

# Spatial and Temporal Variations of Groundwater-Stream Water Interaction in an Agricultural Area, Case study: Haean Basin, Korea

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A spatial and temporal variation of seepage in the Haean basin of Korea was examined using seepage meters and piezometers in the streambeds. More so, stream water budget and groundwater levels were also measured. The streambed of the study area was mostly sand bed forms and the seepage direction show high among 35 piezometer points at two stream transects each. Various upwelling (22.8, 4% at HSV1 and HSV2 in August and 77.1, 71.4% in October), downwelling (68.6, 51.4% in August and 0, 0% in October) and stagnation (8.6, 8.6% in August and 22.9, 28.6% in October) were found during different season. Vertical hydraulic gradients were generally small (-0.3~0.15 at HSV1, -0.1~0.1 at HSV2 in August and 0~0.05 at HSV1, 0~0.05 at HSV2 in October, respectively) but they show a significant variation with season and location. Downwelling was dominant in August while upwelling was dominant in October at HSV1 and HSV2. Furthermore, the proportion of stagnation points was greater in the dry season. A balance of total stream water flux and measured groundwater levels also indicated that the stream was generally losing in wet season. An integrated evaluation of seepage rate, vertical hydraulic gradient, stream flow budget and groundwater levels enhanced understanding of the groundwater-stream water interaction in this study area.

**Keywords:** Groundwater-Stream Water Interaction, Seepage Direction, Vertical Hydraulic Gradient, Stream Flow Velocity

## Introduction

The quantification of groundwater-stream water interactions is pivotally important to evaluate water budget in rural region where a large amount of groundwater and stream water are consumed for agricultural uses. Also, it is essential to manage the stream benthic ecology and to obtain a continuous stability of water resource in a climate change era. Water budgets in rural region are extraordinarily sensitive to climate change (Vörösmarty *et al.*, 2000; Christensen *et al.*, 2004; Chiyuan *et al.*, 2010). The global climate change will affect the balance of water demand and supply immediately and will have a significant influence over rural regions. Therefore, it is important to study the interactions between groundwater and stream water in such areas.

Over the past decades, there exist various methods for estimating the seepage between groundwater and stream water (Taniguchi and Fukuo 1993; Cable *et al.*, 1997; Corbett *et al.*, 1999; Rosenberry *et al.*, 2012). These methods include the seepage estimation by installing the seepage meters and the piezometers (Lee and Cherry 1978; Woessner and Sullivan 1984; Taniguchi and Fukuo 1993; Hatch *et al.*, 2006),

measuring streambed temperature (Constantz *et al.*, 1994; Constantz and Thomas 1996; Constantz *et al.*, 2002; Lowry *et al.*, 2007), injecting tracer (Isiorho *et al.*, 2005; Ruehl *et al.*, 2006; Chen *et al.*, 2007), using differential stream discharge gauging (Oberdorfer 2003; Vogt *et al.*, 2010), water balance calculations (LaBaugh *et al.*, 1997) and numerical modeling (Sophocleous *et al.*, 1999; Cardenas *et al.*, 2008).

Very few researchers have evaluated the magnitude and timing of groundwater-stream water mixing seepage area along streambed. A recent research (Kim *et al.*, 2009; Hyun *et al.*, 2011; Rosenberry *et al.*, 2012) has begun to quantify actual groundwater and stream water contributions in a mixing area through the use of seepage meters or through vertical hydraulic gradient measurements derived from piezometers. The seepage meters and piezometers have been widely used and it is the only way to quantify the seepage flux directly (Lee 1985; Lee and Cherry 1978; Krupa *et al.*, 1998; Rosenberry and Morin 2004; Rosenberry and Meheer 2006; Brodie *et al.*, 2009). The seepage meter is able to measure the seepage rate directly and it is inexpensive and easy to be installed. On the other hand, using a piezometer is a simple and indirect method that is reliable for vertical gradient examination which

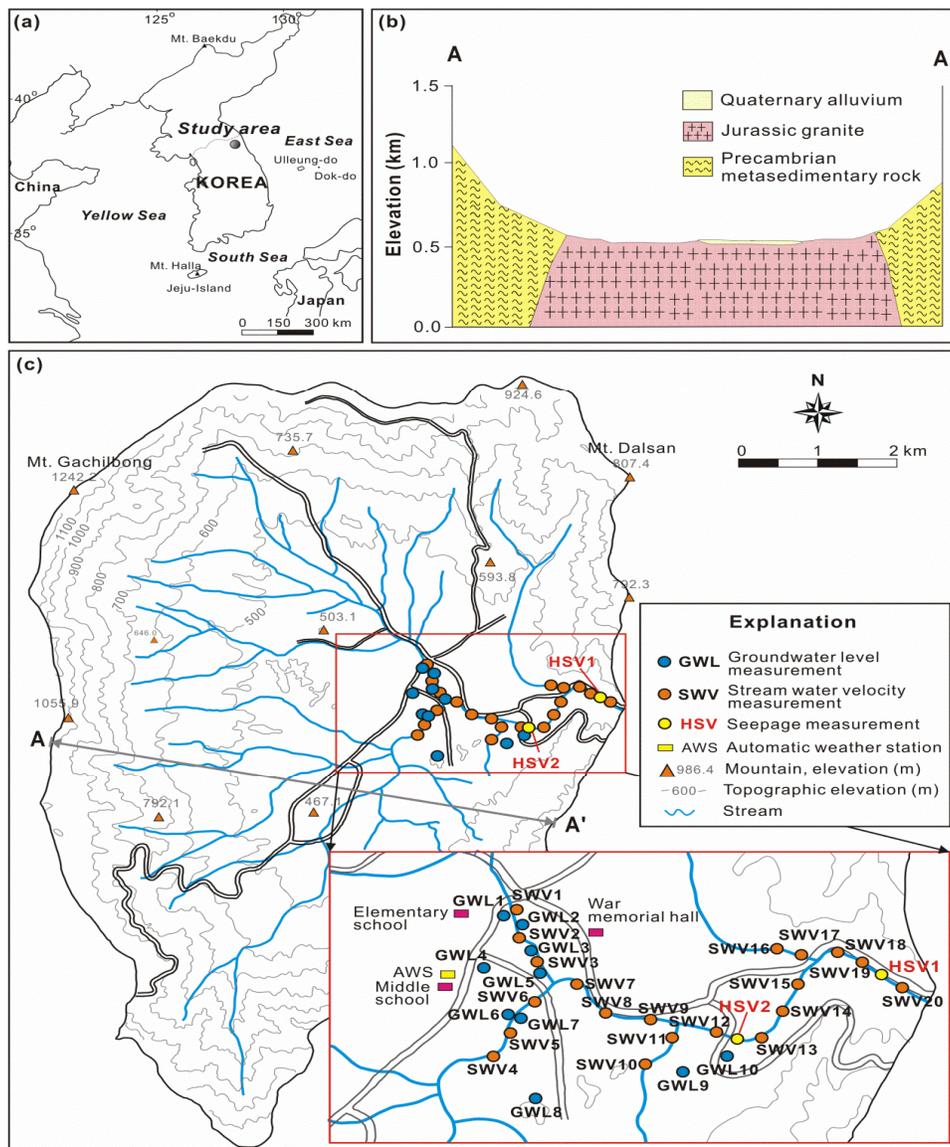
represents the flow direction in groundwater-stream water interaction zone. The flow direction is valuable to define the origin of water (Lee 1977; Rosenberry and Pitlick 2009).

The objective of this study was to examine spatial and temporal variation of seepage resulting from sandbed streams with the goal of quantifying groundwater-stream water exchange in the agricultural area, the Haean basin of Korea. Specific objectives include: (a) to document the seepage rates, directions, spatial and temporal variability in streambed, (b) to compare and measure rates of seepage at different locations across the stream; and (c) to investigate the relationships between observed seepage rate of upper groundwater-stream water interaction area and possible variables, including agricultural pattern, precipitation and substrate type. Also, the groundwater levels and budgets of stream water fluxes were evaluated.

## Materials and Methods

### Study Area

The Haean basin, is located in Gangwon province, Korea (Fig. 1a). The area of the basin is 57.5 km<sup>2</sup>. The highest altitude is 1,304 m and the lowest is 400 m above sea level. The area is surrounded by high mountains whose altitudes are over 1,000 m. Geology of the study area is characterized by Jurassic igneous rocks intruding into the composite metamorphic rocks (Kwon *et al.*, 1990). The extreme region is mainly made up of alternating meta-sedimentary rocks of mica schist, biotite-feldspar gneiss and quartzite. It has peculiar and interesting topographic feature like a bowl. The features of the area have been formed through prolonged differential erosion and the depressed bottom is made up of granite only (Kim and Park 1967). The geological section and profile of the basin are shown in Fig.1b.



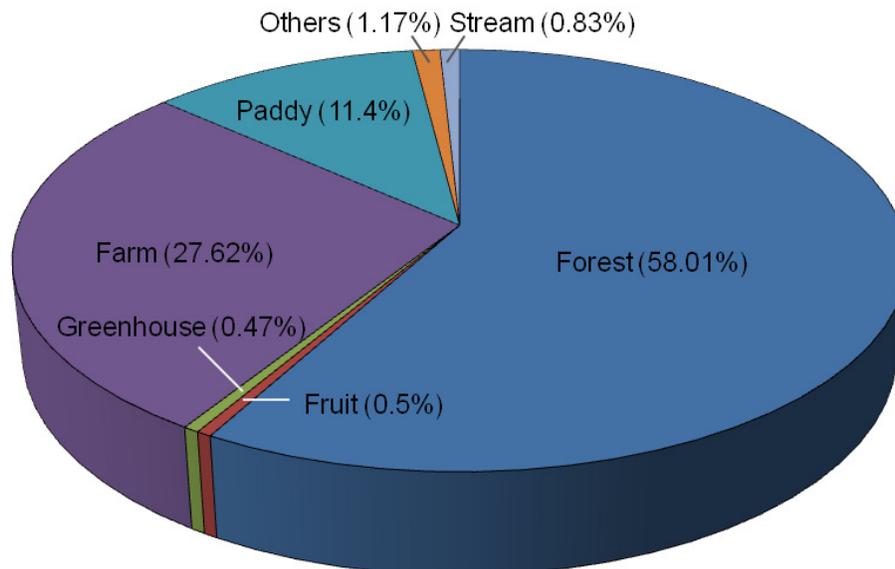
**Fig. 1** (a) Location of the study area, (b) a geologic section of the study area, and (c) locations of the groundwater level monitoring wells, stream water velocity measurement points and seepage measurement points

The contour map in Fig.1c illustrates the size, shape and drainage of the basin. The drainage system specifically shows a dendritic pattern. The total length of streams is about 63 km and the streams flow down to the depression of the basin but only one stream flows out in the east of the basin. Therefore, the hydrographic system of the area is relatively simple when it compares with other areas (Choi and Lee 2010; Lee *et al.*, 2012). The streambed sediments at the basin range from fine sand to coarse gravel. Generally, sediments found upstream are composed mainly of coarse gravel while fine sand is found downstream.

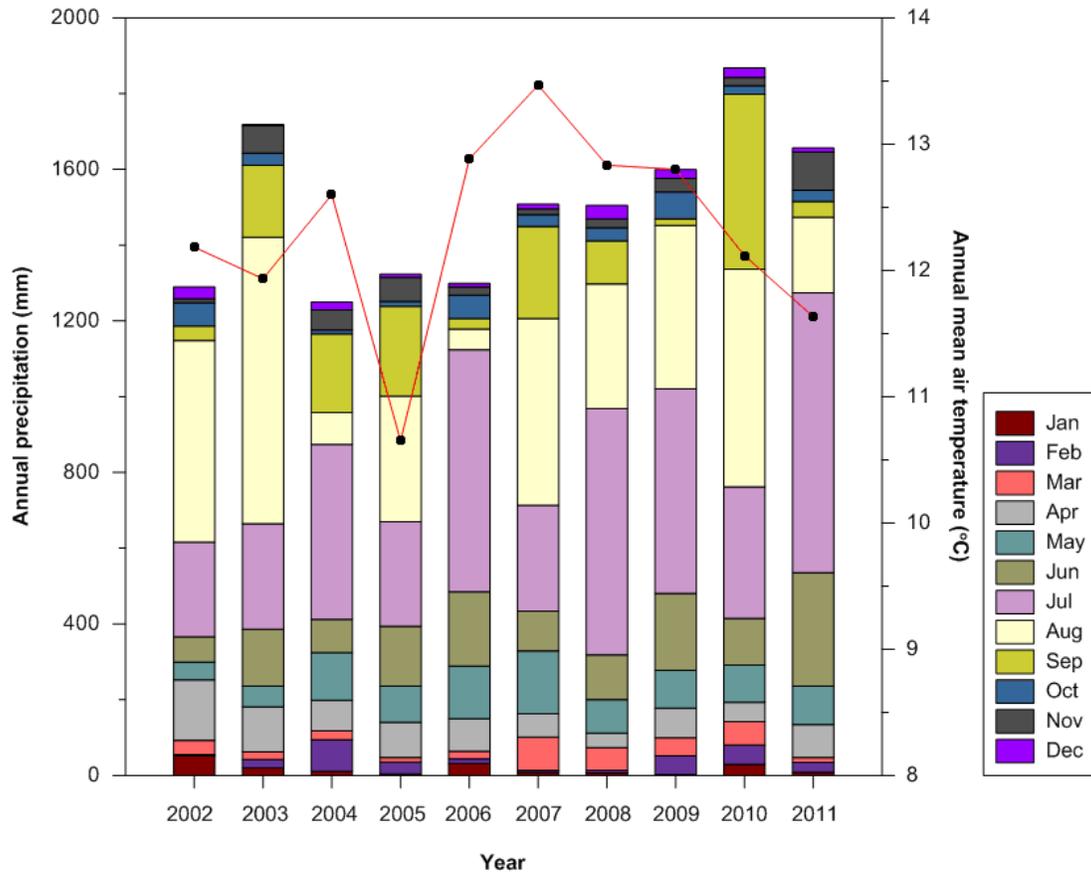
Groundwater levels (depth to water) on the topographic elevation from 400 to 450 m (the lowest elevation) ranged from 1 to 3 m, while that on the elevation from 500 to 600 m, ranged from 5 to 10 m, measured during April-October 2008. The groundwater levels in the study area largely depends on the topographic elevation and groundwater use (Yun *et al.*, 2009). Groundwater flows towards the streams. There are 111 groundwater wells officially reported in the study area (Lee 2009), which corresponds to 1.93 wells/km<sup>2</sup> of the total land area but approximately 10 wells/km<sup>2</sup> of the agricultural area only. Actually, there are many wells much more than reported and most of them are illegally installed in the agricultural area. Among the reported

wells, most (91%) are for agricultural water supply and groundwater pumping in the basin mainly occurs from May to August. Some deep groundwater wells have a pumping rate of over 150 m<sup>3</sup>/day, although the exact pumping amount of others is unknown (Lee *et al.*, 2012).

The high altitude areas above 650-700 m are mainly covered by forests (58.0%), while the moderate and lower areas (<650 m) are mostly used for agriculture, including crop farm (27.6%), rice paddy fields (11.4%) and fruit farm (0.5%) in 2011 (Lee *et al.*, 2012) (Fig. 2). The climate is characterized by distinct wet and dry seasons. From 2002 to 2011, the maximum and minimum of annual mean air temperatures of the basin were 25.3°C and -11.5°C, respectively and their mean was 10.1°C. The average annual precipitation for the period was 1,501 mm. The maximum and minimum of annual precipitations were 1,867.5 mm in 2010 and 1,249.6 mm in 2004, respectively (Fig. 3). In addition, the precipitation has generally increased with year. Based on the precipitations for the decade, the wet and dry seasons were considered to be from July to September and from October to February, respectively. More than 60-70% of total annual precipitations occur in the wet season due to the monsoon weather, which is a characteristic of the climate of Korean Peninsula (Lee and Lee 2000).



**Fig. 2** Land use in the study area as of 2011



**Fig. 3** Annual precipitation and annual mean air temperature for 2002-2011 in the study area

### Seepage Measurements

Groundwater-stream water exchange seepage rates in this study were measured using a seepage meters initially described by Lee (1977). Semi-cylindrical seepage meters were used to measure the seepage rate at the HSV1 and HSV2 sites (see locations in Fig. 1c). The meters were driven into the streambed, open end down, to a depth of 10 cm. Size of the installed seepage meters was 0.3 m in diameter and 0.1 m in height. At each point, the seepage was measured at two times for 24 hours from August 11 to 12 and from October 2 to 3, 2011. The seepage meters were modified from the original Lee design to reduce impacts from stream water flow disturbance (Rosenberry, 2008). A seepage bag shield was constructed from beside the seepage meters. The seepage flux was calculated by volumetric change of bag per unit time as follows.

$$V = \frac{dv}{dt} \quad (1)$$

where  $V$  is seepage velocity (m/d),  $dv$  is volumetric change of bag ( $m^3$ ), and  $dt$  is measurement time.

### Vertical Hydraulic Gradient

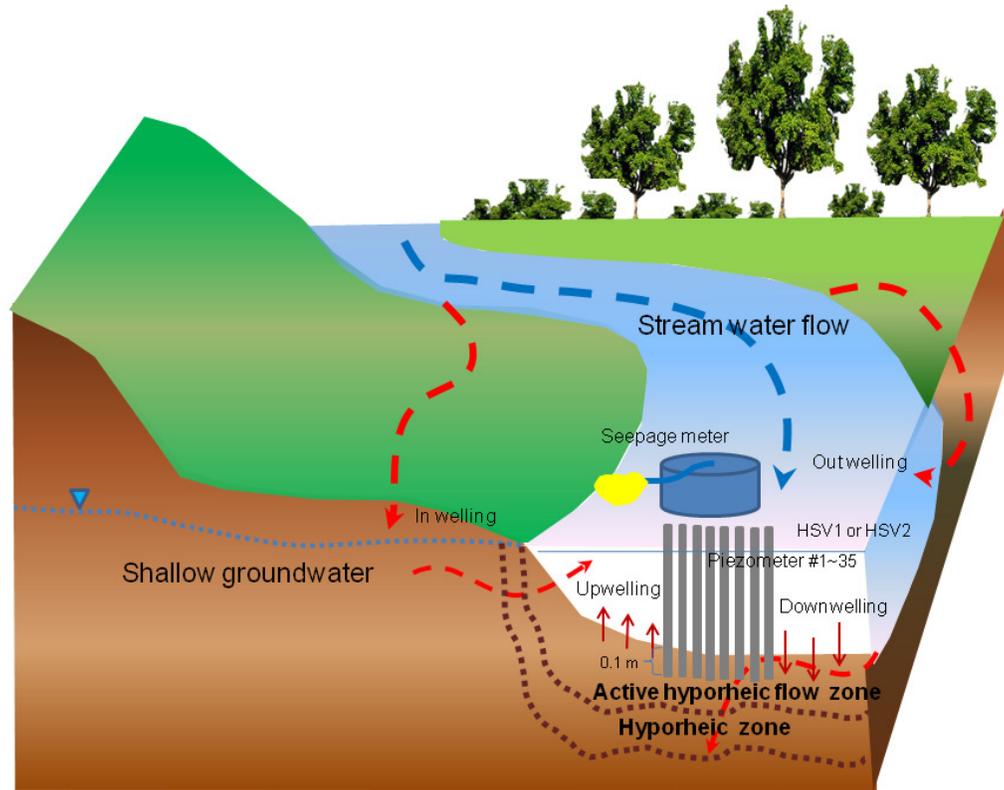
At several times during the seepage measurements, the ambient vertical hydraulic gradient between groundwater and stream water was recorded using piezometer. The vertical hydraulic gradient during the seepage

measurements was calculated using the data from potentiomanometer. Also, direction and magnitude of hydrologic interaction were evaluated at the two sites using piezometer transects. Each piezometer was made up of 2 inch (internal diameter) PVC (polyvinyl chloride) pipe.

At each transect, a total of 35 piezometers were inserted at 0.1 m depth beneath the streambed adjacent to each seepage meter installation point with a regular interval (Fig. 4). At both sites (HSV1 and HSV2), head was measured relative to the stream water surface and vertical hydraulic gradient was determined by dividing  $\Delta h$  by the piezometer insertion depth.

$$VHG = \frac{\Delta h}{\Delta l} \quad (2)$$

where  $\Delta h$  is the difference in water levels of the piezometers and stream water,  $\Delta l$  is the difference in depths between streambed and the point where the piezometers are installed. However, head differences were often very small in the coarse-grained streambeds and thus, three to five observations were averaged to obtain  $\Delta h$  at both sites. The positive and negative vertical hydraulic gradients indicate gaining and losing conditions of streams, respectively.



**Fig. 4** Schematic of seepage meter and piezometers for measuring water flux across the streambed and hydraulic head, respectively

### Vertical Hydraulic Conductivity (K)

Streambed vertical hydraulic conductivity ( $K_v$ ) is an important parameter to estimate in order to quantify the magnitude and spatial distribution of groundwater-stream water exchange. The streambed  $K$  has been estimated using a variety of approaches (Hazen 1893; Hantush 1965; Sophocleous *et al.* 1995; Barlow and Moench 1998; Hunt 1999; Zlotnik and Huang 1999; Rosenberry and Pitlick 2009). In situ values for vertical hydraulic conductivity at the site were determined using the vertical hydraulic gradient and seepage flux. The Darcy equation was used to calculate  $K_v$ .

$$K_v = \frac{q}{i} \quad (3)$$

where  $K_v$  is vertical hydraulic conductivity,  $q$  is the measured seepage rate and  $i$  is vertical hydraulic gradient. The relation of  $q$  and  $i$  is commonly used in hyporheic zones (Storey *et al.*, 2003; Rosenberry, 2008; Kaser *et al.*, 2009).

We also analyzed soil grain size of the streambed at the installed seepage meter and piezometer points to determine hydraulic conductivity. The streambed samples were collected from the upper 0.1 m using an auger type sampler. The grain size distributions were determined by sieve analysis at Kangwon National University in Korea.

### Stream Velocity Measurement

The stream water velocity was measured along each stream transect at 22 different points (see locations in Fig. 1c) using a propeller type current meter (OTTZ30 counter set, OTT MESSTECHNIK Gmbh & Co.). At each point, the stream water velocity was measured at 0.3, 0.6 and 0.9 m above the streambed in August (wet season). Also, it was measured at 0.1, 0.2 and 0.3 m above the streambed in October (dry season). The measured stream water velocities at the three different depths were averaged. In addition, the stream water flux was calculated using the water depth and the stream water velocity measured with a 0.5 m interval.

### Groundwater Level Measurement

The electronic water level meter (Model 101, Solinst Canada Ltd.) was used to measure the groundwater levels at 10 groundwater wells (G1~G10) on 11 August and 10 October in 2011. These wells were very near each seepage meter and piezometric transect in the stream. Each well was made up of galvanized steel pipe with 10 inch in diameter.

### Results and Discussion

#### Seepage Rate, $K_v$ and VHG

The seepages collected at HSV1 and HSV2 for duration of 24 hours were 12 and 5 ml in August and 6 and 2 ml

in October, respectively. A grain size analysis of this streambed indicated that it consisted of 91.5% sand, 0.8% silt and 7.7% clay at HSV1 and 89.2% sand, 0.3% silt and 10.5% clay HSV2, respectively. The soil texture of HSV1 and HSV2 was sand and bulk density and porosity was 1.43, 1.42 g/cm<sup>3</sup> and 0.32, 0.32, respectively. The substrate at the installed seepage meters and piezometers ranged from fine sand to sand texture.

The vertical hydraulic conductivity calculated by using the seepage and vertical hydraulic gradient were  $3.93 \times 10^{-6}$  cm/sec at HSV1-1 and  $1.64 \times 10^{-6}$  cm/sec at HSV2-1. The  $K_v$  of both sites was relatively small but similar, and typical of fine sand sediments. We considered the possibility that substrate texture ranges were influenced by method. However, calculated  $K_v$  and grain size analysis have produced similar results.

Upwelling seepage showed to the stream throughout the groundwater-stream water interaction zone with an average seepage rate of  $11.37 \text{ E-}5$  cm<sup>3</sup>/sec at HSV1 in August and  $9.24 \text{ E-}5$  cm<sup>3</sup>/sec in October and  $5.51 \text{ E-}5$  cm<sup>3</sup>/sec at HSV2 in August,  $3.63 \text{ cm}^3/\text{sec}$  in October, respectively. The average of upwelling seepage rates was not significantly different with season.

However, average of downwelling seepage rate was  $21.47 \text{ E-}5$  cm<sup>3</sup>/sec at HSV1 and  $5.74 \text{ E-}5$  cm<sup>3</sup>/sec at HSV2 in August. There is no downwelling seepage in October with HSV1 and HSV2. There is a marked difference in the average downwelling seepage rates between HSV1 and HSV2. The average rate of HSV1 was 3.7 times larger HSV2 during August.

The vertical hydraulic gradients were small to moderate at both points. The range in values was larger in August than in October. The vertical hydraulic gradients show the groundwater upwelling or stream water downwelling. Interestingly, calculated vertical hydraulic gradients at HSV1 and HSV2 revealed the mixed direction along the stream width in August. The numbers of upwelling and downwelling points were 11

and 24 at HSV1 and 17 and 18 at HSV2 in August.

However, there existed a difference in vertical hydraulic gradients between August and October. The upwelling directions were mostly found at HSV1 and HSV2 in October. However, there were no downwelling points at HSV1 and HSV2 in October. Due to decrease in agricultural groundwater use in the dry season, upwelling was generally found with increase of groundwater levels (Lee *et al.*, 2012).

### Stream Water Velocity and Precipitation

The average stream velocities were: 105.17 cm/sec at HSV1 and 75.56 cm/sec at HSV2 in August; 39.0 cm/sec at HSV1 and 35.0 cm/sec at HSV2 in October, respectively (Fig. 5). The stream velocity at HSV1 in August is 1.4 times larger than that at HSV2 and 1.12 times in October.

The monthly precipitation was 200 mm in August and 29.9 mm in October, respectively and thus the stream velocity was largely affected by the seasonal difference in precipitation. Also, a large amount of precipitation markedly influenced the stream velocity during the same season. These results show that the factors governing the stream velocities are the difference of precipitation with the season and intensity of precipitation. Also, magnitude and timing of precipitation events were examined for their potential influence on temporal variability in seepage patterns.

Furthermore, the hydraulic head differences ( $\Delta h$ ) were enlarged as the stream velocity increased. With regards to the stream velocity at HSV1 in August, the corrected hydraulic head was 2.34 cm. However, the original hydraulic head without considering the stream velocity was -0.8 cm. The measured average hydraulic heads were -0.8 cm and 0.22 cm at HSV1 in August and October, respectively (see Table 1). This result showed that the fast stream velocity affected the measured hydraulic heads.

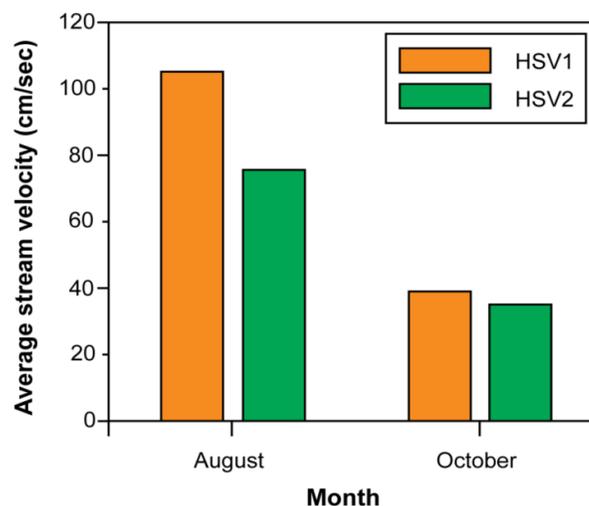


Fig. 5 Mean stream water velocity at HSV1 and HSV2 in August and October of 2011

**Table 1** Head difference  $\Delta h$  and vertical hydraulic gradient (VHG) at HSV1 and HSV2 in August and October of 2011

Points	$\Delta h$	VHG	$\Delta h$	VHG	Points	$\Delta h$	VHG	$\Delta h$	VHG
	(cm)		(cm)			(cm)		(cm)	
	August		October			August		October	
HSV1-1	0.5	0.05	0.1	0.01	HSV2-1	0.5	0.05	0.1	0.01
HSV1-2	-2	-0.2	0	0	HSV2-2	0.5	0.05	0.1	0.01
HSV1-3	-1.5	-0.15	0.2	0.02	HSV2-3	0.5	0.05	0.3	0.03
HSV1-4	-1.5	-0.15	0	0	HSV2-4	0	0	0	0
HSV1-5	0.5	0.05	0.1	0.01	HSV2-5	1	0.1	0	0
HSV1-6	-3	-0.3	0.3	0.03	HSV2-6	1	0.1	0.2	0.02
HSV1-7	-1	-0.1	0.5	0.05	HSV2-7	1	0.1	0.2	0.02
HSV1-8	0	0	0.2	0.02	HSV2-8	0.5	0.05	0.3	0.03
HSV1-9	-1	-0.1	0.3	0.03	HSV2-9	-1	-0.1	0.3	0.03
HSV1-10	-3	-0.3	0.3	0.03	HSV2-10	-1	-0.1	0.2	0.02
HSV1-11	1.5	0.15	0	0	HSV2-11	-0.5	-0.05	0.1	0.01
HSV1-12	-1	-0.1	0	0	HSV2-12	-0.5	-0.05	0.3	0.03
HSV1-13	-1	-0.1	0.2	0.02	HSV2-13	-0.5	-0.05	0	0
HSV1-14	0	0	0.2	0.02	HSV2-14	-1	-0.1	0.2	0.02
HSV1-15	-3	-0.3	0.3	0.03	HSV2-15	-1	-0.1	0.2	0.02
HSV1-16	-2.5	-0.25	0.3	0.03	HSV2-16	0.5	0.05	0.5	0.05
HSV1-17	0	0	0.3	0.03	HSV2-17	0	0	0.3	0.03
HSV1-18	-1	-0.1	0.5	0.05	HSV2-18	-0.5	-0.05	0	0
HSV1-19	-1	-0.1	0.3	0.03	HSV2-19	-0.5	-0.05	0	0
HSV1-20	-0.5	-0.05	0.3	0.03	HSV2-20	-1	-0.1	0.3	0.03
HSV1-21	-0.5	-0.05	0.5	0.05	HSV2-21	-1	-0.1	0.3	0.03
HSV1-22	-1	-0.1	0.2	0.02	HSV2-22	-1	-0.1	0.2	0.02
HSV1-23	-2	-0.2	0.3	0.03	HSV2-23	-1	-0.1	0	0
HSV1-24	-3	-0.3	0.5	0.05	HSV2-24	-0.5	-0.05	0.1	0.01
HSV1-25	-0.5	-0.05	0	0	HSV2-25	-0.5	-0.05	0.1	0.01
HSV1-26	0.5	0.05	0.5	0.05	HSV2-26	-0.5	-0.05	0.1	0.01
HSV1-27	-1.5	-0.15	0.3	0.03	HSV2-27	-0.5	-0.05	0.2	0.02
HSV1-28	-0.5	-0.05	0.3	0.03	HSV2-28	-0.5	-0.05	0.3	0.03
HSV1-29	-0.5	-0.05	0.2	0.02	HSV2-29	0.5	0.05	0.2	0.02
HSV1-30	-1	-0.1	0.3	0.03	HSV2-30	0.5	0.05	0	0
HSV1-31	-0.5	-0.05	0.3	0.03	HSV2-31	1	0.1	0.3	0.03
HSV1-32	0.5	0.05	0	0	HSV2-32	0	0	0.3	0.03
HSV1-33	0.5	0.05	0	0	HSV2-33	1	0.1	0	0
HSV1-34	1	0.1	0.1	0.01	HSV2-34	1	0.1	0	0
HSV1-35	1	0.1	0	0	HSV2-35	0.5	0.05	0	0

**Seepage Velocity and Flux**

The seepage velocity along the width of the stream indicates that stream at HSV1 was strongly losing and weakly gaining at HSV2 in August, consecutively (see Fig. 6). Fig. 7 shows the seepage velocity in October, 2011. The stream was converted to strongly losing stream at HSV2 after considering the stream velocity. With a considerable change of stream type, the variation

of the hydraulic head by stream velocity was observed along the width of stream.

Because there is frequent occurrence of downwelling at the middle of stream (Fig. 8), total seepage flux increased. Based on the seepage flux at HSV1 and HSV2 in October, the results showed that the stream was strongly gaining. The seepage flux was measured as upwelling for the most part of stream along its width.

There were no downwelling points in October. The seepage flux in August clearly showed that mixing of downwelling and upwelling flux occurred. A comparison

of seepage flux with season suggests that downwelling phenomenon is retarded by stream velocity. In particular, the downwelling flux was clearly observed in August rather than October.

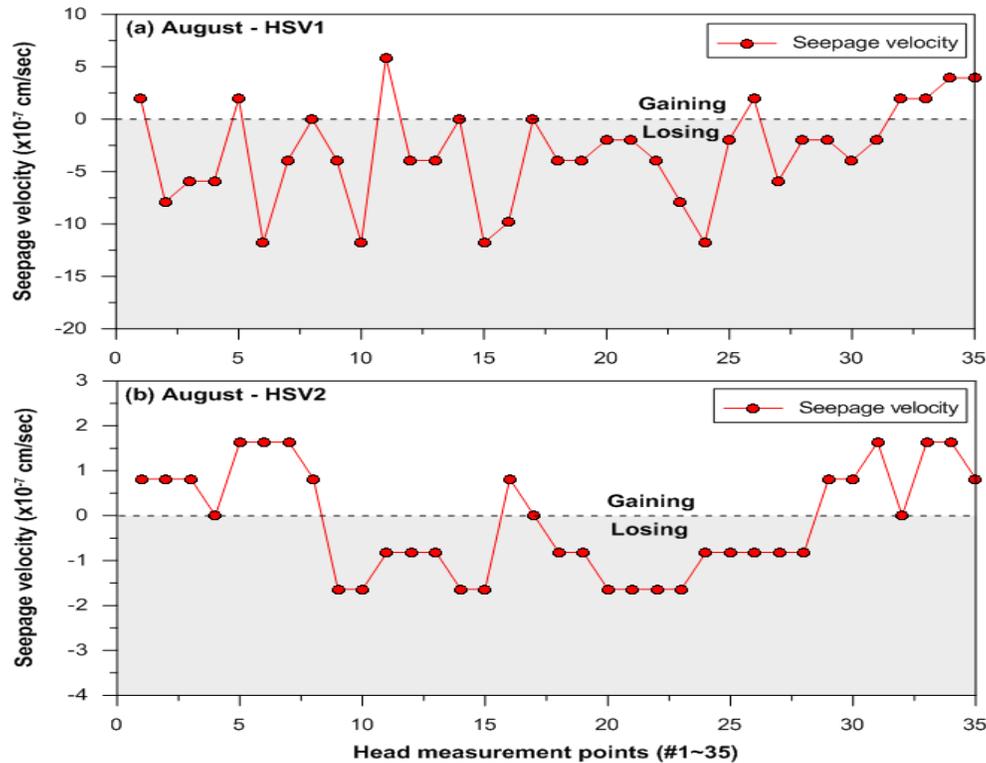


Fig. 6 Seepage velocity of HSV1 and HSV2 in August 2011

**Groundwater Levels**

The depth of groundwater ranged from 1.7 to 2.4 m in August 11 and 1.5 to 2.0 m in October. The change in groundwater levels with time indicates that they readily responded to precipitation and irrigation. The groundwater levels represented the direction of stream water flux and were measured near the stream.

The average level in wet season was 2.11 m while that of dry season was 1.8 m. The maximum groundwater levels were 2.4 and 2.0 m while the minimum levels were 1.7 and 1.5 m in August and October, respectively (Table 2). The levels increased in the dry season and groundwater was consumed more in the wet season than in the dry season in this area (Choi and Lee 2010). Consequently, the streams were generally highly losing which contradicts our expectation.

**Stream Water Flux and Groundwater-Stream Water Interaction**

Stream water flux measured at 20 points (except for HSV1 and HSV2) in August and October 2011 is presented in Table 3. The calculated water balance at the junction SWV7 was 3.75 and 2.09 m<sup>3</sup>/sec in August

and October, respectively. However, the measured stream fluxes were 3.32 and 2.11 m<sup>3</sup>/sec. Thus, the stream water fluxes of 0.43 m<sup>3</sup>/sec was losing due to its penetration into groundwater in the wet season, whereas groundwater fluxes of 0.2 m<sup>3</sup>/sec at SWV7 was upwelling through the groundwater-stream water interaction zone. At the other points, the measured stream water fluxes of SWV12 were 3.84 and 2.52 m<sup>3</sup>/sec and those of SWV18 were 8.92 and 4.61 m<sup>3</sup>/sec in August and October, respectively. However, the calculated stream water flux was 3.95 and 2.59 m<sup>3</sup>/sec at SWV12 and 9.75 and 5.37 m<sup>3</sup>/sec at SWV18 in August and October.

With respect to water balance, stream water flux showed that study area was losing stream pattern with season. Most interesting, was the finding that the losing pattern of stream showed in wet season generally, losing pattern of stream showed in dry season. The stream and groundwater at the basin are highly linked. Therefore, stream water flux was influenced not only by precipitation but also groundwater levels. During the wet season, groundwater level decreased due to excessive pumping for agricultural use.

**Table 2** Groundwater levels (depth to water, m) in August and October of 2011

Groundwater well	Wet season	Dry season
	August 11, 2011	October 10, 2011
G1	2.2	1.7
G2	2.4	1.9
G3	1.8	1.5
G4	1.9	1.7
G5	1.7	1.8
G6	2.0	1.9
G7	2.1	1.75
G8	2.3	1.85
G9	2.4	2.0
G10	2.3	1.9
Average	2.1	1.8
Maximum	2.4	2.0
Minimum	1.7	1.5
Std.deviation	0.25	0.14

**Table 3** Stream water flux at 20 points in August and October 2011

Locations	Measured stream water flux (Q) (m <sup>3</sup> /sec)		Explanation
	August 11, 2011	October 10, 2011	
SWV1	1.82	0.67	
SWV2	1.88	0.96	
SWV3	1.93	1.35	
SWV4	1.78	0.98	
SWV5	1.89	1.07	
SWV6	1.94	1.25	
SWV7	3.32	2.11	Junction
SWV8	3.3	2.15	
SWV9	3.31	2.2	
SWV10	0.64	0.38	
SWV11	0.64	0.39	
SWV12	3.84	2.52	
SWV13	3.88	2.51	
SWV14	4.8	2.55	
SWV15	4.9	2.66	
SWV16	4.9	2.57	
SWV17	4.85	2.71	
SWV18	8.92	4.61	Junction
SWV19	8.8	4.55	
SWV20	8.78	4.58	

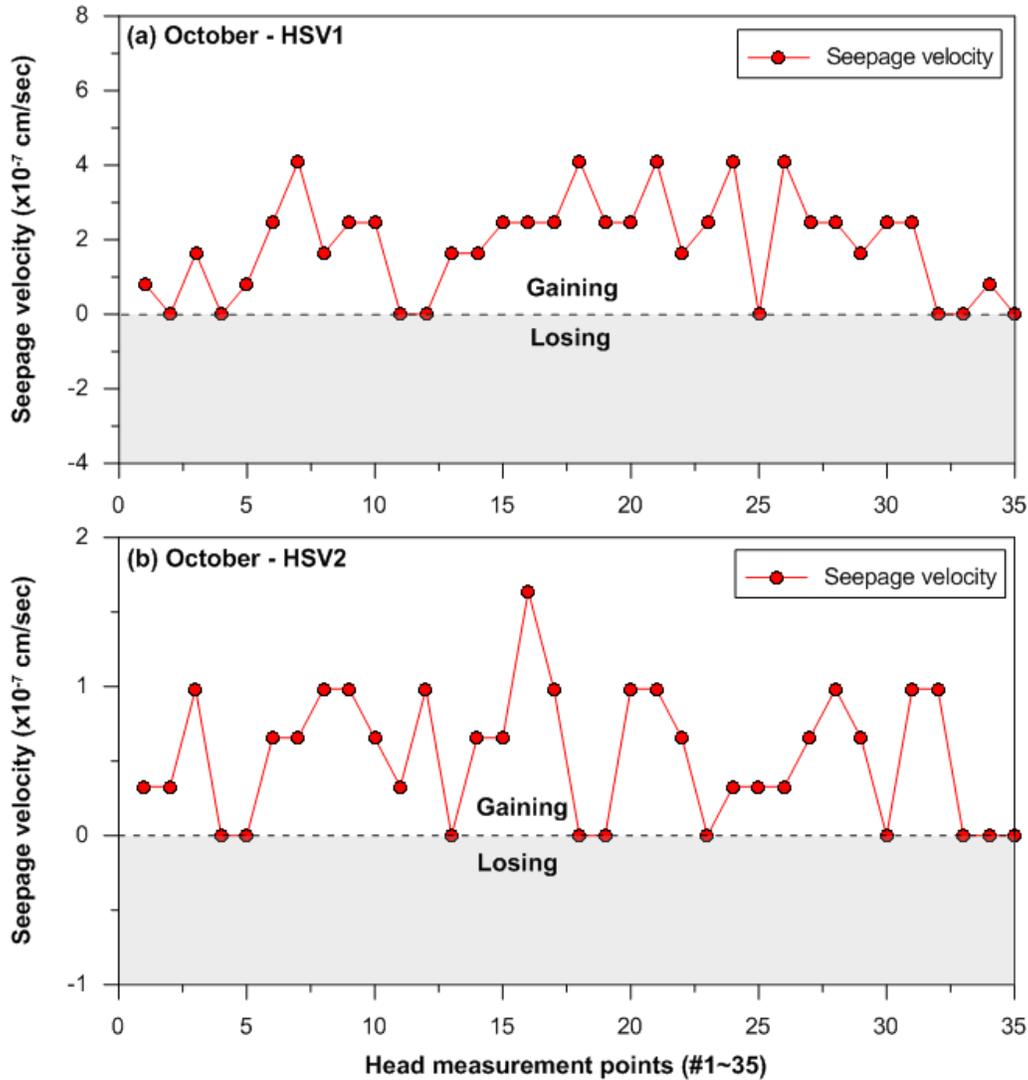


Fig. 7 Seepage velocity of HSV1 and HSV2 in October 2011

**Conclusions**

The seepage fluxes showed a seasonal variation and there was a significant difference between August and October. The rapid stream velocity leads to an increase of the downwelling point and seepage flux in August. Furthermore, the stream in the study area was losing stream regardless of seasons. This result was furthered supported by measured groundwater levels, stream water fluxes and calculated water budget data. The overall average seepage flux of flow measured at two different points was temporal and spatial variations across the wet and dry seasons. The highest observed seepage flux occurred in wet season which is concentrated most by precipitation. However, the flux in the dry season showed a declining trend. There is a variation in quantity of seepage with the season.

The findings indicate that seepage of groundwater-stream water interaction zone is a significant and

ubiquitous process through the upper interaction zone. Several pieces of evidence suggest that both spatial and temporal patterns observed in the rate and directions of seepage are highly linked to stream water flux and groundwater levels. Despite the considerable precipitation, there was surprisingly no significant relationship with seepage patterns. Interestingly, although there was much more precipitation in August, the groundwater levels were much lowered in this wet season than in October.

There was a large amount of groundwater consumption in August (wet season). Agricultural activities affected the hydrologic interaction as much as the precipitation. Consequently, due to the increased groundwater levels in the dry season, the vertical hydraulic gradients of streambed were positive.

Stream water was partially downwelling in all

seasons. These findings will also provide a useful model for predicting groundwater levels connections with stream water for calculating the water budget for agricultural area. An integrated approach using seepage flux, vertical hydraulic gradients, groundwater levels and

stream water budgets can provide substantial evidences of groundwater-stream water interaction. The information is important for predicting future stream responses to climate change and agricultural practices.

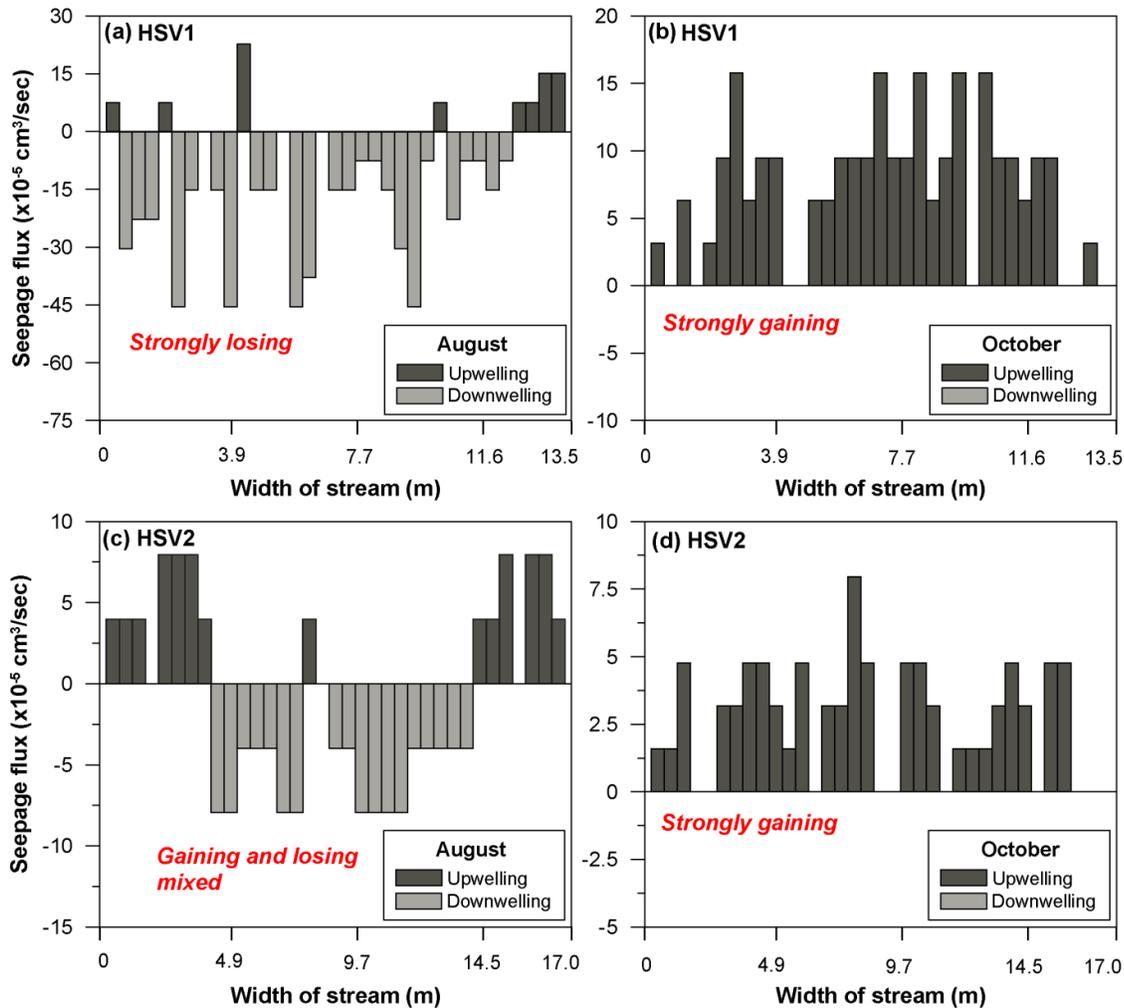


Fig. 8 Seepage flux at HSV1 and HSV2 in August and October of 2011

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### References

- Barlow PM, Moench AF (1998) Analytical solutions and computer programs for hydraulic interaction of stream-aquifer system. USGS Open Field Report 98-415A
- Brodie RS, Baskaran S, Ransley T, Spring J (2009) Seepage meter: progressing a simple method of directly measuring water flow between surface water and groundwater systems. *Australian J Earth Sci* 56: 3-11
- Cable JE, Burnett WC, Chanton JP (1997) Magnitude and variations of groundwater seepage along a Florida marine shoreline. *Biogeochem* 38: 189-205
- Cardenas MB, Wilson JL, Haggerty R (2008) Residence time of heterogeneity, bed forms, and stream curvature on subchannel hyporheic exchange. *Water Resour Res* 40: W08307
- Chen J, Chen C, Chen CY (2007) Analysis of solute transport in a divergent flow tracer test with scale-dependent dispersion. *Hydro Process* 21: 2526-2536
- Chiyuan M, Junren N, Alistair GLB (2010) Recent changes of water discharge and sediment load in the yellow river basin, China. *Progress Physic Geol* 34: 541-561
- Choi HM, Lee JY (2010) Groundwater level distribution and rainfall response characteristics in Haeon basin of Yangju. *J Soil*

- Groundwater Environ 15: 1-8 (in Korean)
- Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the Colorado river basin. *Clim Change* 62: 337-363
- Constantz J, Thomas CL, Zwillweger G (1994) Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge. *Water Resour Res* 30: 3253-3264
- Constantz J, Thomas CL (1996) The use of streambed temperature profiles to estimate the depth, duration, and rate of percolation beneath arroyos. *Water Resour Res* 32: 3597-3602
- Constantz J, Stewart AE, Niswonger R, Sarma L (2002) Analysis of temperature profiles for investigating steam losses beneath ephemeral channels. *Water Resour Res* 38: 1316
- Corbett RD, Chanton JP, Burnett WC, Dillon K, Rutkowski C, Fourqurean JW (1999) Patterns of groundwater discharge into Florida bay. *Am Soc Limnol Oceanol* 44: 1045-1055
- Hantush MS (1965) Wells near streams with semipervious beds. *J Geophys Res* 12: 2829-2838
- Hatch C, Fisher A, Revenaugh J, Constantz J, Ruehl C (2006) Quantifying surface water-groundwater interactions using time series analysis of streambed thermal records: Method development. *Water Resour Res* 42: 10410
- Hazen A (1893) Some physical properties of sands and gravels. Massachusetts State Board, 24th Annual Report
- Hunt B (1999) Unsteady stream depletion from ground water pumping. *Ground Water* 37:98-102
- Hyun, Y., Kim, H., Lee, S.S., Lee, K.K., 2011. Characterizing streambed water flux using temperature and head data in Munsan stream, South Korea. *J Hydrol* 402: 377-387
- Isiorho SA, Matisoff G, Wehn KS (2005) Seepage relationship between lake Chad and Chad aquifers. *Ground Water* 34: 819-826
- Kaser DH, Binley A, Heathwaite AL, Krause S (2009) Spatio-temporal variations of hyporheic flow in a riffle-step-pool sequence. *Hydrol Process* 23: 2138-2149
- Kim BK, Park YA (1967) The origin of the so-called Punch Bowl. *J Geol Soc Korea* 3: 61-66
- Kim H, Hyun Y, Lee KK (2009) Hydroecological characterization in groundwater dependent ecosystem. *J Korean Wetlands Soc* 11: 1-8
- Krupa SL, Belanger TV, Heck HH, Brok JT, Jones BJ (1998) The next generation seepage meter. *J Coastal Res* 25: 210-213
- Kwon YS, Lee HH, Han U, Kim WH (1990) Terrain analysis of Haeen basin in terms of earth science. *J Korea Earth Sci Soc* 11: 236-241 (in Korean)
- LaBaugh JW, Winter TC, Rosenberry DO, Schuster PF, Reddy MM, Aiken GR (1997) Hydrological and chemical estimates of the water balance of a closed- basin lake in north central Minnesota. *Water Resour Res* 33: 2799-2812
- Lee DR (1977) A device for measuring seepage flux in lake and estuaries. *Am Soc Limnol Oceanol* 22: 140-147
- Lee DR (1985) Method for locating sediment anomalies in lake beds that can be caused by groundwater flow. *J Hydrol* 79: 187-193
- Lee DR, Cherry JA (1978) A field exercise on groundwater flow using seepage meters and mini-piezometers. *J Geol Edu* 27: 6-10
- Lee JY, Lee KK (2000) Use of hydrologic time series data for identification of recharge mechanism in a fractured bedrock aquifer system. *J Hydrol* 229:190-201
- Lee JY (2009) Importance of hydrogeological and hydrologic studies for Haeen basin in Yanggu. *J Geol Soc Korea* 45: 405-414 (in Korean)
- Lee JY, Lee KS, Park Y, Choi HM, Jo YJ (2012) Chemical and isotopic compositions of groundwater and stream water in a basin, Korea: indication of fast circulation. *J Geol Soc India* (in press)
- Lowry CS, Walker JF, Hunt RJ, Anderson MP (2007) Identifying spatial variation of groundwater discharge in a wetland stream using a distributed temperature sensor. *Water Resour Res* 43: W10408
- Oberdorfer JA (2003) Hydrologic modeling of submarine groundwater discharge: comparison to other quantitative methods. *Biogeochem* 66: 159-169
- Rosenberry DO, Morin RH (2004) Use of an electromagnetic seepage meter to investigate temporal variability in lake seepage. *Ground Water* 42: 68-77
- Rosenberry DO, Menheer MA (2006) A system for calibrating seepage meters used to measure flow between groundwater and surface water. USGS Scientific Investigations Rep. 2006-5053. USGS, Washington, DC
- Rosenberry DO (2008) A Seepage meter designed for use in flowing water. *J Hydrol* 359: 118-130
- Rosenberry DO, Pitlick J (2009) Effects of sediment transport and seepage direction on hydraulic properties at the sediment- water interface of hyporheic settings. *J Hydrol* 359: 118-130
- Rosenberry DO, Klos PZ, Neal A (2012) In situ quantification of spatial and temporal variability of hyporheic exchange in static and mobile gravel-bed rivers. *Hydrol Process* 26: 604-612
- Ruehl C, Fisher AT, Hatch C, Huertos ML, Stemler G, Shennan C (2006) Differential gauging and tracer tests resolve seepage fluxes in a strongly-losing stream. *J Hydrol* 330: 235-248
- Sophocleous MA, Koussis A, Martin JL, Perkins SP (1995) Evaluation of simplified stream-aquifer depletion models for water rights administration. *Ground Water* 33:579-588
- Sophocleous MA, Koelliker JK, Govindaraju RS, Birdie T, Ramireddygan SR, Perkins SP (1999) Integrated numerical modeling for basin-wide water management: The case of the Rattlesnake Creek basin in south-central Kansas. *J Hydrol* 214: 179-196
- Storey RG, Howard KWF, Williams DD (2003) Factors controlling riffle scale hyporheic exchange flows and their seasonal exchange in a gaining stream: a three-dimensional groundwater flow model. *Water Resour Res* 39: 1034
- Taniguchi M, Fukou Y (1993) Continuous measurements of groundwater seepage using an automatic seepage meter. *Ground Water* 31: 675-679
- Vogt T, Schneider P, Hahn-Woermle L, Cirpka OA (2010) Estimation of seepage rates in a losing stream by means of fiberoptic high resolution vertical temperature profiling. *J Hydrol* 380: 154-164
- Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: Vulnerability from climate and population growth. *Science* 289(5477): 284-288
- Woessner WW, Sullivan KE (1984) Results of seepage meter and mini-piezometer study, Lake Mead, Nevada. *Ground Water* 22(5): 561-568
- Yun SY, Jo YJ, Lee JY (2009) Comparison of groundwater recharges estimated by water level fluctuation and hydrograph separation in Haeen basin of Yanggu. *J Geol Soc Korea* 45(4): 391-404 (in Korean)
- Zlotnik V, Huang H (1999) Effect of shallow penetration and streambed sediments on aquifer response to stream stage fluctuations (analytical model). *Ground Water* 37: 599-605