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# Determination of spatially varying Van der Burgh's coefficient from estuarine parameter to describe salt transport in an estuary

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## Abstract

The estuarine parameter  $\nu$  is widely accepted as describing the relative contribution of the tide-driven and density-driven mixing mechanism of salt transport in estuaries. Van der Burgh's coefficient  $K$  is another parameter that also determines the relative strength of two mechanisms. However, a single value of  $K$ , which has been considered in previous studies, can not represent the spatial variation of these mechanisms in an estuary. In this study, the spatially varying  $K$  has been determined from the  $\nu$  value calculated using intensively observed longitudinal salinity transects of the Sumjin River Estuary with exponential shape. The spatially varying  $K$  describes the spatial variation of these mechanisms reasonably well and is independent of the river discharge downstream of the estuary during spring tide where the strong tides cause well mixed conditions. However,  $K$  values increase upstream and are found to depend on the freshwater discharge, with suppressing vertical mixing. The  $K$  value has been scaled on the basis of the  $\nu$  value and ranges between 0 and 1. If  $K$  is  $<0.4$ , the up-estuary salt transport is entirely dominated by tide-driven mixing during spring tide near the mouth. If  $0.4 < K < 0.8$ , both tide-driven and density-driven mixing contribute to transporting salt in the central regimes. If  $K > 0.8$ , the salt transport is almost entirely by density-driven circulation in the upper most regimes during both spring and neap tides. In addition, another  $K$ -based dispersion equation has been solved by using this spatially varying  $K$ . The spatially varying  $K$  demonstrates density-driven circulation more prominently at the strong salinity gradient location compared with a single  $K$  value.

## 1 Introduction

A general characteristic of estuaries is the presence of a horizontal density gradient, extending from the less dense riverine freshwater to the denser seawater. This horizontal density gradient is the key driving force for the estuarine circulation (Pritchard, 1952), characterizing by a seaward flow at the surface and a landward flow near the

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bottom. The dispersion should be proportional to the salinity gradient if the mixing is mostly density-driven (Savenije, 2006). In contrast, tide-driven dispersion is caused by tidal variations. Spring-neap variations in tidal shear stress may result in spring-neap variations in tidally driven mixing, stratification and gravitational circulation (Jay and Smith, 1990; Uncles and Stephens, 1996; Monismith et al., 1996; Ribeiro, et al., 2004; Savenije, 2005). Nunes Vaz et al. (1989) suggested that the weaker turbulence during neap tide, when vertical mixing is suppressed, could lead to the acceleration of gravitational circulation (density-driven circulation). Such an influence of low mixing during neap tides was noted by Jay and Smith (1990) in the Columbia River Estuary, by Warner et al. (2005) in the Hudson River Estuary and by Shaha et al. (2010) in the Sumjin River Estuary.

On the basis of the estuarine parameter  $\nu$ , Hansen and Rattray (1965, 1966) discussed which of the two mechanisms (density-driven or tide-driven) is dominant to transporting salt in a certain estuaries.  $\nu$  is the proportion of the tide-driven dispersion to the total dispersion and has widely been used to describe the relative strength of salt transport mechanisms (Hansen and Rattray, 1966; Bowden and Gilligan, 1971; Officer and Kester, 1991; Dyer, 1997; MacCready, 2004; Savenije, 2005; Valle-Levinson, 2010). West and Broyd (1981) noted that tide-driven shear mechanism dominated in narrow, shallow estuaries with a constant cross-section whereas density-driven shear mechanism dominated in wide estuaries with a funnel shaped (Smith, 1980). However, tide-driven and density-driven mixing varies along an estuary in accordance with the spring-neap tidal period and freshwater discharge. No single mechanism is solely dominated along an estuary. Tide-driven mixing is dominant mostly downstream of an estuary, a combination of the two mechanisms in the central regimes and gravitational mixing in the inner most regimes (MacCarthy, 1993; Savenije, 2006; Shaha et al., 2010).

Van der Burgh's coefficient  $K$  is another parameter used to describe the nature of salt transport mechanisms (both tide-driven and density-driven dispersion) in estuaries (Savenije, 2006). This coefficient determines the relative weight of these mechanisms.

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If  $K$  is small, then tide-driven mixing is dominant in transporting salt. If  $K$  approaches 1, gravitational circulation is dominant in transporting salt. Tide-driven dispersion dominated near the mouth of the Pungue and Maputo Estuaries (Savenije, 2005). In contrast, density-driven mixing dominated upstream from the location of the strong salinity gradient. The value of  $K$  obtained for both estuaries was 0.3, which implies only the tide-driven dispersion mechanism transported salt in the Pungue and Maputo Estuaries. In reality, two mechanisms existed along the estuaries, indicating that no single value of  $K$  can describe the nature of salt transport in estuaries, but it would vary along an estuary.

Savenije (2005) showed a solution to determine  $K (=1/\nu)$  from  $\nu$  in an estuary with a constant cross-section, following the approach of Hansen and Rattray (1965). According to Hansen and Rattray's definition, Van der Burgh's coefficient is a proportion of the total effective dispersion to the tide-driven dispersion. However, the value of  $K$  obtained from this solution ( $K \geq 1$ ) contradicts with the limits of  $K$  ( $0 < K < 1$ ), as Hansen and Rattray's relationship is derived under the assumption of a constant cross-sectional area along an estuary. However, Savenije (2005) suggested that  $K$  would not be larger than unity in an estuary with an exponentially varying width, but no solution has been reported for determining  $K$  from  $\nu$  for such types of estuary where  $K$  ranges between 0 and 1.

The main focus of this study is to determine the spatially varying Van der Burgh's coefficient  $K$  from the estuarine parameter  $\nu$  in an estuary with an exponentially varying width. The estuarine parameter  $\nu$  has been determined from longitudinal transects of salinity taken in the Sumjin River Estuary from 2004 to 2007, following the approach of Shaha et al. (2010). Thereafter, the values of  $K$  are calculated with the assumption of an exponential function to the proportion of tide-driven dispersion to the total dispersion, i.e.  $\nu$ , following the approach of McCarthy (1993).  $K$  ranges between 0 and 1 by representing both mechanisms of salt transport suggested by earlier researchers (Savenije, 1993, 2005; Eaton, 2007).

The rest of this paper is organized as follows. The study area and data sources are briefly presented in Sect. 2. The methodology is described in Sect. 3. The results are presented in Sect. 4. A discussion follows in Sect. 5, with the conclusions summarized in Sect. 6.

## 2 Study area and data

The Sumjin River Estuary is one of the few natural estuaries on the south coast of Korea. This estuary enters Gwangyang Bay, connected in the south to the coastal sea (South Sea) and in the east to Jinjoo Bay through the narrow Noryang Channel (Fig. 1). The variation in the cross-sectional areas of the Sumjin River Estuary can be approximated by an exponential function, and as a consequence the Nguyen and Savenije model (2006) provided a better result (Shaha and Cho, 2009). The climate of Korea is characterized by four distinct seasons: spring (March, April and May), summer (June, July and August), autumn (September, October and November) and winter (December, January and February). Seasonal precipitation and runoff decrease during spring and winter, but increase during summer (Bae et al., 2008). The river discharge data used in this study were from the Songjung gauge station, located about 11 km upstream from CTD (conductivity-temperature-depth) station 24 operated by the Ministry of Construction and Transportation. The maximum monthly median river discharge appeared to be higher ( $370 \text{ m}^3 \text{ s}^{-1}$ ) during July 2006 and lower ( $11 \text{ m}^3 \text{ s}^{-1}$ ) during January 2005.

Tidal constituents for Gwangyang Bay (GT2, Fig. 1) were obtained from the Korean Ocean Research and Development Institute (<http://www.kordi.re.kr/odmd/harmonic2004/>). The  $M_2$  tide is the primary tidal constituent at the river mouth. Sea level data for 2005 and 2006 from the Hadong tidal (HD) gauge station ([http://www.wamis.go.kr/wkw/WL\\_DUBWLOBS.ASPX](http://www.wamis.go.kr/wkw/WL_DUBWLOBS.ASPX)) were analyzed using the Task-2000 tidal package developed by the Proudman Oceanographic Laboratory (Bell et al., 1999). The tidal amplitudes of the  $M_2$  and  $S_2$  constituents are found to decrease to 12 and 8% within the estuary at HD, respectively (Shaha et al., 2010). The tidal cycle

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is semi-diurnal, with mean spring and neap ranges of 3.40 and 1.10 m, respectively. The tidal information (high and low tides) was collected from the Gwangyang Tidal Station (GT1) operated by the National Oceanographic Research Institute, Korea, during the field observation period.

The longitudinal transects of salinity and temperatures were carried out at high water during both spring and neap tides in each season, from August 2004 to April 2007, using a CTD profiler (Ocean Seven 304 of IDRONAUT Company). A Global Positioning System was used to obtain the locations of the CTD stations (Fig. 1). The nominal distance between the CTD stations was 1 km. Each cruise started from the estuary mouth about one and half hour before high or low waters and took approximately one and half hour to arrive at the last station when high or low waters slack occurred. The high water slack data surveyed from August 2004 to April 2007 were used in this study.

### 3 Methodology

Van der Burgh (1972) developed an empirical method on the basis of the effective tidal average dispersion under equilibrium conditions. The longitudinal variation of the effective dispersion is given as follows:

$$\frac{\partial D}{\partial x} = K \frac{Q}{A} \quad (1)$$

where  $D$  is the longitudinal dispersion coefficient,  $Q$  is the river discharge,  $A$  is the tidal average cross-sectional area and  $K$  is the dimensionless Van der Burgh's coefficient. As  $Q$  has a negative sign, the dispersion decreases upstream (Savenije, 2005).  $K$  determines the relative weights of the tide-driven and density-driven mixing mechanisms (Savenije, 2005). If  $K$  is small, then tide-driven mixing is dominant to transport salt. If  $K$  approaches 1, density-driven mixing is dominant to transport salt.

Hansen and Rattray (1965) assumed that the salinity in the central zone of a narrow estuary with a constant cross-section would decrease linearly. The tide-driven

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dispersion  $D_t$  is then given as follows (Savenije, 2005):

$$\frac{\partial D_t}{\partial x} = \frac{Q}{A} \quad (2)$$

In addition, Hansen and Rattray (1965, 1966) defined the estuarine parameter  $\nu$ , which is the proportion of the diffusive upstream salt flux associated with tidal dispersion ( $D\partial S/\partial x$ ) to the total salt flux advected seaward with the river discharge ( $SQ/A$ ) (Hansen and Rattray, 1966). As a consequence, under steady state conservation of the mass equation for salt,  $\nu$  equals the proportion of the tide-driven dispersion  $D_t (= D\partial S/\partial x)$  to the total dispersion  $D (= SU_f = SQ/A)$  (Savenije, 2005).

$$\nu = \frac{D_t}{D} \quad (3)$$

If  $\nu$  approaches 1, the upstream transport of salt is entirely dominated by tide-driven processes. If  $\nu$  is close to 0, the up-estuary salt transport is almost entirely by gravitational circulation. If  $0.1 < \nu < 0.9$ , the system experiences a contribution of both gravitational circulation and tide-driven dispersion to the upstream transport of salt (Hansen and Rattray, 1966; Bowden and Gilligan, 1971; Officer and Kester, 1991; Dyer, 1997; Savenije, 2005; Valle-Levinson, 2010). This estuarine parameter  $\nu$  was simply determined at the mouth between Narragansett Bay and the adjacent sea on the basis of the flushing rate (Officer and Kester, 1991). Shaha et al. (2010) extended that calculation between multiple segments of the Sumjin River Estuary and adjacent bay to understand the hydrodynamic characteristics along the estuary. A combination of Eqs. (2) and (3) is as follows:

$$\frac{\partial D}{\partial x} = \frac{1}{\nu} \frac{Q}{A} \quad (4)$$

Thus, Van der Burgh's coefficient  $K$  is identical to  $1/\nu$  in an estuary with a constant cross-section and linear salinity distribution (Savenije, 2005).  $K$  leads the following from Eqs. (1) and (4)

$$K = \frac{1}{\nu} \quad (5)$$

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transport in the Sumjin River Estuary. The findings of the spatially varying salt transport mechanisms, on the basis of spatially different  $K$  value, appears to be consistent with the observation of earlier researchers (McCarthy, 1993; Savenije, 1993, 2005; Eaton, 2007, Nguyen et al., 2008). However, a single value of  $K$  can not describe these mechanisms. In addition, this spatially varying  $K$  consistently supports the  $K$ -based dispersion equation given by Savenije (1993) and describes these mechanisms more reasonably compared with a single  $K$  value.

## 4 Results

### 4.1 Estuarine parameter $\nu$

The estuarine parameter  $\nu$ , proposed by Hansen and Rattray (1965, 1966), has been widely accepted for describing the nature of salt transport in estuaries (Bowden and Gilligan, 1971; Fischer et al., 1979; Officer and Kester, 1991; Dyer, 1997; Savenije, 2005; Valle-Levinson, 2010; Shaha et al., 2010). This estuarine parameter  $\nu$  was simply determined by Officer and Kester (1991) at the mouth between Narragansett Bay and the adjacent sea, using the average bay salinity on the basis of the flushing rate to understand the bay hydrodynamics. Shaha et al. (2010) extended that calculation between multiple segments of an estuary and adjacent bay to understand the hydrodynamic characteristics of the estuary. In this study, the spatially varying  $\nu$  was calculated following the approach of Shaha et al. (2010) at twelve locations along the Sumjin River Estuary during spring and neap tides. Interpolation was then performed to obtain  $\nu$  for a total of 23 locations along the estuary, as shown in Fig. 2.

The estuarine parameter  $\nu$  (Hansen-Rattray parameter) obviously illustrates which exchange process is responsible for transporting salt up-estuary (Fig. 2). The tide-driven dispersion is almost entirely dominant landward of 6 km from the mouth of the Sumjin River Estuary during spring tide where  $\nu > 0.9$ . This length also shows well consistency with the calculation of the widely accepted dimensionless stratification pa-

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parameter, which describes the nature of salt transport in estuaries (Hansen and Rattray, 1966; Prandle, 1985; Dyer, 1997; Shaha and Cho, 2009; Valle-Levinson, 2010). The stratification parameter ( $\delta S / \langle S \rangle$ ) is defined as the ratio of the top-to-bottom salinity difference  $\delta S$  to the depth mean salinity  $\langle S \rangle$ . On the basis of this parameter, well-mixed conditions are found over this length (Shaha and Cho, 2009) due to the strong tidal effects during spring tide where the upstream transport of salt is entirely dominated by tide-driven mixing and gravitational circulation ceases.

Landward from 6 to 21 km, both gravitational circulation and tide-driven dispersive fluxes contribute to transporting salt during spring tide, where  $\nu$  ranges between 0.1 and 0.9. In these central regimes, the Sumjin River Estuary shows partially stratified conditions on the basis of the stratification parameter (Shaha and Cho, 2009) and also as a function of the potential energy anomaly on the water column (Shaha et al., 2010). The amount of the potential energy in the water column increases over this length due to decreasing the tidal amplitude (Shaha et al., 2010). As a consequence, the tidal exchange and gravitational circulation are both important for transporting salt upstream in this portion. Landward from 21 km during spring tide, the gravitational flux is almost entirely dominant in transporting salt upstream, where  $\nu < 0.1$ . Savenije (1993) and Nguyen et al. (2008) also found that gravitational circulation exchange dominate in the upper most regimes.

Also during neap tide, both gravitational circulation and tide-driven dispersive fluxes are important in transporting salt from the mouth to about 20 km, where  $0.1 < \nu < 0.9$  (Fig. 2). The weaker turbulence during neap tide induces gravitational circulation by increasing the potential energy on the water column (Shaha et al., 2010), which caused strong stratification along the Sumjin River Estuary. On the basis of the stratification parameter (Shaha and Cho, 2009), strong stratification also appears during neap tide along the entire estuary. As a consequence, both tidal exchange and gravitational circulation are important in transporting salt upstream. Landward from 20 km, gravitational circulation exchange is also much more effective during neap tide, where  $\nu < 0.1$ . MacCready (2004) found  $\nu \sim 0$  at the upstream end and  $\nu \sim 0.8$  near the mouth of the

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Hudson River Estuary. The results of Savenije (1993, 2005), MacCready (2004) and Nguyen et al. (2008) are consistent with this calculation.

## 4.2 Van der Burgh's coefficient $K$

Van der Burgh's coefficient provides a solution for characterizing both salt flux mechanisms in the estuary described above. This coefficient has been calculated over the salt intrusion length of the Sumjin River Estuary using Eq. (6). The value of  $\nu$  calculated by Shaha et al. (2010) has been used to calculate the spatially varying  $K$  along this estuary. Figure 3 depicts the spatial variation of Van der Burgh's coefficient  $K$  during both spring and neap tides along the Sumjin River Estuary. This dimensionless coefficient has been scaled on the basis of the widely accepted estuarine parameter  $\nu$ . Landward of 6 km from the mouth of the estuary, the transport of salt is entirely dominated by tide-driven mixing, where  $\nu < 0.9$  (Shaha et al., 2010). Under such a condition,  $K$  is  $< 0.4$ . Upstream from this location to 21 km, both tide-driven and gravitational circulation contribute to transporting salt up-estuary, when  $\nu$  ranges between 0.1 and 0.9, and  $K$  ranges between 0.4 and 0.8. Gravitational circulation is almost entirely effective in transporting salt landward from 21 km, where  $\nu < 0.1$  and  $K > 0.8$ . The same approach has been followed for scaling  $K$  during neap tide.

A comparison of the estuarine parameter and Van der Burgh's coefficient for characterizing the nature of the transport of salt in estuaries are summarized in Table 1. The  $K$  value of 0.3 for the Maputo Estuary (Savenije, 2005), 0.25 for Flushing Bay (Eaton, 2007) and 0.3 for the Pungue Estuary (Savenije, 2005) imply that tide-driven mixing is the dominant mechanism. These values show well consistency with this scaling (Table 1). The  $K$  value of 0.5 for the Limpopo Estuary (Savenije, 2005), 0.75 for the Chao Phya Estuary (Savenije, 2005) and 0.76 for the Sumjin River Estuary (Savenije, 2005) imply that density-driven mixing is much more effective than tide-driven mixing, which also shows well consistency.

To understand the effects of river discharge on the spatially varying  $K$ ,  $K$  values for each estuarine segment were plotted against the river discharge (Fig. 4). The  $K$  values

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are almost constant (0.35) for all river discharges near the mouth during spring tide. This indicates that tide-driven dispersive flux is entirely dominated over gravitational circulation in transporting salt landward of 6 km from the mouth during spring tide, as a result of the larger tidal amplitude of the spring cycle. McCarthy (1993) reported that density-driven mixing was weak near the mouth of an exponentially varying estuary, and tide-driven exchange was dominant. On the basis of the estuarine parameter, tide-driven mixing is also dominant near the mouth during spring tide (Shaha et al., 2010). In the central regimes (SEG6~11),  $K$  depends on the freshwater discharges and ranges from 0.45 to 0.8. This implies the combined contribution of tidal exchange and gravitational circulation exchange in the central regimes (Fig. 3), where the partially stratified condition is found on the basis of the stratification parameter (Shaha and Cho, 2009) and also as a function of the potential energy anomaly (Shaha et al., 2010). In contrast, a highly significant correlation is found between  $K$  and the river discharges in segments 11 and 12, where  $K$  is  $\geq 0.8$  (Fig. 4). This indicates that gravitational circulation is much more effective in transporting salt to these segments during spring tide. Savenije (1993), McCarthy (1993) and Nguyen et al. (2008) also found that gravitational circulation was dominant mechanism upstream.

During neap tide,  $K$  also depends on the river discharges from segments 1 to 10 (Fig. 5) and ranges between 0.4 and 0.8. This indicates the combined effect of tide-driven and density-driven mixing in transporting salt landward of 19 km from the mouth during neap tide (Fig. 3). The weaker turbulence during neap tide increases the potential energy on the water column (Shaha et al., 2010), which induces density-driven circulation. As a consequence, the combined contribution of tide-driven and density-driven circulation are important in transporting salt upstream. Gravitational circulation is entirely dominant in transporting salt to segment 11 during neap tide, where  $K > 0.8$ , with a highly significant correlation between  $K$  and the river discharge (Fig. 5). Thus, gravitational circulation and tide-driven dispersive flux differ with the rate of change in the salt content for various river discharges that can be described on the basis of the spatially varying  $K$ .

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## 5 Discussion

Landward of 60 km from the mouth of the Schelde Estuary, tidal mixing is the most important mechanism due to the ebb-flood channels interaction (Savenije, 1993). In contrast, density-driven mixing is dominant upstream from 60 to 100 km. The value of  $K$  obtained in this estuary is 0.25, which only depicts the tide-driven dispersive flux of salt. In reality, both tide-driven and density-driven mixing mechanisms exist in this estuary. Therefore, one would expect a higher value of  $K$  for the inner regimes to describe the density-driven mixing mechanism. Likewise, tide-driven mixing is dominant in the wider part (downstream) of the Maputo Estuary, but density-driven mixing is dominant upstream (Savenije, 2005). The value of  $K$  in this estuary is 0.3, which also only demonstrates the tide-driven dispersion of salt. Therefore, the spatially varying  $K$  is indeed required to describe the combined effect of tide-driven and density-driven circulation in an estuary with an exponentially varying width.

Similarly, the  $K$  value of the Sumjin River Estuary is 0.76 (Shaha and Cho, 2009), indicating that gravitational circulation is the dominant mechanism. However, on the basis of the stratification parameter (Shaha and Cho, 2009), the potential energy anomaly and the estuarine parameter (Shaha et al., 2010), tide-driven mixing mechanism is dominant landward of approximately 6 km from the mouth of the Sumjin River Estuary during spring tide. Thus, this single value could not describe the salt transport mechanism downstream. When the spatially different  $K$  values are determined from Eq. (6), those values described the spatially varying salt transport mechanisms reasonably well. These findings are well consistent with the results of McCarthy (1993). He noted that tide-induced landward transport dominates near the mouth of an exponentially varying estuary, with density-driven mixing upstream. In this study, the same mechanisms of salt transport were found during spring tide, when the strong tidal currents caused vigorous mixing near the mouth. As a consequence, tide-driven mixing dominates near the mouth, but density-driven mixing dominates upstream. In contrast, the potential energy on the water column increases near the mouth during neap tide

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when vertical mixing is suppressed (Shaha et al., 2010). As a result, the combined effect of tide-driven and density-driven mixing appears near the mouth. It is interesting that the spatially varying  $K$  describes all these mechanisms of salt transport during both spring and neap tides in the Sumjin River Estuary. Therefore, it is clear that the spatially varying  $K$  is necessary to more reasonably describe the nature of salt transport along the estuary. The value of  $K$  given in Table 1 would assist in understanding the type of salt transport processes that exist along the estuary.

To be sure, the spatially varying  $K$  has also been used to solve the  $K$ -based dispersion equation for describing the relative strengths of the tide-driven and density-driven mixing mechanisms. The dispersion is the maximum near the estuary mouth, decreases in the upstream direction and becomes zero near the toe of the salt intrusion curve (Preddy, 1954; McCarthy, 1993; Savenije, 1993; Savenije, 2005; Shaha et al., 2010). As gravitational circulation is proportional to the density gradient, the dispersion diminishes with the salinity gradient, until it becomes very small near the toe of the salt intrusion curve (Savenije, 2005). Equation (7) below was suggested by Savenije (1993) to describe the combination of density-driven and tide-driven dispersion along the estuary.

$$\frac{D}{D_0} = \left( \frac{S}{S_0} \right)^K \quad (7)$$

where the subscript 0 refers to the situation at the mouth ( $x = 0$ ),  $S$  the observed salinity along the estuary and  $K$  the dimensionless Van der Burgh's coefficient, which ranges between 0 and 1. When  $K$  equals 1, the curves of  $D/D_0$  and  $S/S_0$  coincides. Equation (7) has been applied to 16 different estuaries (Savenije, 1992) and bays (Eaton, 2007) to describe the relative strength of the tide-driven and density-driven mixing mechanisms.

Equation (7) has been solved using both the spatially varying  $K$  derived from Eq. (6) and the single  $K$  value of 0.76 (Shaha and Cho, 2009) for the Sumjin River Estuary. Figure 6 depicts how the normalized dimensionless dispersion curves perform in relation

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to the observed salt intrusion curves during spring tides of winter (discharge  $19 \text{ m}^3 \text{ s}^{-1}$ ) and summer (discharge  $50 \text{ m}^3 \text{ s}^{-1}$ ) in the Sumjin River Estuary. By assumption, the total dispersion is the sum of the tide-driven and density-driven dispersions (Savenije, 2005). Although it is not very easy to exactly scale the density-driven mixing, the difference between  $D/D_0$  and  $S/S_0$  (dark-red line with blank circle for the spatially varying  $K$ , purple line with blank square for the single  $K$  of 0.76) approximately reflects the density-driven dispersion (Savenije, 1993). The tide-driven dispersion is almost constant and large landward of 6 km from the mouth, as a result of the strong tidal effects during spring tide (Fig. 4a). The density gradient is negligible over this length. This length is well consistent with the observed median tidal excursion during spring tide (Shaha and Cho, 2009). Signell and Butman (1992) noted that the tidal exchange zone extended roughly a tidal excursion from the mouth. Burchard and Hofmeister (2008) found that tide-driven exchange becomes dominant when the amount of the potential energy anomaly on the water column ranges between 0 and  $10 \text{ Jm}^{-3}$ , which is also consistent with this length (Shaha et al., 2010).

Landward from this length, density-driven dispersion gradually increases up to 18 km, but then gradually drops to zero near the toe of the salt intrusion curve (Fig. 6a, dark-red line with blank circle). As a result, density-driven dispersion becomes dominant with this rapidly declining salinity gradient. Comparing this dispersion curve with the curve of a single  $K$  value (Fig. 6a, purple line with blank square), it is clear that the spatially varying  $K$  value yields more pronounced density-driven circulation than a single  $K$  value, where the salinity gradient is strong. Thus, the spatially varying  $K$  shows well agreement with the theory (density-driven circulation becomes dominant where the salinity gradient is strong) compared to a single  $K$  value. In contrast, when the river discharge increase in summer ( $50 \text{ m}^3 \text{ s}^{-1}$ ), the tidal exchange is dominant landward of approximately 3 km from the mouth, but density-driven circulation becomes the dominant process landward from this location. In this case, the spatially varying  $K$  also demonstrates density-driven circulation more prominently compared with a single  $K$  value, where the salinity gradient is the steepest (Fig. 6b).

Figure 7 depicts how the normalized dimensionless dispersion curves perform in relation to the observed normalized salt intrusion curve during neap tides of winter (discharge  $20 \text{ m}^3 \text{ s}^{-1}$ ) and summer (discharge  $60 \text{ m}^3 \text{ s}^{-1}$ ) in the Sumjin River Estuary. Both tide-driven and density-driven dispersions are important to the transport of salt from the mouth to the toe of the salt intrusion curve. During neap tide, the vertical mixing is suppressed due to the weaker turbulence (Shaha and Cho, 2009; Shaha et al., 2010). As a consequence, the potential energy on water column increases, which could lead to the acceleration of gravitational circulation from the mouth. In winter, the spatially varying  $K$  also depicts more prominent density-driven circulation compared with a single  $K$  (Fig. 7a). However, in summer, the river discharge increase and the spatially varying  $K$  ranges between 0.67 and 0.99, with an average of 0.75. As a result, there are no significant differences in density-driven circulation between the spatially varying and single  $K$  values (Fig. 7b).

Thus, this study will enhance the application of Eq. (7) from the use of the spatially varying  $K$  determined from  $\nu$  to describe the relative strength of tide-driven and density-driven mixing mechanisms of salt transport in an estuary with an exponentially varying width, because Eq. (6) describes the mixing processes well near the mouth, in the central regimes and near the toe of the salt intrusion curve in the Sumjin River Estuary during both spring and neap tides.

## 6 Conclusions

Van der Burgh's coefficient  $K$  can be used to describe the nature of the spatially varying salt transport mechanism in estuaries.  $K$  is independent of the river discharge near the mouth under well-mixed conditions during spring tide, where tide-driven mixing is dominant with  $K < 0.4$ . However,  $K$  depends on the river discharges in the central and inner regimes under partially mixed and stratified conditions during spring and neap tides, where both tide-driven and density-driven mixing contribute to transporting salt

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up-estuary with  $0.4 < K < 0.8$ . Density-driven circulation is entirely dominant in the inner most regimes, with  $K > 0.8$ .

The spatially varying Van der Burgh's coefficient  $K$ , determined from the estuarine parameter  $\nu$  with the assumption of an exponential function, is physically appealing for the following reasons: (i) the spatially varying  $K$  can describe the spatially different tide-driven and density-driven mixing contributions along the estuary compared with a single  $K$  value. This describes the mixing processes reasonably well near the mouth, in the central regimes and near the toe of the salt intrusion curve in the Sumjin River Estuary during both spring and neap tides, which corresponds with the observations of earlier studies, and (ii) the spatially varying  $K$  also supports another  $K$ -based dispersion equation, which has been applied to 16 different estuaries and bays to describe the relative strength of the tide-driven and density-driven mixing mechanisms. Particularly, the spatially varying  $K$  demonstrates density-driven circulation conspicuously at the strong salinity gradient location compared with a single  $K$  value, which corresponds reasonably well with the theory. Thus, the spatially varying  $K$  would enhance the application of the  $K$ -based dispersion equation. However, future study is necessary to derive an exponential function mathematically.

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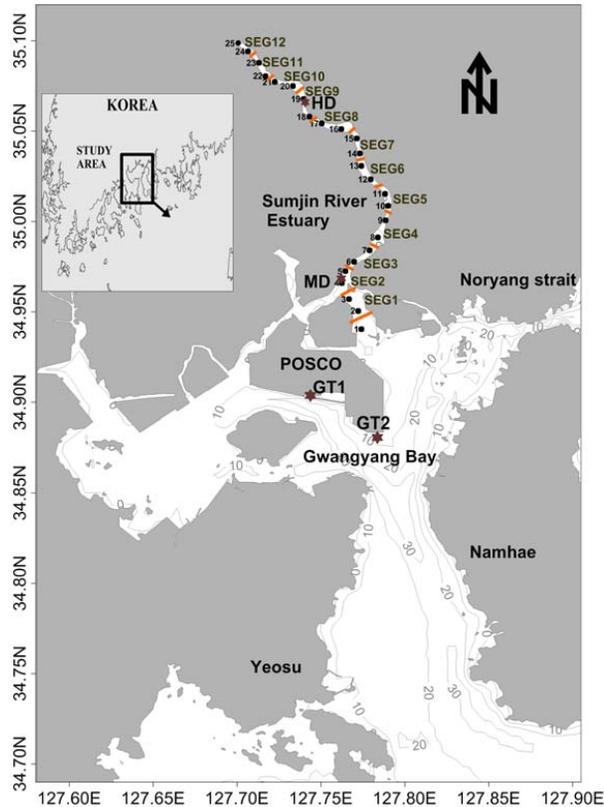
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**Fig. 1.** Map of the study area. The solid circles indicate the CTD stations. The stars denote the locations of the Gwangyang (GT), Mangdock (MD) and Hadong (HD) tidal stations. The orange solid line indicates the location of the boundary where the estuarine parameter  $\nu$  and Van der Burgh's coefficient  $K$  were calculated.

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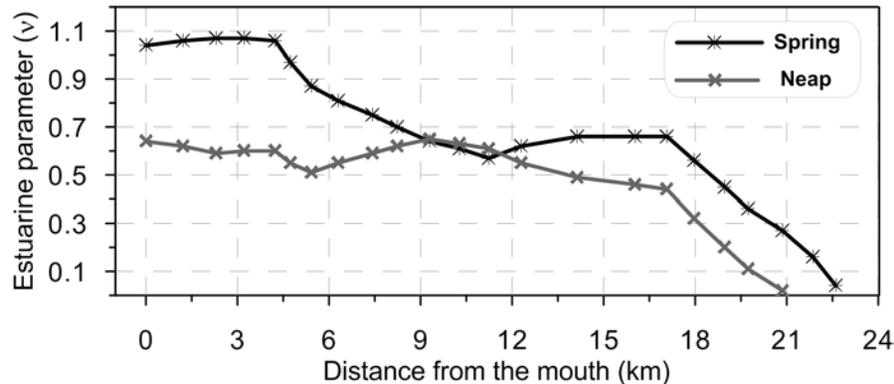
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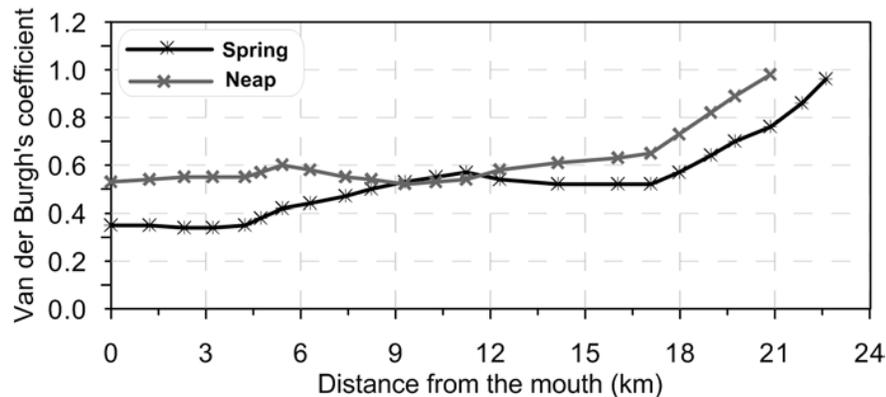


**Fig. 2.** Spatial variation of the median estuarine parameter ( $\nu$ ) during spring (a) and neap (b) tides along the Sumjin River Estuary. If  $\nu \sim 1$ , up-estuary transport of salt entirely by tide-driven mixing. If  $\nu \sim 0$ , up-estuary salt transport almost entirely by gravitational circulation. If  $0.1 < \nu < 0.9$ , both gravitational circulation and tide-driven circulation contribute to transporting salt up-estuary.

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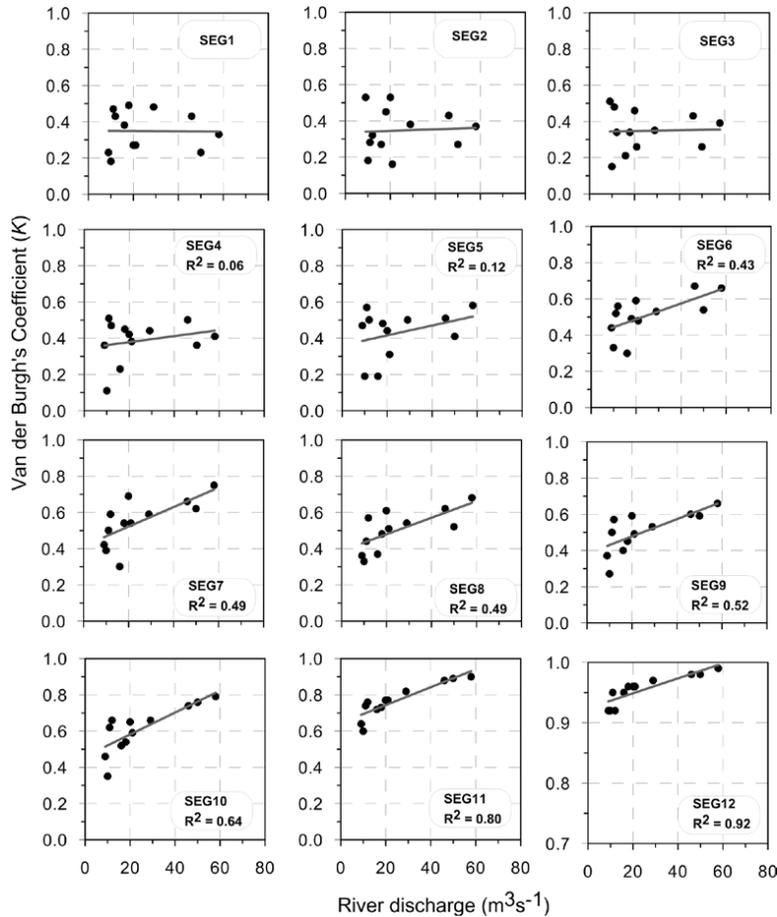


**Fig. 3.** Spatial variation of Van der Burgh's coefficient ( $K$ ) during spring (a) and neap (b) tides along the Sumjin River Estuary. If  $K < 0.4$ , up-estuary transport of salt entirely by tide-driven mixing. If  $K > 0.8$ , up-estuary salt transport almost entirely by gravitational circulation. If  $0.4 < K < 0.8$ , both gravitational circulation and tide-driven circulation contribute to transporting salt up-estuary.

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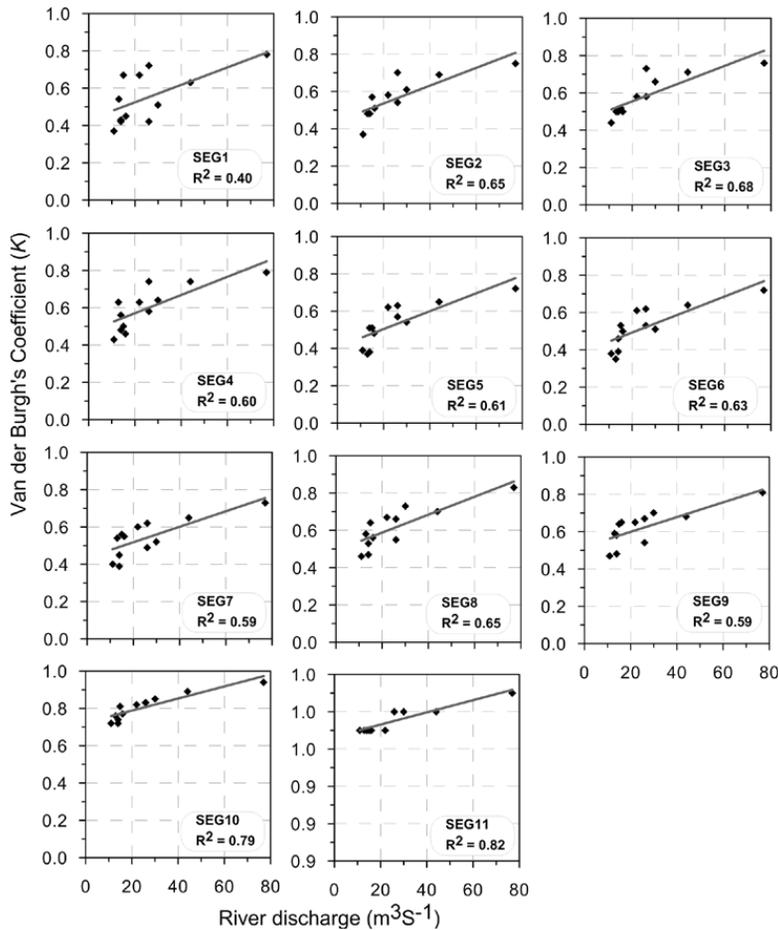
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**Fig. 4.** Plots of the dimensionless Van der Burgh's coefficient ( $K$ ) against the river discharge for various segments of the Sumjin River Estuary during spring tide.

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**Fig. 5.** Plots of the dimensionless Van der Burgh's coefficient ( $K$ ) against the river discharge for various segments of the Sumjin River Estuary during neap tide.

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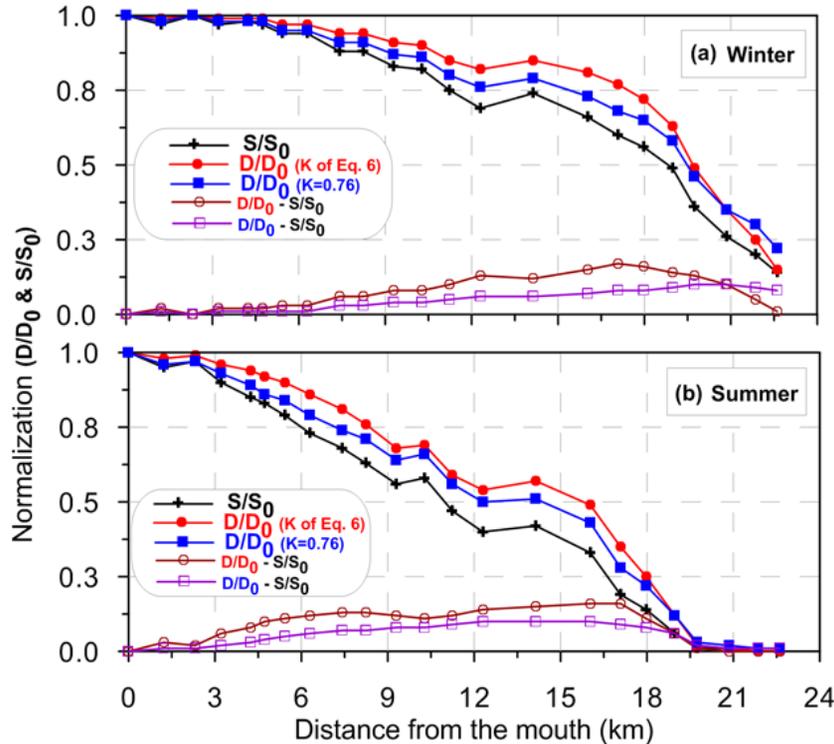


Fig. 6. Normalized dimensionless dispersion curves during spring tide of winter (discharge  $19 \text{ m}^3 \text{ s}^{-1}$ ) and summer (discharge  $50 \text{ m}^3 \text{ s}^{-1}$ ) in the Sumjin River Estuary.

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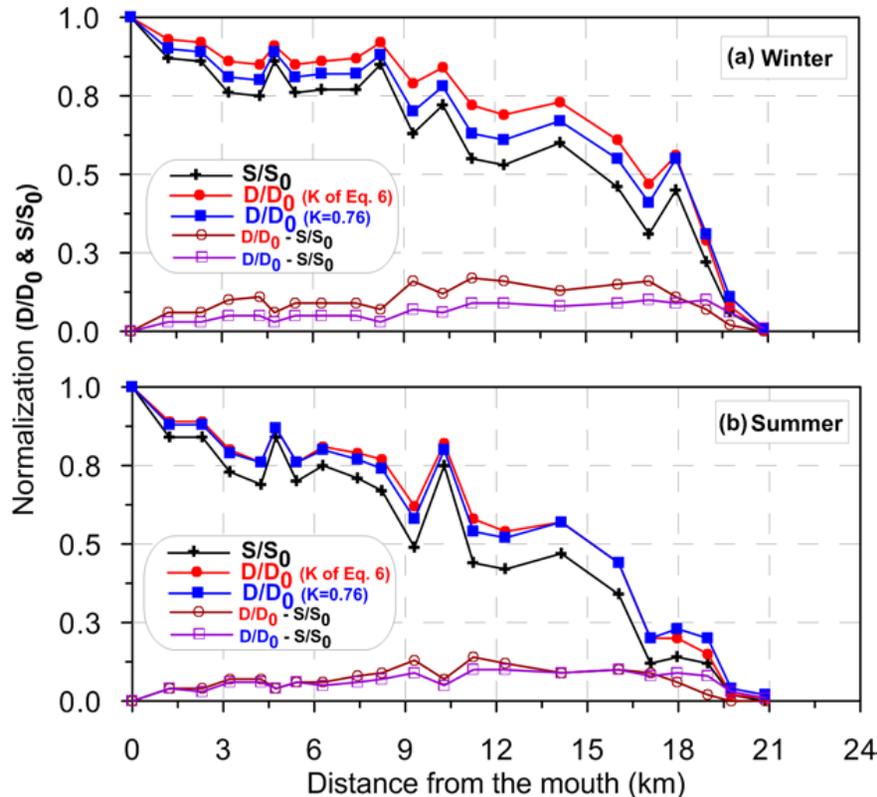
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**Fig. 7.** Normalized dimensionless dispersion curves during neap tide of winter (discharge  $20 \text{ m}^3 \text{ s}^{-1}$ ) and summer (discharge  $60 \text{ m}^3 \text{ s}^{-1}$ ) in the Sumjin River Estuary.

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