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INTERACTION PROCESS BETWEEN STREAM AND AQUIFER IN ALLUVIAL FAN OF THE YASU RIVER

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SYNOPSIS

Stream-water not only flows in a river channel but also has some relationship with riparian groundwater through the influent seepage into a river-bed or the effluent seepage from an aquifer. Although such exchange quantity between stream and aquifer may be relatively small in comparison with the stream discharge in the rainy season, the interaction between both is one of the important factors governing the stream flow condition with small discharge in the dry season and/or in the downstream from the intake dam. Because a remarkable decrease in the discharge affects both water quantity and quality and temperature, it may be necessary to keep a minimum discharge in order to preserve the river environment including ecological integrity. In this paper, for evaluation of the minimum discharge, the stream-aquifer interaction and its effects on the stream flow condition are investigated through field observations and a hydraulic model. According to the observations in an alluvial fan of the Yasu River in Japan, it is thought that variation of the stream discharge may be caused by the water exchange with aquifer. The findings from the hydraulic computations indicate that the model is a useful tool for quantitative evaluation of the minimum discharge required to maintain suitable stream flow conditions.

INTRODUCTION

A river or stream running through an alluvial basin usually has some interaction with a riparian aquifer. A stream with the effluent seepage from aquifer is referred to as a '*gaining stream*', or a stream with the influent seepage into channel beds is referred to as a '*losing stream*'. The effects of the interaction between stream and aquifer have not been considered to be significant in the rainy season because they are relatively small in comparison with sufficient discharge of perennial streams. However, in streams whose discharge decreases considerably in the dry season or in streams whose water is taken artificially for water supply and electric power generation, the hydraulic relationships between stream and aquifer may become important factors governing the stream flow condition. For example, in a downstream reach of an intake dam, the stream discharge decreases further due to the

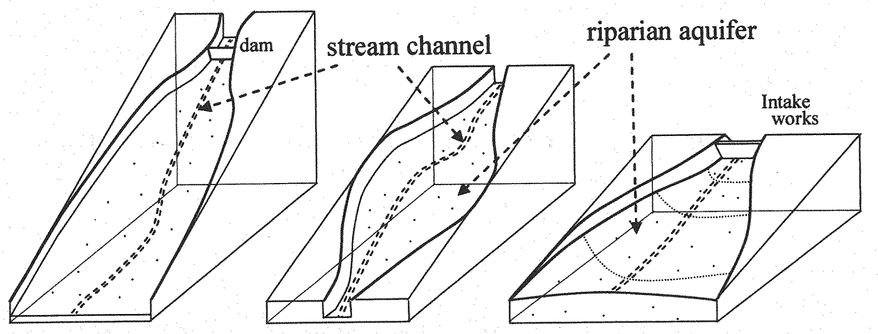


Fig. 1 Combined systems of stream and riparian aquifer

influent seepage into underlying permeable beds, so-called 'channel transmission losses'. Especially in the case where streams run on a highly permeable field such as an alluvial fan, the seepage loss becomes more significant. According to the reports on some rivers in an alluvial fan, values of the seepage loss along a stream may vary from 1.4 to 2.0 $m^3 s^{-1}$ per 1 km of stream-length (1). In cases where the seepage loss becomes much larger, the streams may occasionally run dry, such as the '*arroyo*' or the '*wadi*' in arid regions.

The stream-aquifer interaction in an actual watershed takes place in various geomorphologic situations as shown in Fig. 1. The figures show (a) a mountainous valley, (b) an alluvial basin in the mountains, and (c) an alluvial fan in the plain. For the steady flow problem, Harada and Takagi (2) dealt with hydraulic factors governing the influent seepage process from the stream channel in a downstream reach of an intake dam, such as case (a). Harada et al. (3) investigated the flow condition of a stream running through a permeable basin such as case (b), based on a hydraulic model and laboratory experiments. For the unsteady flow problem such as the flood phenomena, Harada et al. (4) and Hantush et al. (5) analyzed the dynamic interaction between stream and aquifer, and provided solutions to the bank storage problem using the concept of linear response function.

A remarkable decrease of the stream discharge due to the influent seepage causes serious environmental problems in the alluvial fan such as case (c) of Fig.1, because it affects not only hydraulic quantities but also the water quality. For instance, decreases of the water depth and the flow velocity cause flow stagnation and water temperature fluctuations. Furthermore, they lead to deterioration of the water quality such as decrease of the dissolved oxygen and increase in concentrations of agricultural pollutants. Therefore, it is necessary to keep a minimum discharge in order to maintain this resource for water use, recreation, and preserving ecological systems. In this paper, as a basic study for evaluation of the minimum discharge, the relationships between stream and riparian aquifer in the alluvial fan, and their effects on the stream flow condition are investigated through field observations and hydraulic analyses.

FIELD OBSERVATION IN THE YASU RIVER BASIN

Alluvial Fan of the Yasu River

In order to investigate the stream-aquifer interactions in an alluvial fan, field observations were carried out in the Yasu River basin. The Yasu River is located in Shiga Prefecture, Japan, and flows into Lake Biwa. The area of the basin is 387 km^2 and the length of channel is 62 km. Similarly to other rivers in the east of Lake Biwa, the alluvial fan formed in the lower region of the basin, as shown in

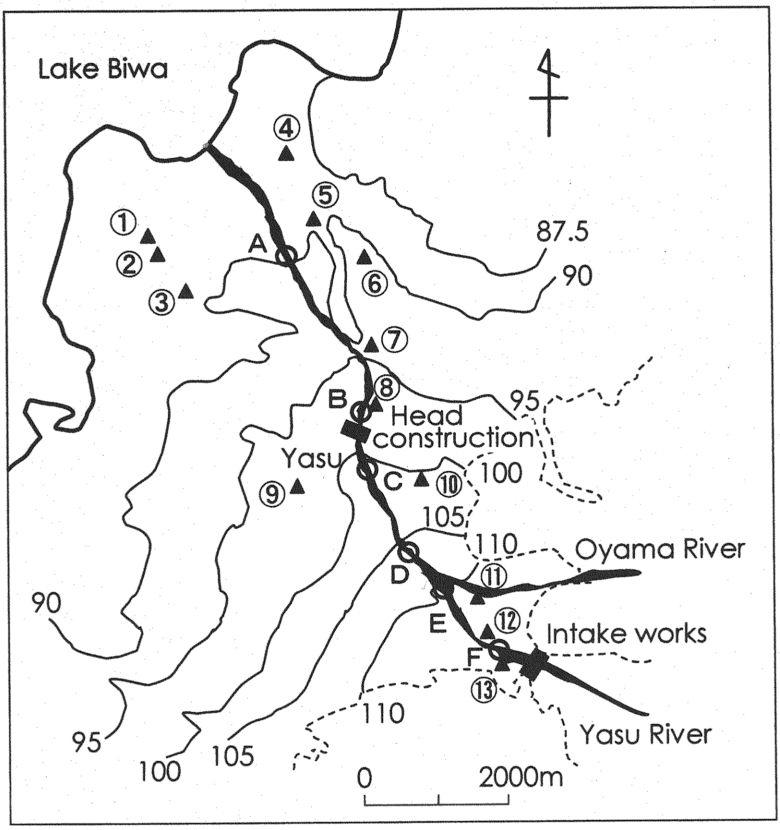


Fig. 2 Hydrologic observation points in the Yasu alluvial fan
○ : Stream discharge observatory ▲ : Groundwater observation well

Fig. 2. Since the elevation of river-bed rose up due to quantities of sediments, a diversion channel to prevent a potential catastrophic flood was constructed in 1979, and the head construction was set up at a conjugation point with the natural stream (6). Up gradient from the confluence of the Yasu and Oyama Rivers, the intake works was constructed for the agricultural water use in 1954 (Fig.2). As a result, in the downstream reach (14 km length) from the intake works, the stream flow sometimes decreases and has occasionally dried up. The Oyama River is the only tributary that merges with the Yasu River. In this research project, in order to investigate the stream-flow response to the stream-aquifer interactions, the stream discharge was observed at 6 points (○) along the reach as shown in Fig. 2, and the groundwater conditions were measured at 13 wells (▲) in the alluvial fan.

Fig. 3 shows the stream discharge fluctuation at the Yasu observatory located in middle of the reach. From the figure, it can be seen that the number of the days when the discharge falls below 3 m^3 s^{-1} is more than about 100. Especially it should be noticed that the stream dried up for several ten days in May and August due to the agricultural water use and seepage losses. Based on these facts, we found that it was necessary to sustain a minimum threshold flow rate for the improvement of the flow condition of the Yasu River.

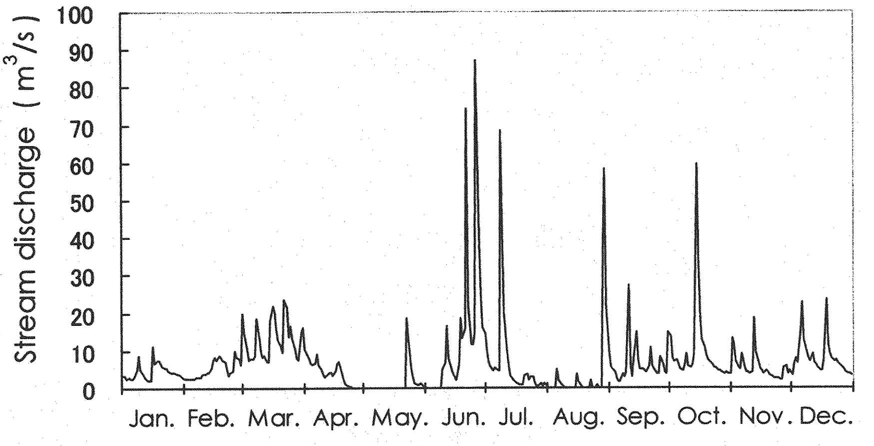


Fig. 3 Stream discharge fluctuation of the Yasu River at the Yasu observatory (1996)

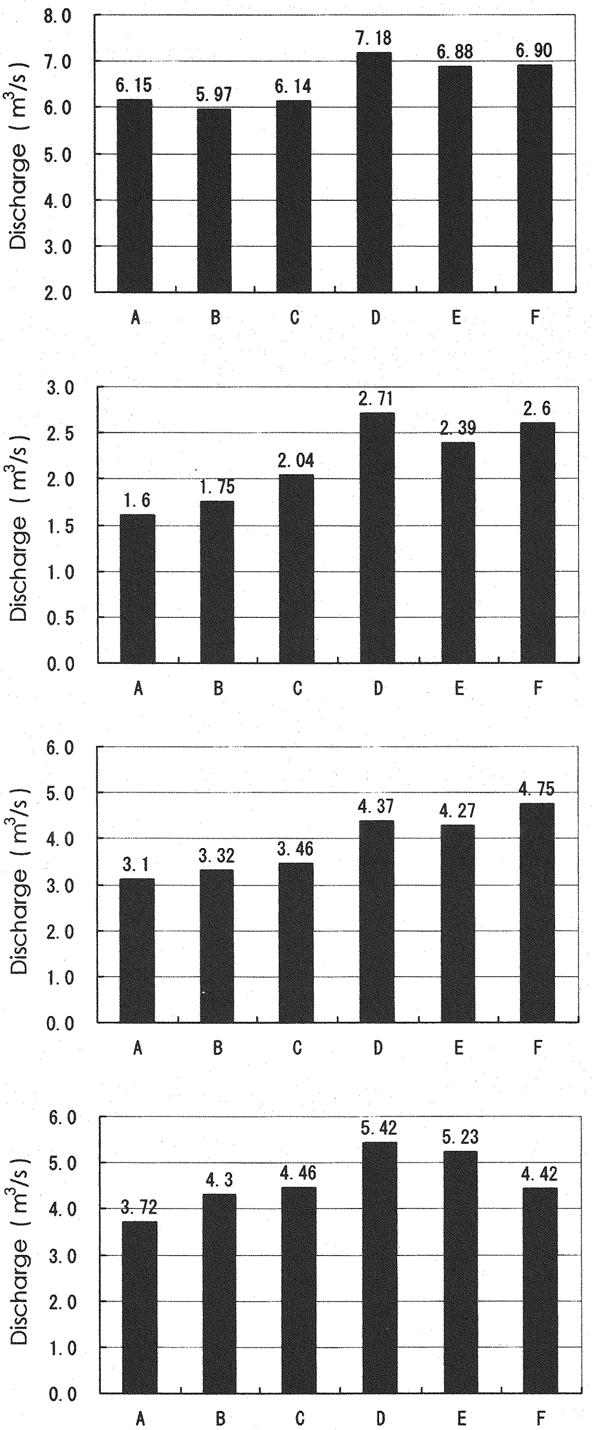
Observation of Stream Discharge

To investigate the spatial behavior of the stream flow from the intake works, the spatial distribution of the stream discharge was observed at 6 points (A – F) shown in Fig. 2 in a same day, simultaneously. The discharge observation at each point was made by measuring the depth at 1 m intervals and the velocity at 2 m intervals by an electromagnetic velocity meter. To check the accuracy of the observation, measurements were repeated 5 times at a same point. According to the example measurements shown in Table 1, maximum value of the relative error in all measurements is only about 4 %. Therefore, we can recognize this particular observation as sufficiently reliable.

The discharge observations were carried out a total of 10 times during baseflow conditions unaffected by rainfall. Fig. 4 gives examples of the data observed from September to November in 2001 and 2002. Since the Oyama River is the only tributary in the reach from the intake works to the river mouth, spatial variation of the discharge, except the contribution by the confluence of the tributary, must be explained by the water exchange between the Yasu River and the riparian groundwater. As recognized from the figure, the discharge decreases slightly in section from point F to E, and then increases slightly from E to D due to the confluence of the tributary. However, in section from D to B, the discharge decreases largely in all of Fig. 4 (a) – (d), and then gently increases sometimes from B to A (e.g., Fig. 4 (a)).

Table 1 Accuracy of measurements for stream discharge

	measured discharge ($m^3 s^{-1}$)	relative error (%)
1st	3.12	3.94
2nd	3.19	1.79
3rd	3.26	0.37
4th	3.39	4.37
5th	3.28	0.99
Mean	3.248	-
SD	0.091	-
CV	0.028	-



(a) Oct. 26, 2001

(b) Sept. 3, 2002

(c) Oct. 11, 2002

(d) Nov. 6, 2002

Fig. 4 Observation results of stream discharge at 6 points along of the Yasu River

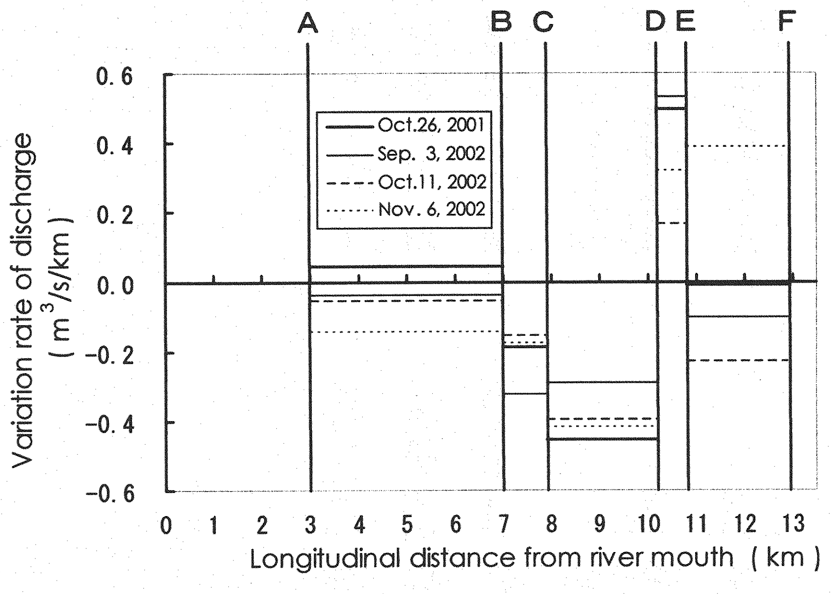
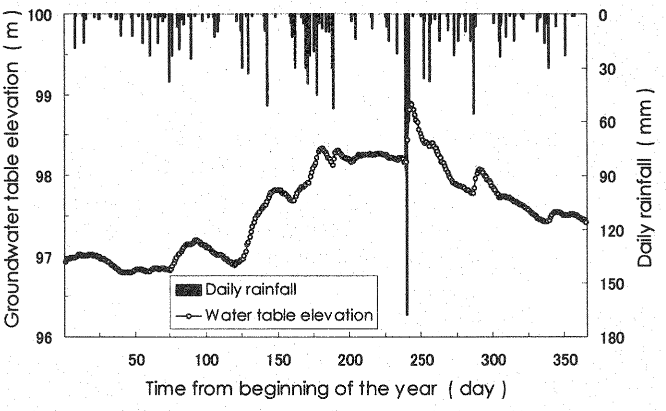


Fig. 5 Longitudinal distribution of variation rate of the stream discharge

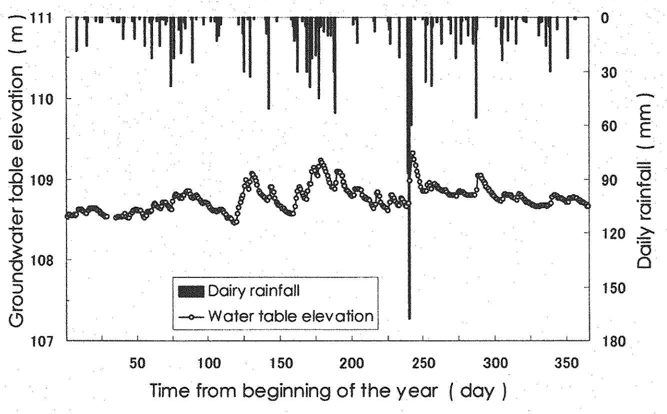
Because distances between the observed points are not constant, by dividing difference of the observed discharge between two points by the separating distance along the channel, the variation rate of the discharge per one kilometer of the stream was calculated as shown in Fig. 5. From this figure, we can see that variation rate of the discharge is clearly negative in sections from D to B. Since there are not any tributaries in this section as stated above, it is very likely that this decrease of the stream discharge is caused by seepage losses through the river-bed. For the same reason, it is likely that slight increase in section from B to A is due to the effluent seepage from the aquifer (i.e., groundwater discharge) in the lower area of the alluvial fan.

Groundwater Condition in the Yasu Alluvial Fan

In order to measure the fluctuation of the unconfined groundwater table in this area, a number of observation wells were set up by MLIT (the Ministry of Land, Infrastructure and Transport, Japan), as plotted in Fig. 2 (7). Fig. 6 shows examples of the annual fluctuation of groundwater level at two wells No.10 and 12 (locations of wells are depicted in Fig. 2). From these observed data, it is recognized that the fluctuation of the groundwater table is strongly affected by rainfall, but the influence by the seasonal irrigation (about 125 – 275 days in Fig.6) depends on the well location. Fig. 7 shows a comparison of the average groundwater table elevation in February and August with the ground surface elevation at the wells. From the broken line of the figure, we can recognize that the depth of groundwater table from the ground surface is relatively deep in the area where the ground surface is higher (i.e., the top of the alluvial fan), and the depth of table is very shallow in the area where the ground level is lower (i.e., the end of the fan).



Well ⑩ in Fig. 2



Well ⑫ in Fig. 2

Fig. 6 Examples of annual fluctuation of the groundwater level (1996)

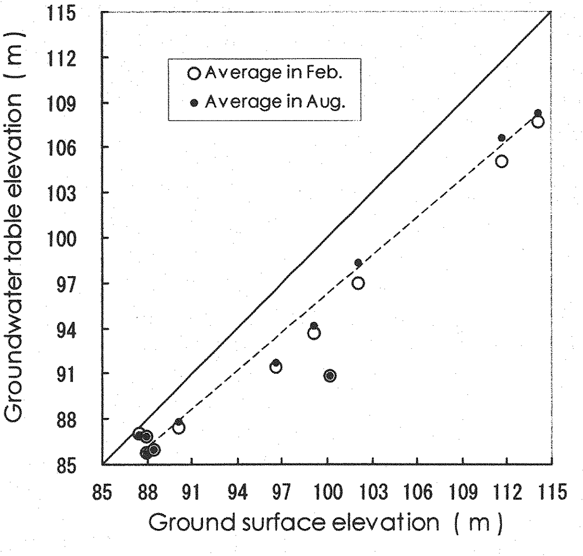


Fig. 7 Relationships between the groundwater table elevation and the ground surface elevation

AN INTEGRATED MODEL OF STREAM-WATER AND GROUNDWATER

Modeling of Stream-Aquifer Interaction

For purpose of analyzing stream-water, groundwater and their water exchange in the alluvial fan, a hydraulic model that integrates the stream with the aquifer was constructed. Needless to say, the stream is the open-channel flow governed by Manning formula, whereas the groundwater is the seepage flow governed by Darcy's law. The water exchange between stream and aquifer is controlled by relative elevation of their water levels. For instance, in case where the stream-water level is higher than the riparian groundwater level, the water exchange is from the stream to the aquifer (i.e., influent seepage). However, in case where the stream-water level is lower than the groundwater level, the exchange is reversed (i.e., effluent seepage from aquifer).

Therefore, on the one hand the stream discharge varies according to the riparian groundwater condition; and on the other hand the groundwater flow is also affected by the stream-water level as a prescribed head boundary condition. Because of such interaction, it is necessary for the hydrologic analysis to deal with an integrated hydraulic system that consists of the open-channel equation, the aquifer equation, and the exchange rate at the interface. In this research, we apply the hydraulic model to the Yasu alluvial fan, and attempt to evaluate the stream-aquifer interaction and simulate the observed data. The analysis is carried out under steady state conditions because it aims to address the minimum discharge of the Yasu River.

Fundamental Equations of Hydraulic Analysis

The fundamental equations and the numerical procedure are outlined here. We assume an open-channel flow reaching downstream from an upper boundary; in this research, the top of the alluvial fan. The continuity equation on the steady state channel flow is expressed as follows:

$$Q(s) = Q_0 - \int_0^s q^*(s)ds \tag{1}$$

where $Q(s)$ = the channel discharge at distance s from the upper boundary $[L^3T^{-1}]$; Q_0 = the inflow discharge released from the intake works at the boundary $[L^3T^{-1}]$; and $q^*(s)$ = the seepage rate per unit stream-length $[L^2T^{-1}]$, in case of the influent seepage from the channel, $q^*(s) > 0$, or in case of the effluent seepage to the channel, $q^*(s) < 0$. Assuming the stream flow to be uniform in the wide rectangular channel, the stream-water depth is calculated from Manning formula (in metric units):

$$h(s) = \left(\frac{n\,Q(s)}{B\,S_0^{\,1/2}} \right)^{\frac{3}{5}} \tag{2}$$

where $h(s)$ = the water depth in the channel [L]; B = the channel width [L]; S_0 = the channel slope; and n = Manning roughness coefficient.

Assuming the aquifer to be a two-dimensional horizontal field, the unconfined groundwater equation is formulated from Darcy's law and Dupuit's assumption as follows:

$$\frac{\partial}{\partial x}\left(K(x,y)H(x,y)\frac{\partial \phi(x,y)}{\partial x} \right) + \frac{\partial}{\partial y}\left(K(x,y)H(x,y)\frac{\partial \phi(x,y)}{\partial y} \right) + r(x,y) = 0 \tag{3}$$

where $\phi(x, y)$ = the groundwater level at location (x, y) in the field [L]; $K(x, y)$ = the hydraulic

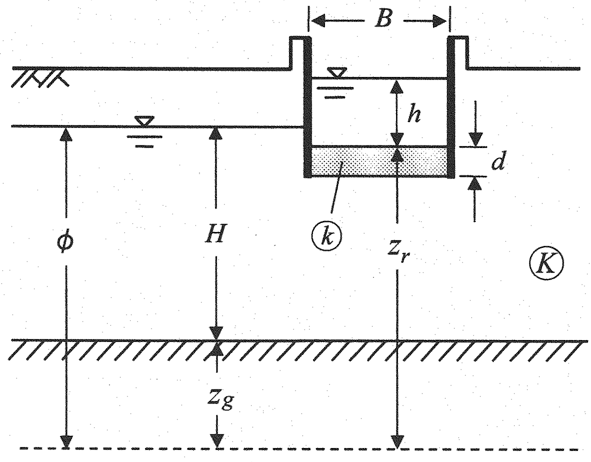


Fig. 8 Schematic of the influent/effluent seepage between stream and aquifer

conductivity of aquifer [LT^{-1}]; $H(x, y)$ = the average thickness of aquifer [L]; and $r(x, y)$ = the source/sink intensity [LT^{-1}], in case of the rainfall recharge, $r > 0$, or in case of the pumping withdrawing, $r < 0$. In addition, hydraulic influence of the channel on the aquifer is represented by considering the seepage rate $q^*(s)$ to the term $r(x, y)$ at the aquifer coordinate (x, y) which corresponds to the stream coordinate (s).

Since the stream flow has shallow depth, the seepage rate $q^*(s)$ is evaluated from difference between the stream-water level and the groundwater level just below the river-bed (8, 9),

$$q^*(s) = \frac{k}{d}\left\{ \left(h(s) + z_r(s)\right) - \phi(s) \right\} \cdot B \tag{4}$$

where k = permeability of the sediment layer below the river-bed [LT^{-1}]; d = its thickness [L]; and $z_r(s)$ = the height of the river-bed relative to an arbitrary datum [L], as shown in Fig. 8. Once $q^*(s)$ is evaluated by eq. (4) from assumed water levels of $(h(s) + z_r(s))$ and $\phi(s)$, the discharge $Q(s)$ is calculated by eq. (1). Substituting $Q(s)$ into eq. (2), the stream-water depth $h(s)$ is obtained. Besides, the groundwater level $\phi(x, y)$ is computed by solving eq. (3) numerically under $q^*(s)$ and appropriate boundary conditions around the aquifer. By using new values of $h(s)$ and $\phi(s)$, new seepage rate $q^*(s)$ is recomputed by eq. (4). This process is repeated until convergence, and the stream discharge and the groundwater level distribution are determined as the results of the stream-aquifer interaction.

Numerical Computation in the Yasu alluvial Fan

For the numerical application of model, boundary conditions and hydraulic parameters have to be assumed suitably for the actual phenomena. In the groundwater analysis, the governing equation (3) is solved by the implicit difference method using IADI-procedure (8) by dividing the objective region into square grids of $\Delta x = \Delta y = 250$ m as shown in Fig.9. From geological aspects of the region, the hydraulic conductivity of the aquifer are set as $K(x, y) = 0.002$ m s^{-1} for a sandy gravel layer. Spatial distribution of the impervious bottom of the aquifer is estimated by referring to core samples from boreholes drilled at a number of points in the region. The boundary conditions of the aquifer are assumed to be a constant head at the shoreline along Lake Biwa, an impervious condition at other

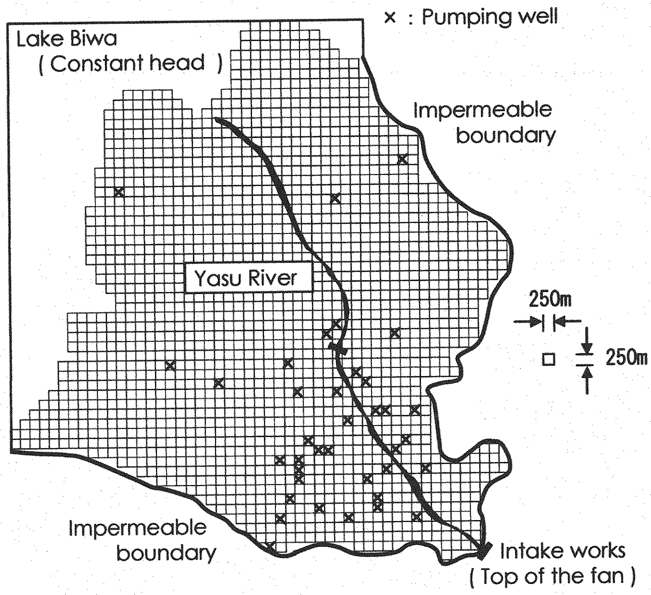


Fig. 9 Discretized map and boundary conditions of the Yasu alluvial fan for numerical model

boundaries. The recharge intensity by rainfall depends on both season and land-cover of the region. Because this simulation is carried out in the dry season without irrigation, the rainfall recharge is set as $r(x, y) = 0.0$ or 0.5 mm day^{-1} in the pervious area. The pumping rates of groundwater are given from surveying data of 37 factories distributed in the region. The seepage rate $q^*(s)$ from the stream is counted as the recharge intensity $r(x, y)$ in the aquifer grids covering a part of the channel:

$$r(x,y) = \frac{q^*(s)}{B} \cdot \frac{B\,\Delta s}{\Delta x\,\Delta y} \tag{5}$$

where Δs = the length of channel through each grid of the aquifer, and $(B\,\Delta s)/(\Delta x\,\Delta y)$ means areal occupation ratio of the channel to the aquifer grid, as shown in Fig. 10.

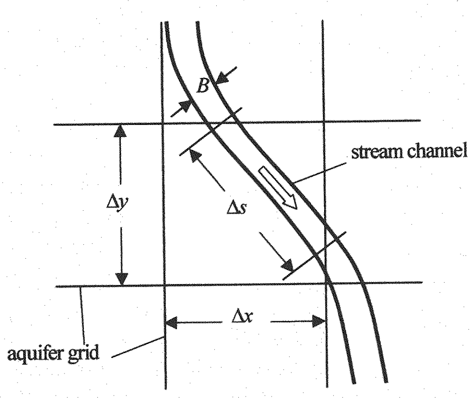
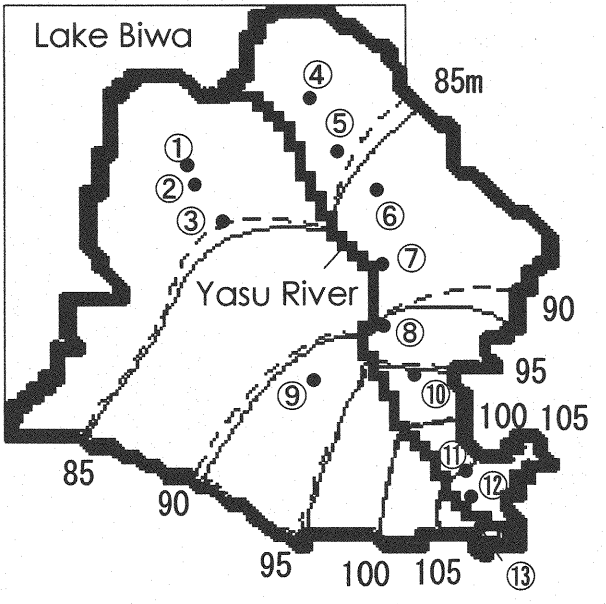


Fig. 10 Relationship between stream channel and aquifer grids

In the stream flow analysis, the channel reach is discretized according to the aquifer grids. But, the short segment for 1 km near the river mouth is excluded from analysis of the uniform flow because it may be affected by the backwater of Lake Biwa. The boundary condition of channel is the inflow discharge Q_0 released from the intake works at the upper boundary, and the confluent discharge of the Oyama tributary is also considered for solving the continuity equation (1) in the channel. The average channel width and Manning roughness for eq. (2) are set as $B = 20$ m and $n = 0.05$ m$^{-1/3}$ s respectively. The channel slope S_0 is given from the longitudinal distribution of the river-bed elevation. The thickness and the permeability of the river-bed layer are assumed to be $d = 1$ m and $k = 0.0002$ m s^{-1} respectively, based on an investigation report on the sedimentary structure of the Yasu River (10) and our results of grain-size analyses on the river-bed materials at 15 points.

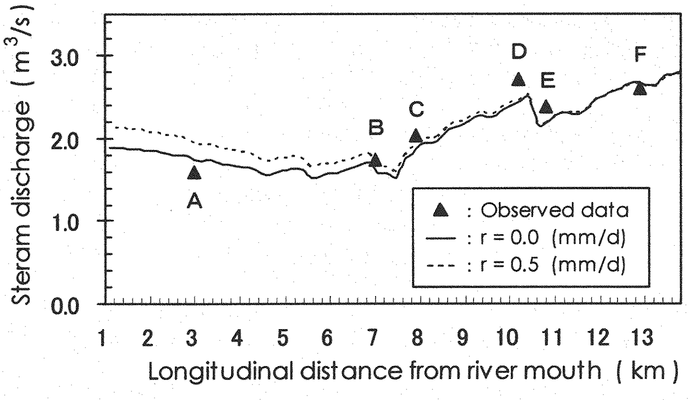
Simulation Results and Comparison with Observed Data

In order to verify applicability of the hydraulic model for actual phenomena, numerical solutions were compared with observed data on September 3, 2002. Fig. 11 gives the simulation results with the inflow discharge $Q_0 = 2.80$ m^3 s^{-1} and the rainfall recharge $r = 0.0$ or 0.5 mm day^{-1}. Fig. (a) shows horizontal distribution of the groundwater level, (b) and (c) are longitudinal distribution of the stream discharge and the water-depth, and (d) is a comparison of the simulation with the groundwater observation at wells. We can see from figure (a) that the groundwater table distribution follows rather gently the topography of the ground surface as shown in Fig. 2. According to figures (b) and (c), computed results of the stream discharge and the water-depth almost agree with the observed data in the section from point F to B. In this section of the reach, the discharge decreases due to the influent seepage to the aquifer, and then recovers slightly by confluence of the tributary. In the downward section from the head construction at 7.5 km, the computed results of the stream discharge show a gradual increase due to the effluent seepage from the aquifer, however, it does not reproduce the

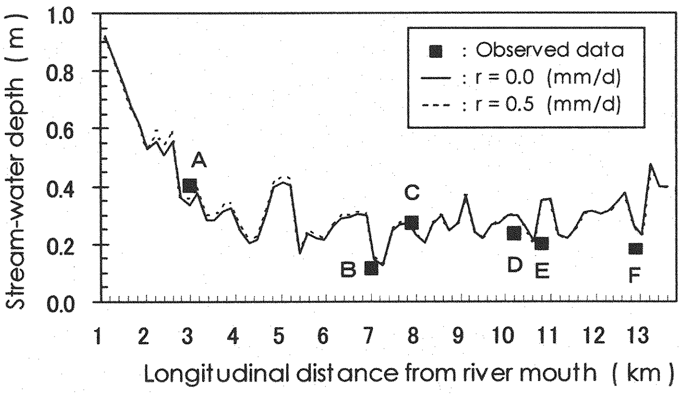


(a) Horizontal distribution of groundwater level (unit: m)

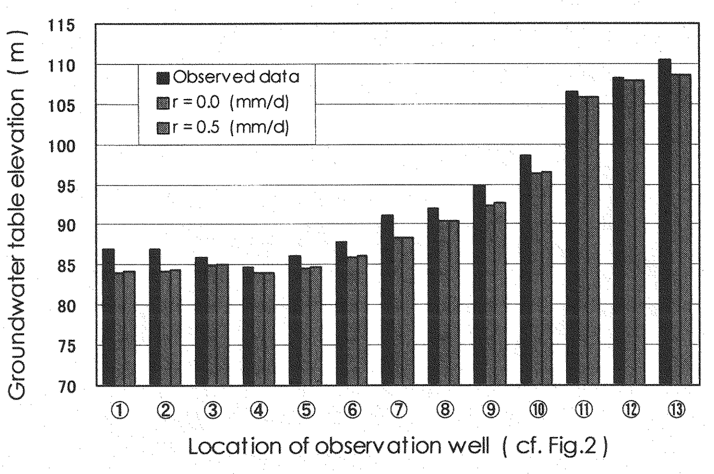
Fig. 11 Comparison of simulation results with observed data: $Q_0 = 2.80$ m^3 s^{-1}



(b) Longitudinal distribution of stream discharge

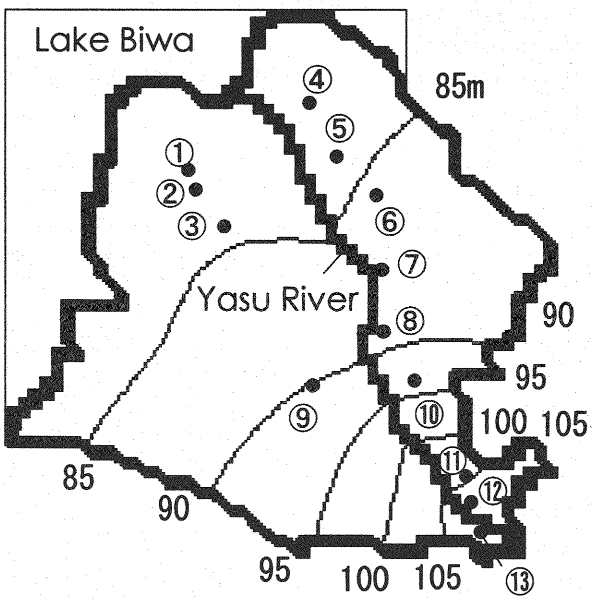


(c) Longitudinal distribution of stream-water depth

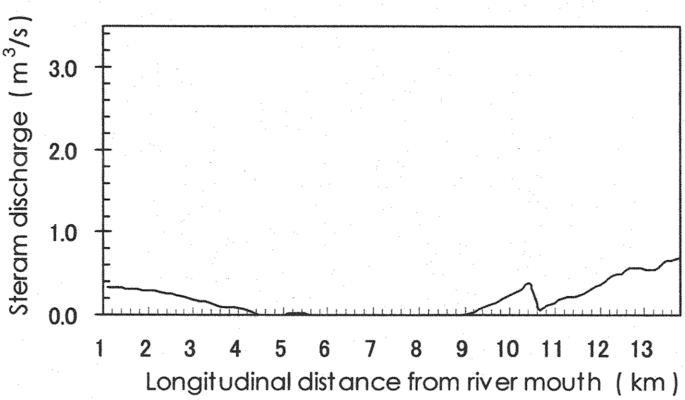


(d) Comparison of computation of groundwater level with observation at wells

Fig. 11 (continued) Comparison of simulation results with observed data: $Q_0 = 2.80\,m^3\,s^{-1}$



(a) Horizontal distribution of groundwater level (unit: m)



(b) Longitudinal distribution of stream discharge

Fig. 12 Imaginary simulation results for small inflow discharge: $Q_0 = 0.70\,\mathrm{m^3\,s^{-1}}$

observed value at point A. On the groundwater level shown in figure (d), roughly speaking, simulation results show good agreement with the observed data. However, looking closely, solutions somewhat consistently underestimated the data. The cause of these differences is an issue to be considered.

In order to attempt a practical application of this model, a simulation was carried out for an imaginary case of small inflow discharge $Q_0 = 0.70\ \mathrm{m^3\ s^{-1}}$. According to the simulation results shown in Fig. 12, (a) horizontal distribution of the groundwater level is about same as in Fig. 11, but (b) longitudinal distribution of the stream discharge is completely different. In the section from distance 4.4 to 9.0 km in figure (b), the stream discharge decreases markedly due to seepage losses, and the channel dries up locally. Thus, because the discharge from upstream has a great influence on the flow condition downstream, in order to preserve the stream environment in the downstream reach, it is very important to evaluate properly the inflow discharge released from the intake works. By utilizing the integrated hydraulic model presented here, it is possible to evaluate quantitatively the minimum discharge for the stream environment in consideration of the stream-aquifer interaction.

CONCLUSIONS

As a basic research to evaluate the stream discharge for the environmental preservation, the stream-aquifer interaction in an alluvial fan was investigated by a two-dimensional hydraulic model and field observations in the Yasu River basin. The following findings were obtained through this research:

(1) According to the field observations on stream and aquifer, the stream discharge decreases in the middle of the alluvial fan. This is believed to be caused by the influent seepage of the stream-water into the river-bed.

(2) A hydraulic model which integrates the stream with the aquifer was established. In spite of simplicity of the model, numerical solutions of the stream discharge and the groundwater level can simulate the measured data at a number of observation points with sufficient accuracy.

(3) The application of the model provides evidence that the inflow discharge released from the intake works at the top of the alluvial fan has a great influence on the flow condition in the downstream reach.

In order to improve the accuracy of the hydraulic model presented in this research, it is necessary to collect more detailed data of the hydrological factors such as the aquifer structure, boundary conditions and the sink/source intensities.

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This research was accomplished in cooperation with Yasu River Research Committee organized by Kyoto University as the core. The research committee deals with hydrological problems in the Yasu River basin which is one of HELP (Hydrology for the Environment, Life and Policy) basins by an initiative of UNESCO/WMO. Our special thanks are due to Biwa Lake Construction Work Office of MLIT and Nikken Consultants, Inc. for providing us with the hydrological valuable data.

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APPENDIX – NOTATION

The following symbols are used in this paper:

B = channel width of stream;

d = thickness of sediment layer below river-bed;

h = water depth in channel;

H = average thickness of aquifer;

k = permeability of sediment layer below river-bed;

K = hydraulic conductivity of aquifer;

n = Manning roughness coefficient;

q^* = seepage rate per unit stream-length from/to channel,
$q^* > 0$ for influent seepage, $q^* < 0$ for effluent seepage;

Q = channel discharge of stream;

Q_0 = inflow discharge released from upper boundary;

r = source/sink intensity, $r > 0$ for rainfall recharge, $r < 0$ for pumping withdrawing;

s = distance along stream from upper boundary;

S_0 = channel slope of stream;

x, y = coordinates along horizontal axes in aquifer;

z_r = height of river-bed relative to arbitrary datum;

Δs = channel length through each grid of aquifer;

$\Delta x, \Delta y$ = grids size of aquifer in x, y direction; and

ϕ = groundwater level relative to arbitrary datum.

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