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SEPARATION OF SUBSURFACE AND GROUNDWATER COMPONENTS IN A RIVER WITH SANDBAR

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The characteristics of surface-subsurface water interaction in a river with sandbar are three-dimensional. The exchange phenomena at the surface-subsurface water interface are still unknown. An investigation has been carried out by tracer experiment and vertical 2D (V2D) simulation at the interface with various bed shapes and hydraulic conditions to understand the phenomena as well as to delineate the subsurface water and groundwater components. The flow properties at the surface and subsurface zone are verified by 1D Darcy theory. A line, which separates the subsurface and ground water components, is determined for individual cases. The experiment as well as V2D simulation shows that at the interface subsurface water components are found to be about 80-90% of the total flow (subsurface plus groundwater) components. The subsurface flow is found to be two-dimensional within the surface water zone and one-dimensional at the subsurface zone, which satisfies the Dupuit's assumption.

Key Words: *subsurface water, groundwater, bed shape, water component separation, interaction*

1. INTRODUCTION

The subsurface flow and the interaction between surface and subsurface water with alternate sandbars in a river (**Fig.1**) has an important role as a habitat for hypohreo (life things living in substrate) and also as a media for changing river water quality by biological effect. When we evaluate and estimate its effect quantitatively, at first, we should know the thickness and flow rate of subsurface water being exchanged with surface water in hydraulic point of view. In general, under the consideration that the phenomena are 3-dimensional as Bouwer (1978)[1)]stated, in order to estimate these two values' distribution, the phenomena are treated as 3-D or quasi-2D problem using available software, for instance MODFLOW, and in the field chemical tracers are used for one-by-one cases (Benner et al. 1995[2)], Kim et al. 1992[3)]). But water components (groundwater and subsurface water) are seems to be separated vertically, then, extension of the application of horizontal 2-D calculations, which is average flow for whole depth originally, is expected. Therefore, for those applications in the future, authors set the understanding of vertical water movement and separation of water components near the surface water edge (**Fig.1** b), c)), which are affected by bed shape and hydraulic conditions, as the objective problem. In this study, numerical simulation and experiment are conducted; then, followings are discussed as objectives:

- To understand the basic phenomena of surface-subsurface water interaction at the surface water edge with sandbar
- To get subsurface water components interchanged by surface water components within the domain of surface-subsurface water flow regime in a river with alternate sandbar
- To delineate the groundwater component by a separation line between subsurface water and groundwater
- To get relationships of exchange ratios for specified bed shapes and hydraulic conditions by horizontal 2D flow analysis

2. MODELLING OF THE PROBLEM

(1) Vertical 2-D model

In order to simulate the problems of separating the subsurface and groundwater components, a vertical 2D(V2D)-simulation model with parameters in x-z coordinates is used.

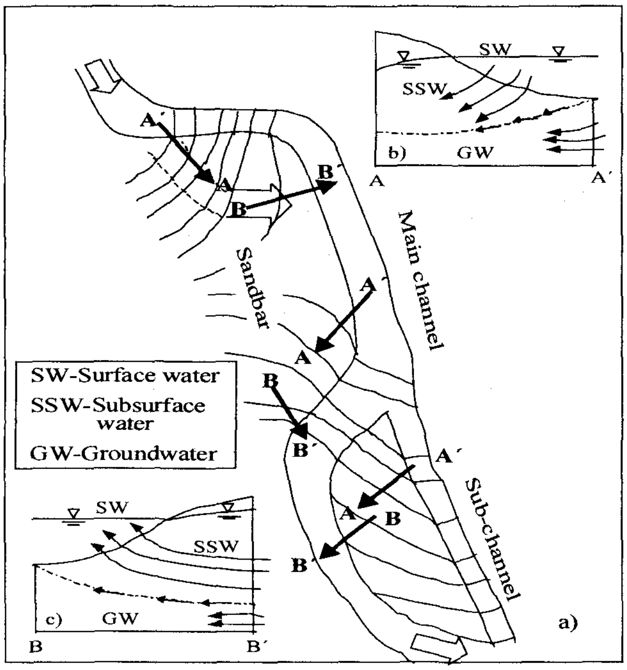


Fig.1 Interaction between surface and subsurface water in a river with alternate sandbar; a) Plane view, b) Section A-A′ (inflow case) and c) Section B-B′ (outflow case)

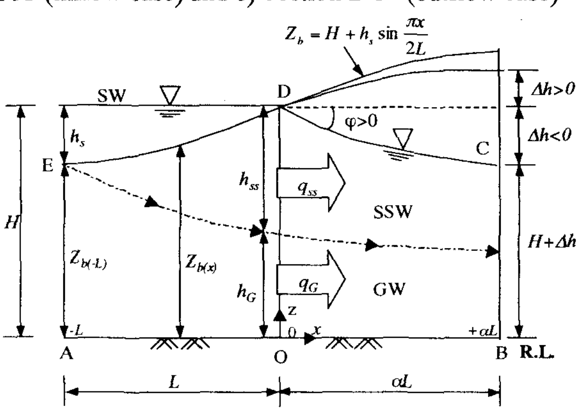


Fig.2 Schematization of the problem

In this study, steady state condition is assumed. Subsurface water level under different conditions of surface water level is used as the boundary condition of the model. The governing equation of the model based on 2D Darcy theory can be written as follows:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \tag{1}$$

Where, $\phi = z + p/\rho g$; ϕ is the hydraulic potential, z is the vertical distance, p is the pressure, ρ is the specific gravity of water and g is the acceleration due to gravity.

The numerical description of the problem is schematically illustrated in **Fig.2**. It is assumed that the bottom impervious layer is horizontal and the distribution of sand is homogeneous and isotropic.

In this figure, the following notations are used for the analysis as the boundary conditions:

A-B : $\partial\phi/\partial z = 0$ (impermeable layer)
B-C : $\phi = H + \Delta h$
C-D : $p = 0$ (surface)
D-E : $\phi = H$ (subsurface water at interface)
E-A : $\phi = H$ (ground water)

The governing parameters involved in finding out the relationships between bed shape (Z_b) and hydraulic parameters (Δh, h_s) are:

Hydraulic conductivity, k; Length of surface water column, L; Surface water depth with respect to the impermeable layer, H; Surface water depth over bed, h_S; Subsurface water depth, h_{SS}, water level difference between surface and subsurface, Δh; the constant α and the length of subsurface water column, αL.

Under these conditions, governing equation (1) is solved using Finite Difference Method on the staggered grid.

In order to separate the components of subsurface water and groundwater, numerical tracer is adopted using result of V2D flow analysis. Putting numerical tracer at E as shown in **Fig.2** and tracing by using the results of flux vector distribution, we can separate both subsurface water component and flow depth connected to surface water from groundwater component and flow depth. The approximate movement of tracer for the cases as shown in Fig.1b is shown *in* **Fig.2**.

The main objective of this study is to discuss the variations of r_{hss} and r_{qss} with different bed shapes and hydraulic conditions. Here, r_{hss} and r_{qss} can be expressed as:

$$r_{hss} = \frac{h_{SS}}{h_{SS} + h_G} = \frac{h_{SS}}{H} \tag{2}$$

$$r_{qss} = \frac{q_{ss}}{q_{ss} + q_G} = \frac{q_{ss}}{q} \tag{3}$$

Here, r_{hss} is the ratio of subsurface water depth to total water depth at the interface and r_{qss} is the ratio of subsurface water flux contributed by surface water to total flux, h_G is the groundwater depth, q_{ss} is the subsurface water flux, q_G is the groundwater flux, q is the total flux per unit width. These relationships vary with bed shapes and hydraulic conditions.

(2) Horizontal 1-D model

In order to investigate the water movement, 1D depth-averaged flow analysis has been performed, which corresponds to the subsurface flow domain (O-B, in **Fig.2**) to compare with horizontal 2D's treatment at 3D problem. According to the Dupuit's

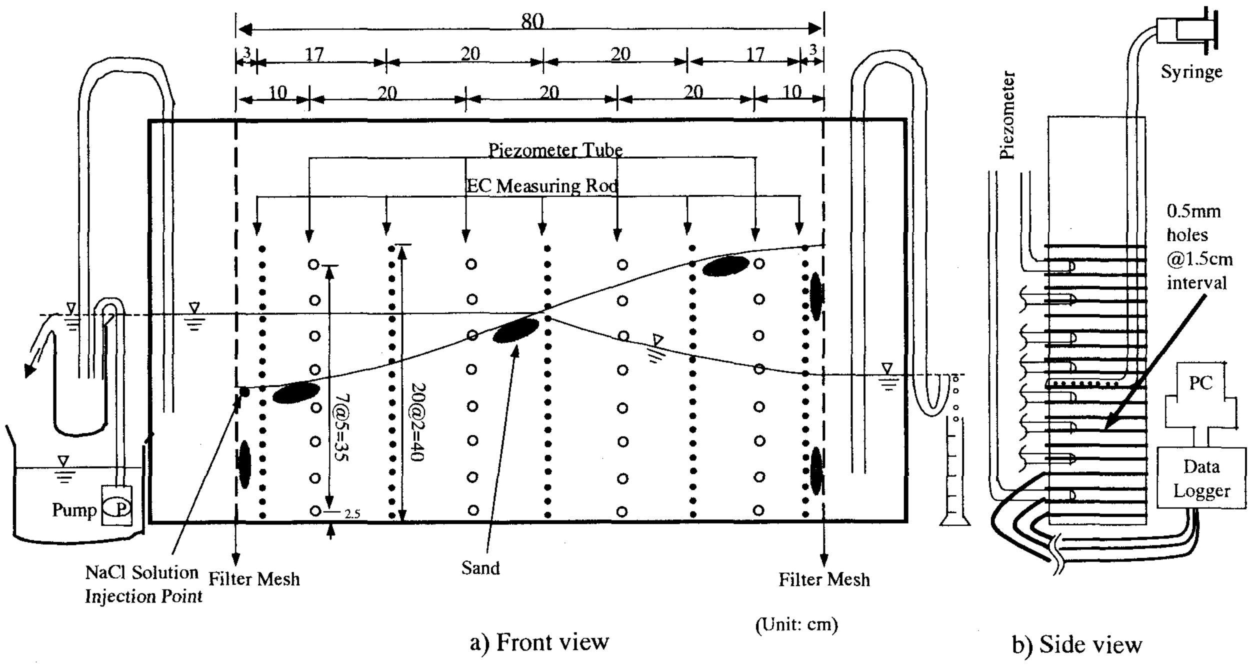


Fig.3 Experimental setup

assumption with 1D theory, flux per unit width of the permeable layer is written as:

$$q = -kh\frac{dh}{dx} \tag{4}$$

$$x = \frac{k}{2q}(H^2 - h^2) \tag{5}$$

Putting $H = h_1$ at $x = 0$and $H\text{-}\Delta h = h_2$ at $x = L$, we get total flux,

$$Q = B\frac{k}{2L}(h_1^{\,2} - h_2^{\,2}) \tag{6}$$

Where, B is the width of the permeable layer. The comparison between 1D Darcy theory and vertical 2D numerical simulation is done to compare total flux and subsurface water level distribution.

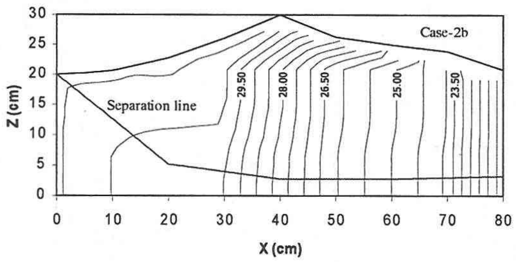
3. EXPERIMENTS

The tracer experiments are conducted in a flume for different hydraulic and geometric conditions and measured hydraulic gradients and tracer movements in the subsurface. An 80cm long and 15.4cm wide glass-sided horizontal flume is used for the tracer experiments. The experimental set-up is shown in **Fig.3**. A total of 32 piezometers are emplaced at four cross-sections to measure hydraulic potentials and 100 horizontal rods are also placed at five cross-sections to measure the electrical conductivity (EC) of the injected tracer between adjacent rods to determine its (tracer) relative concentration. Bed shape, which represents the bottom of surface water, is given in the flume by sine curve.

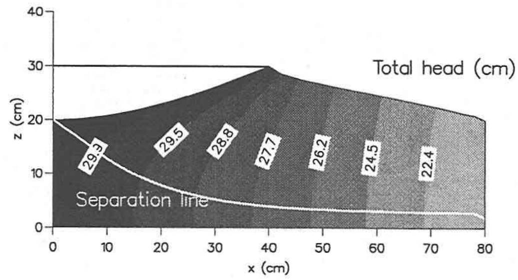
Well-graded sand with median diameter 0.3mm is used to shape up the sandbar. The hydraulic conductivity and porosity of the sand material is measured to be 0.08 cm/s and 0.36 by tests. A miniature submergible pump is placed in a bucket to supply steady state flow at the upstream side and a collector is placed at the downstream side to collect outflow water discharged through the porous media. A total of 40 sensors with cable are connected between EC measuring rods and Data Logger, which is again connected to the PC. An amount of 6cm^3 Sodium Chloride (NaCl) solution with concentration of 2.36 g/l is injected as tracer element at the tail of sandbar at the upstream of the flume for each experimental run and EC values of the NaCl solution are monitored by the PC until the solution reached at downstream end. The aim of the injection is to find the groundwater flow paths. During the model run hydraulic heads are measured in all piezometers and also the upstream and downstream surface water levels are measured. The volume of water transported through the porous media is also measured for setting time. The experimental and numerical conditions are shown in **Table 1**.

Table 1 Experimental and numerical conditions

Case	L (cm)	H (cm)	αL (cm)	$Z_{b(-L)}$ (cm)	h_s (cm)	Δh (cm)
1a	40	30	40	25	5	-5
1b	40	30	40	25	5	-10
1c	40	30	40	25	5	-15
2a	40	30	40	20	10	-5
2b	40	30	40	20	10	-10
2c	40	30	40	20	10	-15
3a	40	30	40	15	15	-5
3b	40	30	40	15	15	-10
3c	40	30	40	15	15	-15

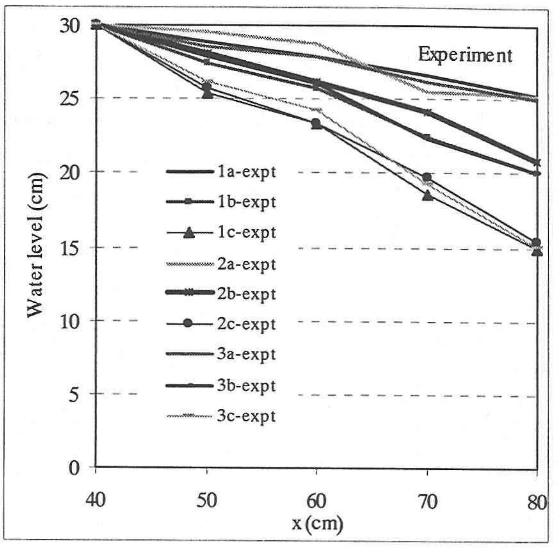


a) Experiment (Case-2b)

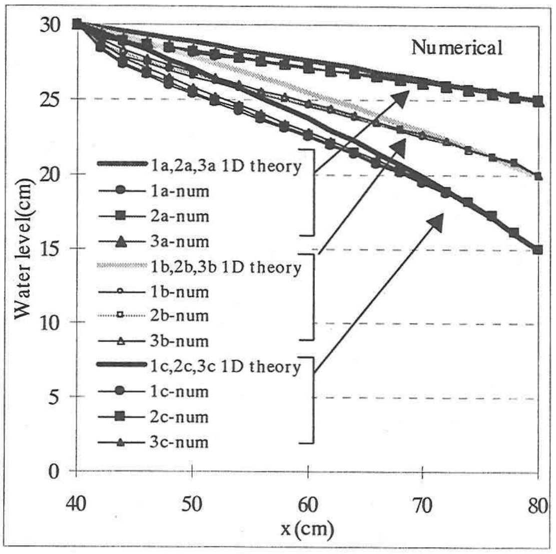


b) V2D numerical simulation (Case-2b)

Fig.4 2D distribution of subsurface water level



a)Experiment



b) 1D theory and V2D simulation

Fig.5 Subsurface water table: comparison between experiment and numerical

4. RESULTS AND DICUSSION

(1) 2D distribution of subsurface water level

The 2D distribution of subsurface water levels based on experimental and V2D simulation data for a standard case (case-2b) is shown in **Fig.4**. The **Fig. 4a** and also **4b** shows that under surface water, subsurface flow contour lines are inclined which shows 2-D flow pattern but beyond the surface and subsurface water interface (x>40cm), contour lines are almost parallel which indicates the flow trend is one-dimensional and this property agrees well with the Dupuit's assumption for 50<x<80cm. At inflow region, due to sinuous bed shape, most inflow fluxes generate by surface water and flows through the subsurface and the bed shape governs the direction of flow. The separation line (as discussed later) shows that groundwater thickness is very low in comparison with subsurface water. The same scenario is found for all the cases discussed in this paper.

(2) Subsurface water table

Subsurface water table for different cases obtained by experiment and computed by numerical simulation is shown in **Fig.5**. The comparison shows satisfactory agreement between them. The comparison among the cases shows that the water table gradient is steep for higher Δh and becomes steeper for thick permeable layer. For mild curvature of the sinuous bed shape along surface water flow, water table becomes lower. **Fig.5b** shows that water level found in 1D-theory matches well with V2D-simulation at the downstream part, but differs at the upstream part near surface water due to 2D effect in inflow domain (0<x<50cm).

(3) Total flux

The comparison of total flux between measured in experiment and computed by 1D theory and V2D simulation are shown in **Fig.6**. Based on the comparison between experiment and V2D result, k = 0.120 cm/s is estimated. This value is 1.5 times of measured value by the usual sample test, and this can be considered as representative one of this setup.

The case-by-case comparison in **Fig.6** shows that total flux is higher for high Δh with high surface water elevation. In the experiment, higher relative surface water depth (h_s/H) cases (3a, 3b, 3c) show higher total flux than others among same Δh cases. This figure also shows the total flux of 1-D theory

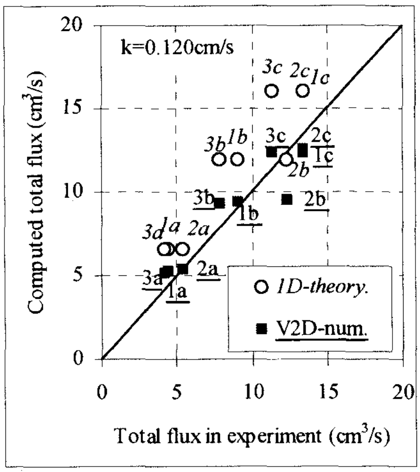
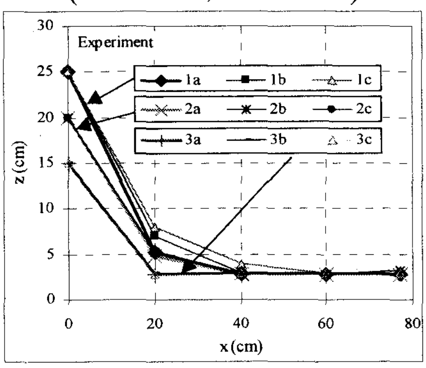
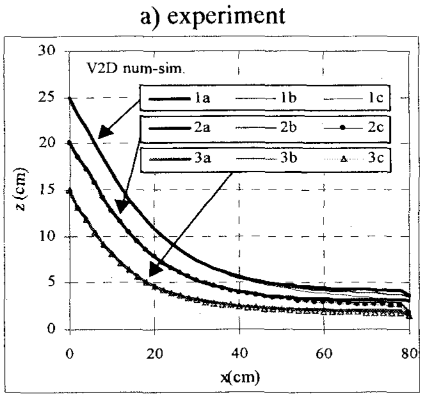


Fig.6 Comparison of total flux (k=0.12 cm/s, at V2D-sim.)



a) experiment



b) numerical

Fig.7 Component separation line

is higher than that of experiment and V2D numerical results. This is due to the 2 dimensional effect in inflow domain (0<x<50cm), where hydraulic gradient of subsurface water is found to be smaller. This effect is expected to be determined from bed shape and hydraulic conditions quantitatively.

(4) Separation of components

The flow path followed by tracer in the experiment is detected by inspecting maximum EC values and the component separation line within the domain is shown in **Fig.7a**. This figure shows that path line is longer for thick permeable layer under the surface water.

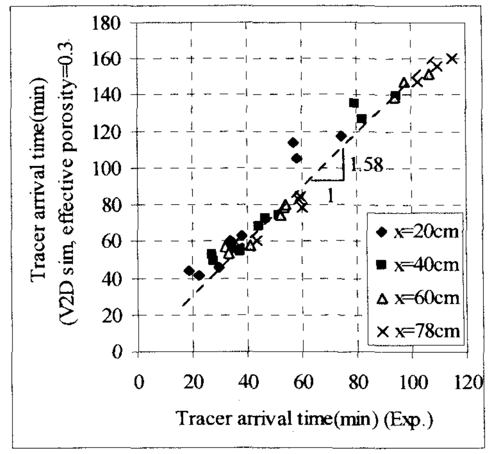


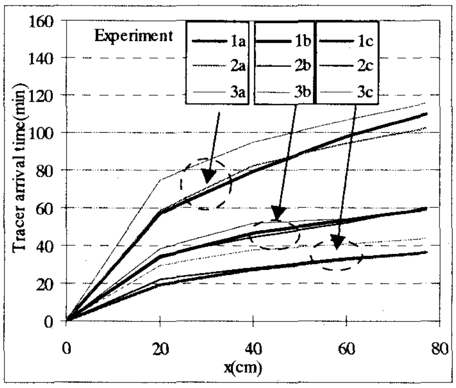
Fig.8 Tracer arrival time: comparison between experiment and V2D simulation.

The case-to-case variation is distinct up to interface (x=40cm) and beyond that the difference lies within 2cm. This is the interval of the rods and this method could not have higher precision. **Fig.7b** shows the separation line obtained by V2D simulation. The figure shows similar trend as of experiment but the difference is larger beyond the interface. Fig. 7a and 7b shows that the tracer's path line varies slightly with Δh for the same bed shape cases. The tracer arrival time from inflow to outflow end in V2D simulation is found to be 1.5 times longer than that of experiment (**Fig.8**). The tracer arrival time is then recalculated by introducing effective porosity (=0.24) which is 1.58 times smaller than the initial porosity (=0.38). The recalculated arrival time in V2D simulation seems similar to the arrival time in experiment (**Fig.9a and 9b**).

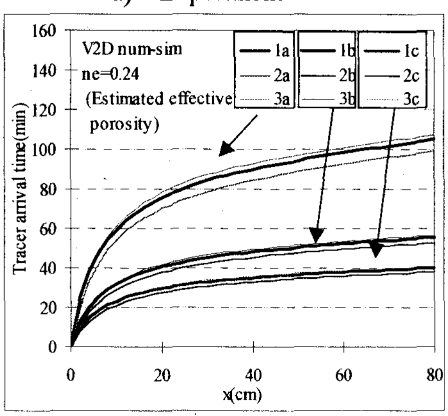
The difference of separation line's level (h_G) at x=40cm between experiment and V2D simulation is shown in **Fig.10**. This figure shows that the separation line's level in V2D simulation is higher than that of experiment, however, the values show almost linear relationship.

(5) Relationships of r_{hss} and r_{qss}

These relationships are established on the basis of experiment and V2D simulation data. **Fig. 11** shows the scattered plot of r_{hss} values in experiment versus r_{hss} values in V2D simulation for all cases and agreement between experiment and V2D simulation is found almost close to each other. It is evident that subsurface water depth at the interface is found to be 80-90% of the total water depth. The case-to-case difference is very small. The r_{hss} values and the corresponding r_{qss} values obtained by V2D simulation are plotted against each other and they are almost equal (**Fig.12**), but r_{qss} is higher than r_{hss} due to higher gradient in upper inflow region by 2-D effect.



a) Experiment



b) V2D simulation

Fig.9 Tracer arrival time for different cases

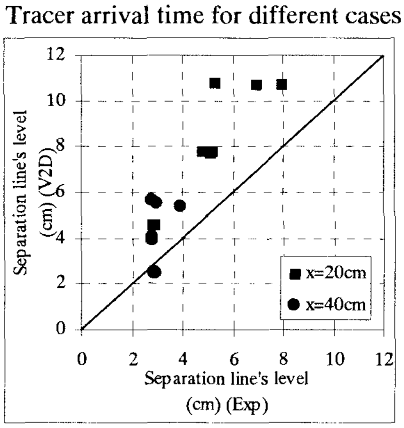


Fig.10 Separation line's level: comparison between experiment and V2D sim

5. CONCLUSIONS

The three-dimensional phenomena of surface-subsurface water interaction in a river with sandbar or vertical 2D phenomena at the edge of surface water with sandbar is understood by the experiment, V2D numerical simulation and 1D theory. Separation between subsurface water and groundwater components is depicted for various bed shapes under given hydraulic conditions. The trend of separation lines obtained by tracer experiment is found to be similar with V2D simulation. Both experiment and V2D simulation results revealed that groundwater component in the measure of flow depth and flux is very less in comparison with

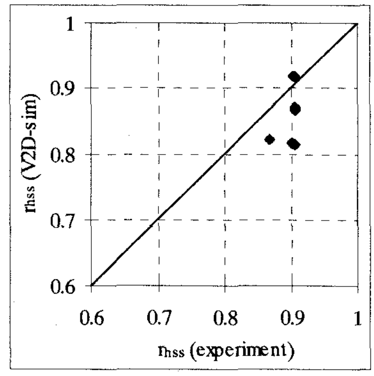


Fig.11 r_{hss} in experiment and V2D sim

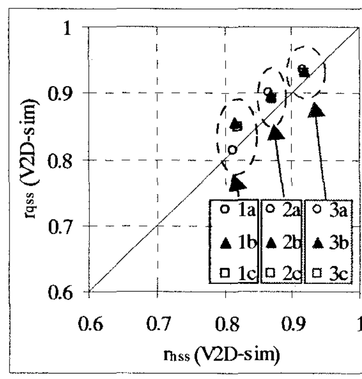


Fig.12 r_{hss}-r_{qss} relationship for different cases (V2D-sim)

subsurface water components. At the interface, subsurface water components are found to be 80-90% of the total component. The shape of the bed curvature along the surface water zone predominates in producing infiltration flux and most of those flux only flows within the subsurface zone. The 2D distribution of subsurface water level within the surface water zone shows two-dimensional flow pattern but within the subsurface zone it is one-dimensional, which satisfies the criteria of Dupuit's assumption. Based on these properties, determination of relationship among r_{hss}, r_{qss}, bed shape and hydraulic conditions is needed for extensive applications of horizontal 2-D analysis. The predictive certainty ensures the application of V2D simulation model in field case.

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