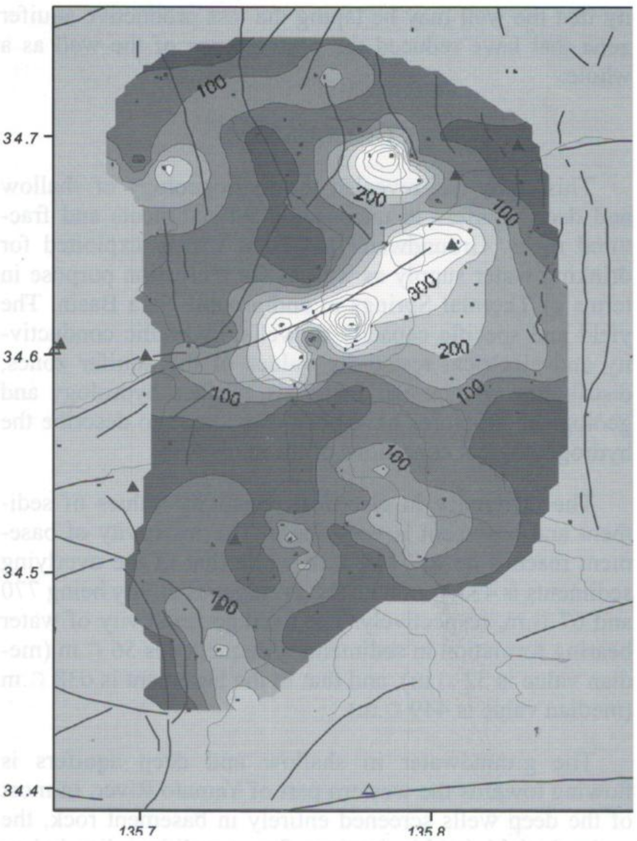

Fig. 6: Contour map of the specific capacity in the shallow wells in unconsolidated sediments. Triangles are the location of wells in basement. Thick solid lines are active faults.

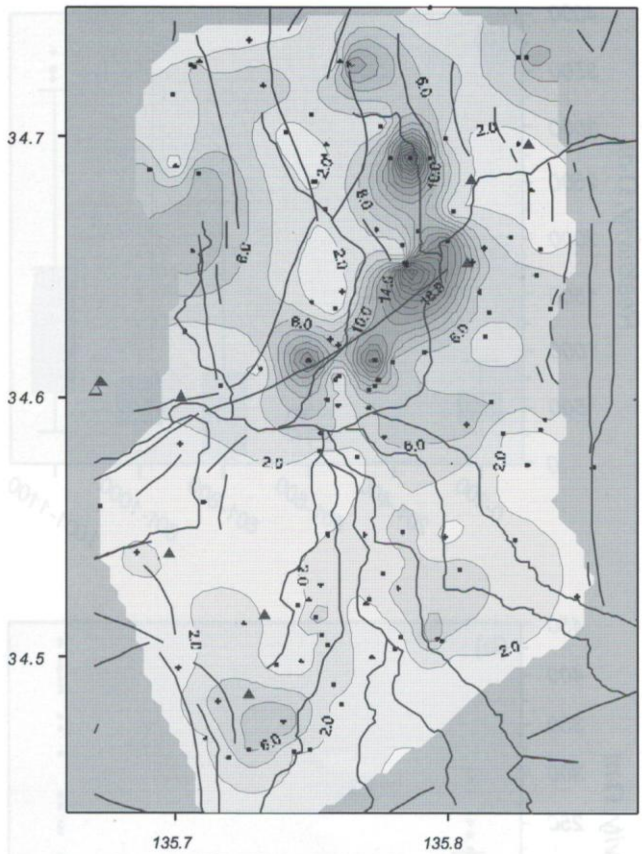

Fig. 7: Contour map of hydraulic conductivity values (m/day) in the basin. The thick solid lines are the active faults.

of the well logs (Fig. 9). The percentage of the permeable material is higher around and north of the confluence of Yamato River and its tributaries. South of Yamato River, higher percentages of aquifer materials are distributed in western and southern part of the study area. However, the yield and specific capacity of wells and hydraulic conductivity values of aquifers are higher in the northern part regardless of the sediment size. Further, these values are higher in the northeastern part even in the very deep wells drilled in the basement rocks. The basement aquifer is superior in the northern part irrespective of the thickness of overlying sediments. Principally, the effect of the variation in aquifer parameter of the overlying sedimentary sequences should not have significant effect to the very deep wells.

Since the drainage density and the distribution of permeable materials are showing no much effect on the variation of specific capacity of wells and hydraulic conductivity of the aquifer, the third factor, i.e. active fault lineaments has been considered to have a significant role. The fault lineaments are mostly north-south trending, however few are trending on other direction too. The basement rocks in the study area is subjected to fracturing at variable strengths and depths because of these active faults. The intensity of faulting is comparatively less in the extreme south and southeastern part of the study area. The wells drilled in the basement rocks are utilizing the water trapped in the fractured aquifer that is resulted due to the tectonic activities developing the active fault lineaments in the area.

The yield, specific capacity and hydraulic conductivity of the wells can be judged considering their approximation to the active fault lineament. In order to evaluate this aspect all the existing faults in the study area has been plotted together with the location of wells (Figs 6 and 7). These structures are obtained from the publication 'Active fault of Japan' (Research Group for Active Faults in Japan, 1991). The density of active fault lineament is more in northern part of the study area. However the wells lying either farther from the fault or in the south have low specific capacity and hydraulic conductivity. Besides, the wells, which are screened at deeper level (HS123, HS128, HS53 and HS104) also show low specific capacity. The reason may be the decrease in the aperture size of the faults and also the reduction of fracturing intensity with depth. The effective apertures and fracture densities plays a vital role on the productive capacity of wells located in rocks (Fernandes and Rudolph, 2001). Further, screening at the wider range of depth (e.g. HS104 and D18) also result in decreased specific capacity. This can be explained regarding the possibil-

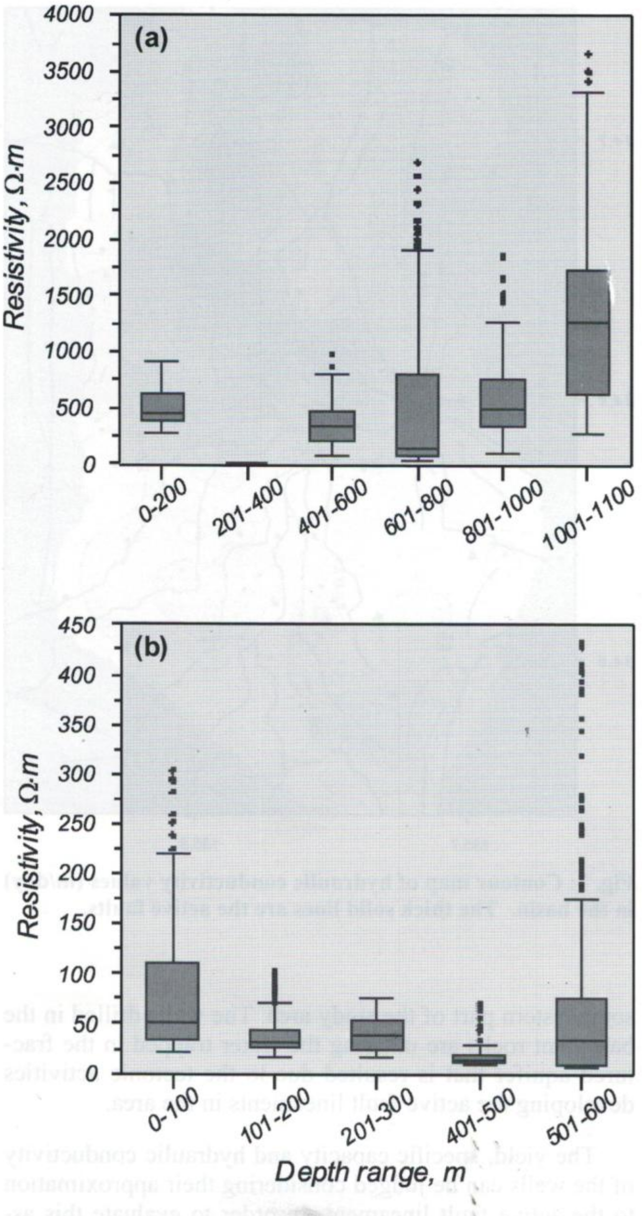

Fig. 8: Variation of resistivity values of (a) fractured aquifer, and (b) unconsolidated sedimentary aquifer at different depth ranges.

ity that the well may be taping the less productive aquifer zone that have reduced the performance of the well as a whole.

CONCLUSIONS

This study has revealed the hydrogeology of shallow and deep aquifers in unconsolidated sediments and fractured rocks. Groundwater has been widely exploited for drinking water supply as well as for recreation purpose in terms of Thermal Springs in and around Nara Basin. The yield and specific capacity of wells, hydraulic conductivity and electrical resistivity values of the aquifer zones, distribution of granular materials, surface hydrology and geological structures have been considered to describe the hydrogeological conditions of the study area.

The difference in electrical resistivity values of sediment and basement is very sharp. The resistivity of basement reaches up to 7140 Ω.m while that of the overlying sediments is 433 Ω.m with the average resistivity being 770 and 67 Ω.m, respectively. The average resistivity of water bearing formation in sedimentary sequence is 56 Ω.m (median value is 32 Ω.m), and that in the basement is 638 Ω.m (median value is 449 Ω.m).

The groundwater in shallow and deep aquifers is flowing towards the western part of Yamato River. In most of the deep wells screened entirely in basement rock, the optimal yield (within laminar flow condition) lies below 200 m3/day. This value increases up to 500 m3/day for the wells either screened in very deep sediment or screen covering both sediments or fractured rocks. The shallow well in sediments (depth 250 m) has a discharge as high as 2600 m3/day within laminar flow condition. The specific capacity of wells in sedimentary aquifer and fractured aquifer ranges from 7 to755 m3/day/m, and from 0.41 to 541.44 m3/day/m, respectively. While the hydraulic conductivity ranges from 11to 583x10-2 m/day and from 0.3 to 606 x10-2 m/day, respectively in unconsolidated sediments and fractured rocks.

All the higher productive wells are lying in the northeastern part of the study area. Though the active faults are distributed throughout the valley periphery, its density is higher in the northern part. The porosity and permeability of the granular zones in and around the recent- and paleo-chennels seem to be enhanced by the presence of a number of active faults nearby the area. The active fault running along the Yamato River in NE-SW trend is playing vital role in making the area a potential groundwater zone. In the deep and fractured aquifer also, these active faults might have played vital role in increasing the aperture size of the fractures resulting in higher groundwater potentiality in fractured rock aquifer in the northeastern part.

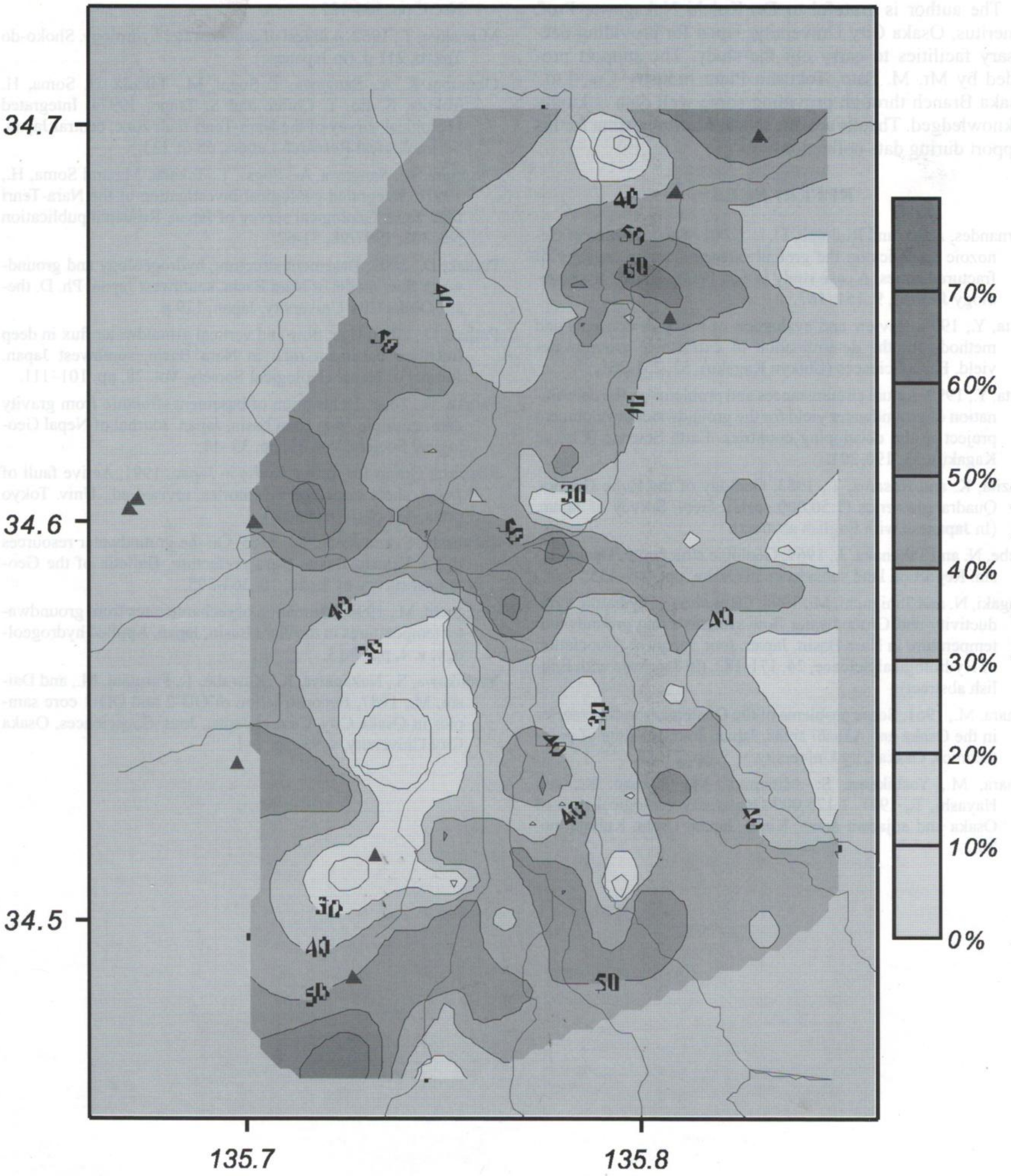

Fig. 9: Distribution of aquifer materials (sand/gravel) in the unconsolidated sediments within the top 100 m.

ACKNOWLEDGEMENT

The author is grateful to Dr. Koichi Nakagawa, Prof. Emeritus, Osaka City University, Japan for providing necessary facilities to carry out the study. The support provided by Mr. M. Sato, Tokushu Plant Industry Co., Ltd., Osaka Branch through providing some well data is kindly acknowledged. Thanks are due to Mr. M. Shibayama for his support during data collection.

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