Hydrol. Earth Syst. Sci. Discuss., 3, 499–527, 2006
www.hydrol-earth-syst-sci-discuss.net/3/499/2006/

Hydrology and
Earth System
Sciences
Discussions

Salt intrusion in multi-channel estuaries: a case study in the Mekong Delta, Vietnam

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Received: 6 December 2005 – Accepted: 6 February 2006 – Published: 13 April 2006

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Abstract

There is a well-tested theory for the computation of salt intrusion in alluvial estuaries that is fully analytical and predictable, in the sense that it has well-tested analytical equations to predict the mixing behaviour of the estuary based on measurable quantities, such as channel topography, river discharge and tidal characteristics. This theory has been described in a range of publications (Savenije, 1986, 1989, 1993) and a recent book (Savenije, 2005). This theory applies to single-channel topographies and estuaries that demonstrate moderate tidal damping. The Mekong delta is a multi-channel estuary where the tide is damped due to a relatively strong river discharge (in the order of 2000 m^3/s), even during the dry season. As a result the Mekong is a strongly riverine estuary. This paper aims to test if the theory can be applied to such a riverine multi-channel estuary, and to see if possible adjustments or generalisations need to be made. The paper presents salt intrusion measurements that were done by moving boat in 2005, to which the salt intrusion model was calibrated. The theory was expanded to cater for tidal damping. Subsequently the model was validated with observations made at fixed locations over the years 1998 and 1999. Finally it was tested whether the Mekong calibration fits the overall predictive equations derived in other estuaries. The test was successful and led to a slight adjustment of the predictive equation to cater for estuaries that experience a sloping bottom.

1 Introduction

The recent book on Salt Intrusion and Tides in Alluvial Estuaries (Savenije, 2005) presents a comprehensive theory for the modelling of steady state and unsteady state salt intrusion in alluvial estuaries. It is based on the analysis of some 17 estuaries world-wide on the basis of which a general predictive theory has been developed that is claimed to be predictive, meaning that it can be applied to predict the salinity distribution in any alluvial estuary provided some basic information on topography, tide and river discharge is known. Limitations of the theory are that it has been derived for single channel estuaries and for estuaries where the tide experiences only modest damping or amplification. The Mekong Delta is an alluvial estuary that consists of many branches and that transports a large amount of fresh water to the sea, even during the dry season (in the order of 2000 m^3/s), as a result of which the tide is strongly damped and the branches of the delta are rather prolonged. This gives the Mekong estuary a clearly riverine character, putting it at the fringe of applicability of this theory.

Looking at other branched alluvial estuaries in the world, it appears that they have similar characteristics: (i) If an estuary is divided into two branches by an island, the branches are of almost equal length. (ii) There are no large differences between the branches in area, width and depth. Examples of branched estuaries are the Loire estuary in France, the Tanintharyi estuary in Myanmar, the Hau and CoChien branches of the Mekong Delta in Vietnam, the Dhamra estuary in India and the Yangtze river estuary in China (see Fig. 1)

The question now is: does the method of Savenije (2005) apply to these estuaries as well, or is there a need to extend the theory so that it can be applied to branched estuaries as well. In this paper, we shall demonstrate that the method is indeed applicable to branched estuaries but that a certain procedure needs to be followed. We also present some refinements to the method for estuaries that experience strong tidal damping or that have a prominent bottom slope.

2 Summary of the method

Savenije (2005) demonstrated that the steady state salt balance equations for High Water Slack (HWS), Low Water Slack (LWS) and Tidal Average (TA) could be written as:

$$S_i - S_f = c_i \frac{\partial S_i}{\partial x} \tag{1}$$

Where i=1,2,3 indicating the three different states: HWS, LWS and TA. S_i is the steady state salinity, S_f is the fresh water salinity. The coefficient c_i is an x-dependent coefficient defined by:

$$c_i = \frac{A}{Q_f} D_i \tag{2}$$

Where D_i (L^2T^{-1}) is the dispersion coefficient for each state i, Q_f (L^3T^{-1}) is the river discharge, which is negative since the positive x-axis points upstream, and A(L^2) is the tidal averaged cross-sectional area.

The relationship between the salinity and the dispersion coefficient, based on previous work by Van der Burgh (1972) is defined by:

$$\frac{D_i}{D_{i0}} = \left(\frac{S}{S_{i0}}\right)^K \tag{3}$$

Where K (–) is the Van der Burgh's coefficient, and D_{i0} (LT^{-2}) and S_{i0} (ML^{-3}) are the boundary conditions at the river mouth (x=0) for the HWS, LWS or TA conditions. The values of K and D_{i0} can be obtained through calibration. The relation for the dispersion, as a function of x, is:

$$\frac{D_i}{D_{i0}} = 1 - \beta_i \left(\exp\left(\frac{x}{a}\right) - 1\right) \tag{4}$$

Where:

$$\beta_i = -\frac{KaQ_f}{D_{i0}A_0} = \frac{Ka}{\alpha_{i0}A_0} \quad \text{and} \quad \alpha_{i0} = -\frac{D_{i0}}{Q_f}$$

Where A_0 (L^2) is the tidal average cross-sectional area at the estuary mouth and a (L) is the cross-sectional area convergence length.

As a result, the longitudinal variation of the salinity can be computed by the following equation:

$$\frac{S_i - S_f}{S_{i0} - S_f} = \left(\frac{D_i}{D_{i0}}\right)^{\frac{1}{K}} \tag{5}$$

The salt intrusion curve derived for the TA situation, which represents for the TA longitudinal variation of the salinity, can be used for LWS and HWS as well, by shifting the curve upstream or downstream over half the tidal excursion E.

Finally:

$$L_i = a \ln\left(\frac{1}{\beta_i} + 1\right) \tag{6}$$

Where L_i (L) is the salt intrusion length.

Condition for the derivation is that the cross-sectional area follows an exponential function, which is presented in the next section.

Because the method has been applied in 17 different estuaries all over the world, particularly for the HWS situations, it was possible to derive two predictive equations for K and D_0^{HWS} (Savenije 1993). These relations were generalised and improved by Savenije (2005) into:

$$D_0^{HWS} = 1400\frac{\bar{h}}{a}\sqrt{N_R}\,(\upsilon E) \tag{7}$$

and

$$K = 0.2 \times 10^{-3}\left(\frac{E}{H}\right)^{0.65}\left(\frac{E}{C^2}\right)^{0.39}(1-\delta b)^{-2.0}\left(\frac{b}{a}\right)^{0.58}\left(\frac{E a}{A'_0}\right)^{0.14} \tag{8}$$

Where A'_0 (L^2) is the cross-sectional area at the estuary mouth, b (L) is the width convergence length; E (L) is the tidal excursion. H (L) is the tidal range, $\bar{h}$ (L) is the constant tidal average depth along the estuary, N_R (–) is the Estuarine Richardson number given by: $N_R=\frac{\Delta\rho}{\rho}\frac{ghQ_fT}{A_0E_0\upsilon_0^2}$, T (T) is the tidal period, υ (LT^{-1}) is the tidal velocity amplitude. In ideal estuaries, the tidal range, the tidal velocity amplitude, the tidal excursion and the depth are constant along the estuary, while the convergent lengths of the width and the cross-sectional area are equal: $b=a$. In estuaries where there is a certain degree of damping or amplification, the ratio of H/E is still constant, but values of E and υ vary along the estuary. Finally if $a\neq b$ there is a bottom slope and the depth is not constant. In the Mekong estuary branches these situations apply, and subsequently procedures need to be developed to deal with such situations.

The assumption made in Eq. (1) to arrive at the steady state equation for conservation of mass, requires that in the estuary an equilibrium condition is reached between, on the one hand, advective salt transport through the downstream flushing of salt by the fresh water discharge, and on the other hand, the full range of mixing processes. Savenije (2005) proposed an expression derived for the system response time as a function of the steady state salinity distribution in order to investigate how quickly an estuary system adjusts to a new situation. If the time required for the system to adjust is not too long in relation to the variation of the boundary conditions, then a steady state model may be used. The expression reads:

$$T_s \approx -\frac{1}{Q_f S\left(L/2\right)}\int_{L/2}^{L} AS dx \tag{9}$$

Where: T_s (T) is the system response time, which represents the time required for the system to adjust itself from one steady state to another.

3 The Mekong Delta in Vietnam

3.1 Overview

The Mekong river when it enters Vietnam splits into two branches, the Bassac (known as Hau river in Vietnam) and the Mekong (known as Tien river in Vietnam). The two branches form the Mekong delta. The Hau river is the first branch of the Mekong. When the Hau approaches the sea, it splits into two branches: Tran De and Dinh An. The Tien river is the second branch of the Mekong river system. At Vinh Long, the Tien separates into two river branches: Co Chien and My Tho. At a distance of 30 km from the South China Sea, the Co Chien River again splits into two estuary branches, Co Chien and Cung Hau (see Fig. 2). Although there are more estuary branches: Tieu, Dai, Ba Lai and Ham Luong, this paper concentrates on these four estuary branches: Tran De, Dinh An, Cung Hau and Co Chien.

Tides in the South China Sea are predominantly semi-diurnal. Each day the tide has two crests and two troughs, the height of each crest and trough varies from day to day over a period of 15 days. The amplitude can be up to 3 m, while the phase lag between two troughs is half the tidal period. When one trough decreases down, the other trough increases gradually from day to day, and vice versa (Nguyen and Nguyen, 1999).

As a typical delta, the Mekong delta is affected by both river floods and the tide. In the past (before 1980), every year during the dry season, agricultural areas in the Mekong delta were affected by salinity, amounting to 1.7–2.1 million ha out of 3.5 million ha. In the 1980's and 1990's, a number of salinity control projects were implemented, leading to closure dams and sluice gates in the navigation canals connecting the branches of the delta. Nowadays, salinity affects only 0.8 million ha every year. However, the fresh water intakes along the estuary branches are usually affected by high salinity (Nguyen and Nguyen, 1999). Every year, these intakes have to be closed for considerable periods of time (from some weeks to one or two months) to prevent salt intrusion.

3.2 The shape of the Mekong Delta estuaries

The estuary branches Dinh An, Tran De, Co Chien and Cung Hau have the characteristics that we mentioned in the Introduction. We shall investigate if it is possible to combine two branches into one single branch, which would not only simplify the computation, but could also enhance the overall performance of the model. Moreover since the estuary system functions as an entity, it could very well be that the description of a branched estuary as one single branch is more in agreement with the physical laws that guide the formation of ebb and flood channels than a separate treatment.

The estuarine characteristics of the Tran De – Dinh An system and the Co Chien – Cung Hau system correspond very well with the exponential functions that follow from the concept of ideal estuaries:

$$A = A_0 \ln\left(-\frac{x}{a}\right) \tag{10}$$

$$B = B_0 \ln\left(-\frac{x}{b}\right) \tag{11}$$

and

$$h = h_0 \ln\left(\frac{x}{d}\right) \tag{12}$$

Where A (L^2), B (L) and h (L) are the area, width and depth at the location x (km) from the mouth, respectively. A_0 (L^2), B_0 (L) and h_0 (L) are the area, width and at the mouth. Finally, a (L), b (L) and d (L) are the area, width and depth convergence length, respectively. It follows that $d=(a-b)/ab$. It can be seen very clearly in Fig. 3, Fig. 4 and Table 1 that the combined estuary indeed behaves as a single estuary with a regular topography according to Eqs. (10–12).

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4 Data sets of the Mekong Delta estuaries

Salinity data of the Mekong Delta using in this paper consists of two sets: (i) The first set is from field measurements carried out by the authors during the dry season of 2005 and (ii) the second set is from data of a network of fixed stations.

The authors carried out field measurements on the Hau river in the dry season of 2005, using the “moving boat” method described by Savenije (1992). The method can be summarized as follows: A single observer in a small outboard driven boat travels with the tidal wave and measure the entire salt intrusion curve at LWS, and after finishing the LWS measurement, the observer returns to the estuary mouth and repeat the measurement for HWS. The first and second measurements were carried out at the moment of LWS and HWS on 8 April and 9 April during spring tides in the Tran De and Dinh An branches. The third and fourth measurements in the Hau river were conducted on 21 May in Tran De and on 22 May in Dinh An. The field measurements in the Co Chien and Cung Hau estuary branches were carried out on 21 and 22 April at the moments of LWS and HWS during spring tide.

The second data set is obtained from the network of fixed stations near intakes and quays, which measure salinity values during the dry season at hourly intervals.

During these measurements, we could manage to measure vertical salinity distribution at several points in the Dinh An, Tran De, Co Chien and Cung Hau branches. It appeared that these branches lie in the category of partially-mixed and well-mixed estuaries corresponding to classification of Dyer (1997, chapter 2).

River discharge and tidal data during the 2005’s field measurements provided by the Vietnamese National Hydrometeorology Services can be briefly presented in Table 2. One can see that within two successive days river discharge and tidal range variations are small, and therefore salinity variations are supposed to be small as well.

5 Salinity computation for the Mekong Delta estuaries

In this section, two approaches shall be used to compute the salinity distribution in the Mekong Delta estuaries.

The first approach considers every single branch as an individual estuary and the Savenije's method (2005) is used to determine the longitudinal salinity distribution.

Because of the similarities between the estuary branches, the second approach considers the combination of two estuary branches as a single estuary. Once again, the Savenije's method is applied under some modifications. Comparing to the first approach, the second approach offers the better results, therefore it is further validated. Finally, based on calibrated and validated results of the second approach, a predictive model for the Mekong Delta estuaries is proposed.

5.1 Approach 1: Analysis of individual branches

The first approach considers every single branch as an individual estuary (i.e. Tran De, Dinh An, Cung Hau, Co Chien). The channel topography of each estuary is shown in Table 1. Using Eqs. (4) and (5), we can compute the longitudinal variation of the salinity in every individual estuary. The calibrated results, based on measurement data of 8, 9, 21, 22 April and 21, 22 May, 2005, are presented in Fig. 5.

We can see from Fig. 5 that the Savenije's method can be used to describe the salinity distribution in the Hau river and the Co Chien-Cung Hau river. The measured data in the Dinh An estuary branch can be considered to be the best measured data out of four branches as the results of series of boat buoys that gave the authors a clear view for HWS and LWS moments. We can recognise that the mixing coefficient values of branches (α (branch) in Fig. 5), are always larger than these values of the main rivers (α (main) in Fig. 5). It is understandable that since the river discharge is split over two branches, while the tidal range remains the same, α is bigger in the individual branches than in the main channel.

We can also notice that the mixing coefficient values for the main river channels are more or less the same in all there cases: 1.55 and 1.55 for Tran De and Dinh An on 8 and 9 April; 1.21 and 1.22 for Tran De and Dinh An on 21 and 22 May; and 1.91 and 1.90 for Cung Hau and Co Chien on 21 and 22 April, 2005. It tells us that the estuary system seems to function as an entity.

One other thing we can obtain from the measurement data is that the tidal excursion, which represents the distance that a water particle travels between LWS and HWS, does not appear to be constant. The tidal excursion in the Hau and the Co Chien – Cung Hau branches corresponds very well to the exponential function, i.e. $E=E_0 \ln\left(-\frac{x}{e}\right)$ where E (L) is the tidal excursion at the location x (km) from the mouth, E_0 (L) is the tidal excursion at the mouth and e (L) is the tidal excursion convergence length. This could be because of characteristics of branch estuaries and because of the considerable large discharge even during dry seasons.

5.2 Approach 2: Combination of two branches into a single estuary

With the consideration from Sect. 5.1 that the estuary system seems to function as an entity, the second approach considers the combination of two branches as a single estuary. The combination of the Dinh An and Tran De branches is named "Combined Hau estuary" and the combination of the Co Chien and Cung Hau branches is named "Combined Co Chien-Cung Hau estuary". The channel topography of the combined estuaries is shown in Table 1. The salinity of one combined estuary is taken as a weighted mean between the cross-sectional areas of the branches. Using Eqs. (4) and (5), we can compute the longitudinal variation of the salinity in every combined estuary. The calibrated results for the combined estuaries are presented in Fig. 6.

One can see that the method can produce very good results when being applied to the second approach. The overall performance of the model is better than that of the first approach. This underlines the assumption that the estuary system functions as an entity.

For both approaches, the K values of 0.55 and 0.50 for the Hau and the CoChien-CungHau respectively are reasonable and they can be used for further computations.

The K values imply that the Hau and Co Chien estuaries are in the balance of tide driven mixing and density driven mixing mechanisms. In the Hau estuary, it seems that the density driven mixing mechanism plays a slightly bigger role because of the large fresh discharge.

5.3 Validation of Approach 2

As we mentioned in Sect. 4, in the Mekong delta, there is a network of fixed stations near intakes and quays, which measure salinity values during the dry season at hourly intervals. Unfortunately, this information is not ideal since it does not permit the direct derivation of the longitudinal distribution of the maximum and minimum salinity (i.e. salinity at LWS and HWS), partly because they are often not located near the main current (sometimes even within a canal opening or intake), and partly because of the timing. However, we shall use these maximum and minimum daily values as indicators for the HWS and LWS salinity, to validate the model.

The validated results are presented in Fig. 7 (for the combined Hau estuary) and Fig. 8 (for the combined Co Chien – Cung Hau estuary).

Generally, the model performs reasonably well, especially at HWS moments. At several stations, e.g. TraKha (4 km from the Dinh An mouth) and Hung My (12.7 km from the Co Chien mouth), the salinity values are too small and inaccurate. This is to be expected since these stations are located in the mouth of a canal or close to the river banks.

5.4 Predictive model

Based on calibrated and validated results of the second approach (see Sects. 5.2 and 5.3), we can use Eqs. (7) and (8) to turn the salinity model of the Mekong Delta into a predictive model. The values of K, obtained from calibration, are 0.55 and 0.50 for the Hau and the CoChien-CungHau respectively, which compare fairly well with predicted values of 0.42 and 0.45, which are computed by Eq. (8). Similarly, the values of D_0^{HWS}

for the Hau estuary and the Co Chien – Cung Hau estuary should be compared to Eq. (7). We notice that the calibrated values of D_0^{HWS} for the measurement described in Figs. 7 and 8 fit Eq. (7) well (see Fig. 9) if we use b (i.e. the width convergence length) instead of a (i.e. the area convergence length) and if the average depth over the salinity intrusion length is taken instead of the depth at the estuary mouth.

For the Hau estuary and the Co Chien-Cung Hau estuary, the predictive equation then reads:

$$D_0^{HWS} = 1400\frac{\overline{h}}{b}\sqrt{N_R}\,(\upsilon_0 E_0) \tag{13}$$

In Fig. 10, these results are plotted together with the estuaries presented by Savenije (2005). What we observe in Fig. 10 is that the salt intrusion lengths at HWS of the Hau and the Co Chien-Cung Hau computed by the modified predictive model using Eq. (13) and Eq. (6) (blue triangles) plot very well within the set. To permit a good comparison, the intrusion lengths in the other estuaries have also been computed using Eq. (13).

6 Discussion

One thing we have to bear in mind is that the method presented in the Sect. 5 is applied for a steady state salinity distribution. Estuaries require a certain time to adjust to changes in order to reach the steady state equilibrium. Savenije (2005) found that the system response times for different estuaries are in order of magnitude of days to months. From Eq. (9), we could compute the system response time for the Mekong estuaries. The computed system response times for the Hau estuary on 8 April, 2005 and 21 May, 2005 and the Co Chien-Cung Hau estuary on 21 April, 2005 are 7 days, 18 days and 3 days, respectively. These values indicate that the estuary system adjusts itself rather quickly to a new situation, and doesn't lag far behind an equilibrium state during the dry season. Therefore, we can use the steady state method to compute salinity distribution in the Mekong estuaries.

As we mentioned in Sect. 5.3, in the Mekong delta there is a network of fixed stations along the banks, which measure salinity values during the dry season. These stations provide hourly salinity values. Unfortunately, these values are not very adequate for the HWS-LWS method. For validation, we took the maximum and minimum daily values of the salinity at these stations and we assumed that these values are more or less close to HWS and LWS values in the same day. This assumption is rather weak because the stations are generally not located near the centre of the stream but rather in the lee, near intakes and canals.

The Van der Burgh's coefficient, K, has been taken from the calibrated process from field data in 2005. These values compare fairly well with the predictive Eq. (8). We should realise that the predictive equation for K is still rather weak and may have to be improved in the future. Therefore, the calibrated K values for the Hau and the Co Chien – Cung Hau estuaries are considered to be the most reliable ones.

There are several limitations in this study. Firstly, there is lack of updated topographical data of the Mekong Delta. The data used in this paper are obtained from the survey of 1991, when the biggest measurement campaign so far was carried out under the sponsorship of the Finnish government. Although later, the Mekong Committee developed a topographical database of the lower Mekong Delta, however this database is essentially composed of the data of 1991 with only minor modification and updates. As we know, the Mekong Delta is morphologically active and the topography is changing due to high sediment transport capacity of the river. As a result, we expect modifications in the delta topography. As a result, there still is room for improvement of the salinity model through topographical data.

Secondly, there is sensitivity of the predictive model to a number of parameters that have a certain degree of uncertainty. These are the mean estuary depth $\overline{h}$, the river discharge Q_f and the tidal excursion E_0. The estuary depth has a high impact on the predictive Eq. (13) for the dispersion at the estuary mouth (to the power 3/2). There is uncertainty in the determination of the average depth over the cross-section, particularly when (for instance in the Dinh An) there is a shallow part and a deep part, and when the estuary depth is not constant (there is a slight bottom slope). Similarly, there is an effect of a possible error in the river discharge. From existing hydrodynamic models, we derived a discharge ratio between the Hau and the Tien rivers of 53/47 of the total discharge. From updated computations (Southern Institute for Water Resources Research, Vietnam, unpublished), this ratio has been changed to 55/45 or even 60/40 as a result of the construction of inland canals and channel networks, which convey water from the Hau to the Tien river. If we take the values of 60/40, we get slighter more satisfactory results. However, compared to the influence of the average depth (power 3/2), the influence of the discharge is much less (power 1/2). Considering that the discharge can have an error in the order of 10% and the average depth in the order of 10% or more, the average depth seems to be the most important factor. Of course the average depth can also be estimated indirectly, e.g. through the analytical relations for tidal damping and wave propagation presented by Savenije (2005, 2001), Savenije and Veling (2005), but this will require additional observations of tidal damping, wave propagation and longitudinal salinity distributions. Additional field measurements are scheduled for the dry season of 2006 to improve the situation. These measurements shall be carried out on the same day for 2 branches (i.e. Dinh An and Tran De, Cung Hau and Co Chien).

7 Conclusion

In this paper, the theory for the computation of salt intrusion in single alluvial estuaries described by Savenije (2005) is for the first time applied to a multi-channel estuary, the Mekong delta, Vietnam. The Mekong Delta is a riverine multi-channel estuary with increasing depth in upstream direction and damped tidal excursion. Although the theory has not been developed for this situation, it is well applicable under some modifications. These modifications are that the average depth over the branch is used in the predictive model in stead of the depth at the estuary mouth, and that the width convergence length is used instead of the area convergence length.

In view of the similar hydraulic, topographical and salinity characteristics of the branched estuaries in the Mekong, it has been assumed that the multi-channel estuarine system functions as an entity and that two branches can be combined into a single estuary branch. This procedure has been successfully applied and tested in the Dinh An and Tran De branches (the combined estuary named the Hau estuary) and the Co Chien and Cung Hau branches (the combined estuary named the Co Chien-Cung Hau estuary).

Based on salinity measurements during the dry season of April and May 2005, an analytical model has been developed to compute the longitudinal salinity distribution (at HWS and LWS) for the combined estuaries, e.g. the Hau estuary and the Co Chien-Cung Hau estuary. The model has also been validated by data of the dry seasons in 1998 and 1999. The overall results of salinity computation indicate that the assumption of combined branches is acceptable and that the simplified method can produce satisfactory results for a complex system such as the Mekong delta.

Acknowledgements. The authors would like to acknowledge the Southern Institute for Water Resources Research (SIWRR), Ho Chi Minh City, Vietnam for their enthusiastic supports during the data collection period and the field measurement campaign. We are particularly grateful to Le Sam, Tang Duc Thang and Nguyen Van Sang (SIWRR), who have kindly provided the database of the Mekong Delta salinity, topography and hydrology.

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Table 1. Estuarine characteristics of 4 branches in the Mekong Delta.

River	Estuary	A_0 (m^2)	B_0 (m)	$\overline{h}$ (m)	H_0 (m)	a (km)	b (km)	d (km)
Hau river	Dinh An branch	18 400	3400	7.1	2.8	100	35	55
	Tran De branch	8200	1500	5.4	2.9	∞	∞	∞
	Combined Hau estuary	26 500	4900	7.5	2.85	105	51	100
Co Chien river	Co Chien branch	11 100	1600	6.0	2.1	75	75	∞
	Cung Hau branch	13 200	2500	5.3	2.1	32	31	∞
	Combined Co Chien-Cung Hau estuary	24 300	4100	6.2	2.1	65	56	400

Note: The values for the width, depth and cross-sectional area were measured at Mean Sea Level (MSL). H_0 is the tidal range at the mouth.

Table 2. River discharge and tidal range data in the Mekong estuaries.

Estuary name	Date	River discharge (m^3/s)	Tidal range (m)
Hau	08 April 2005	1064	2.89
	09 April 2005	1038	2.90
	21 May 2005	930	2.62
	22 May 2005	975	2.75
Co Chien – Cung Hau	21 April 2005	680	2.07
	22 April 2005	655	2.14

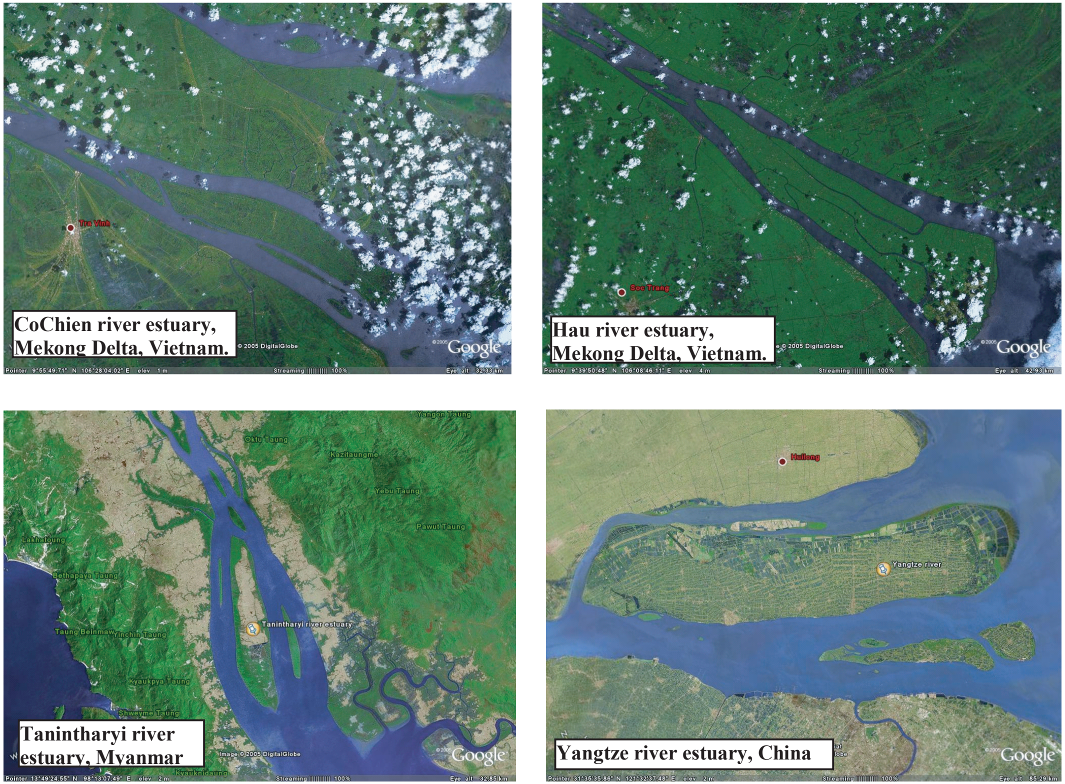

Fig. 1. Some examples of branched estuaries (source: Google Earth).

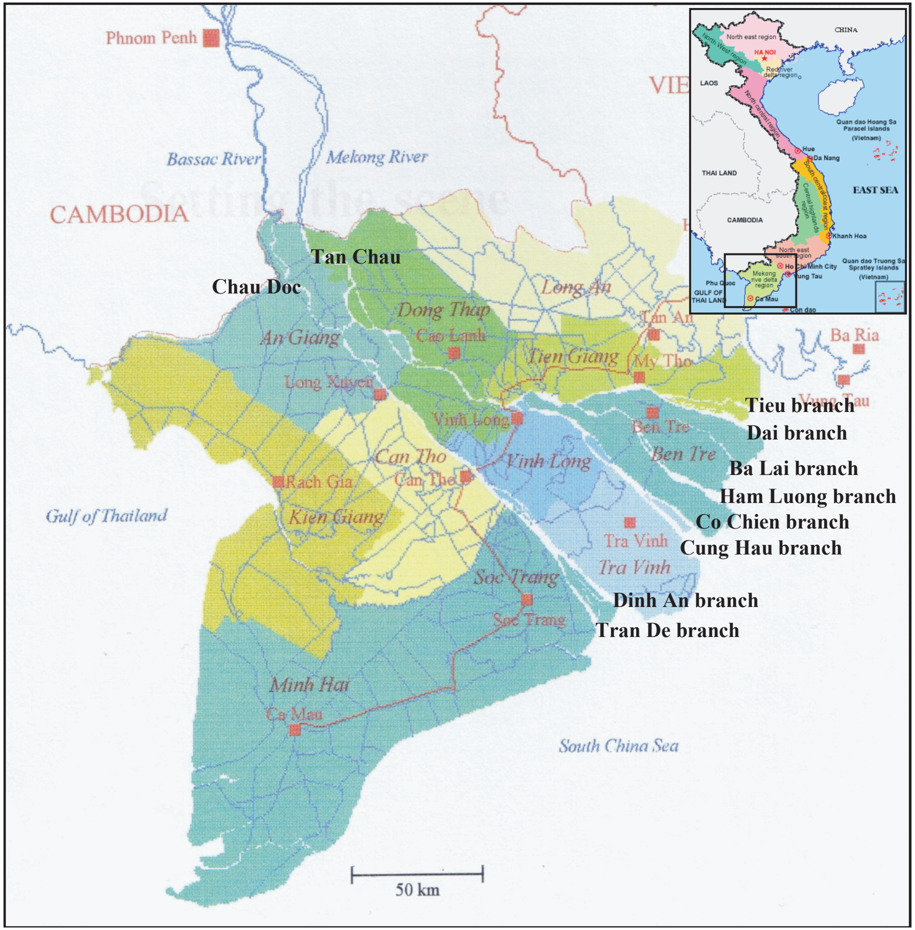

Fig. 2. The Mekong delta.

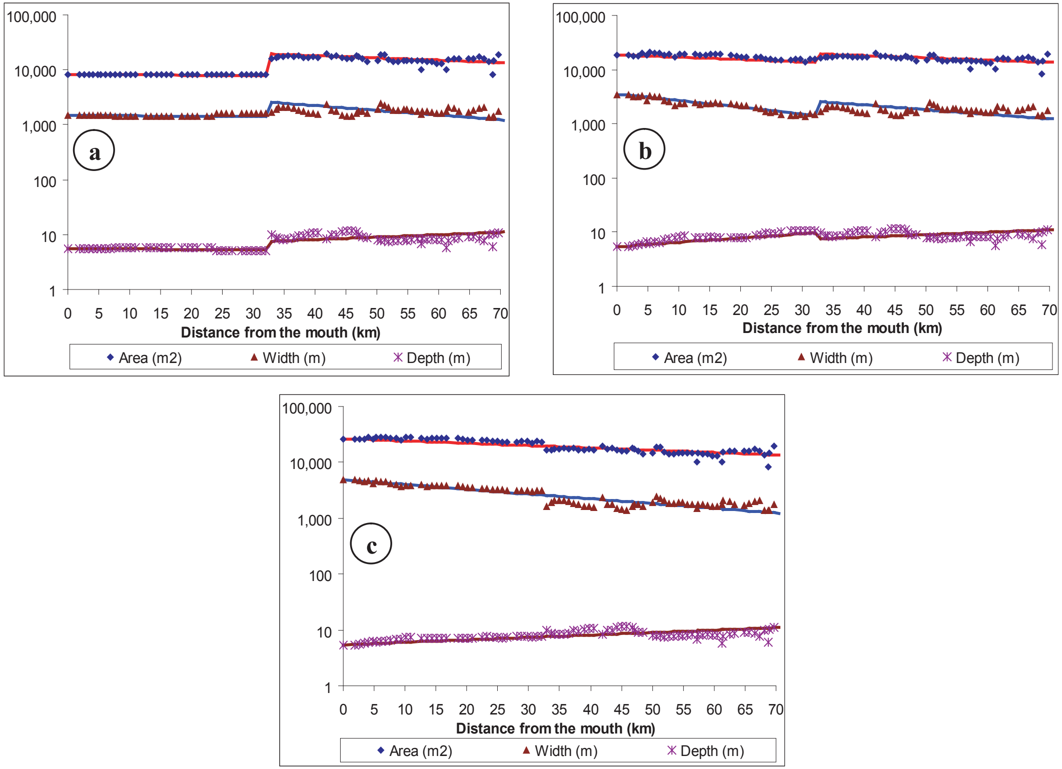

Fig. 3. Shape of the individual branches **(a)** Tran De and **(b)** Dinh An. **(c)** Shape of the Hau (combined Tran De and Dinh An) estuary, showing *A* (diamonds), *B* (triangles) and *h* (crosses).

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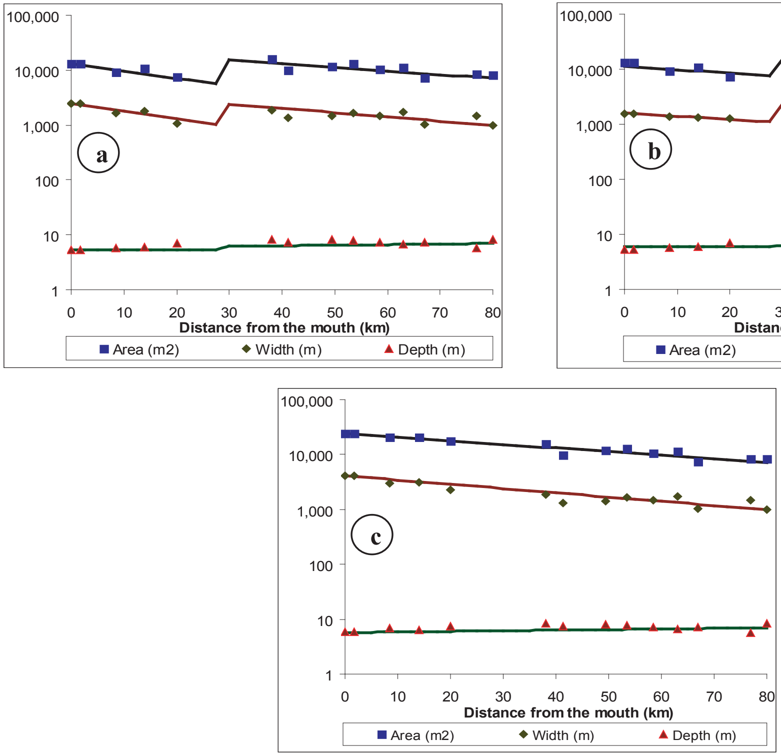

Fig. 4. Shape of the individual branches: **(a)** Cung Hau and **(b)** Co Chien. **(c)** Shape of the Co Chien – Cung Hau (combined Co Chien and Cung Hau) estuary, showing *A* (squares), *B* (diamonds) and *h* (triangles).

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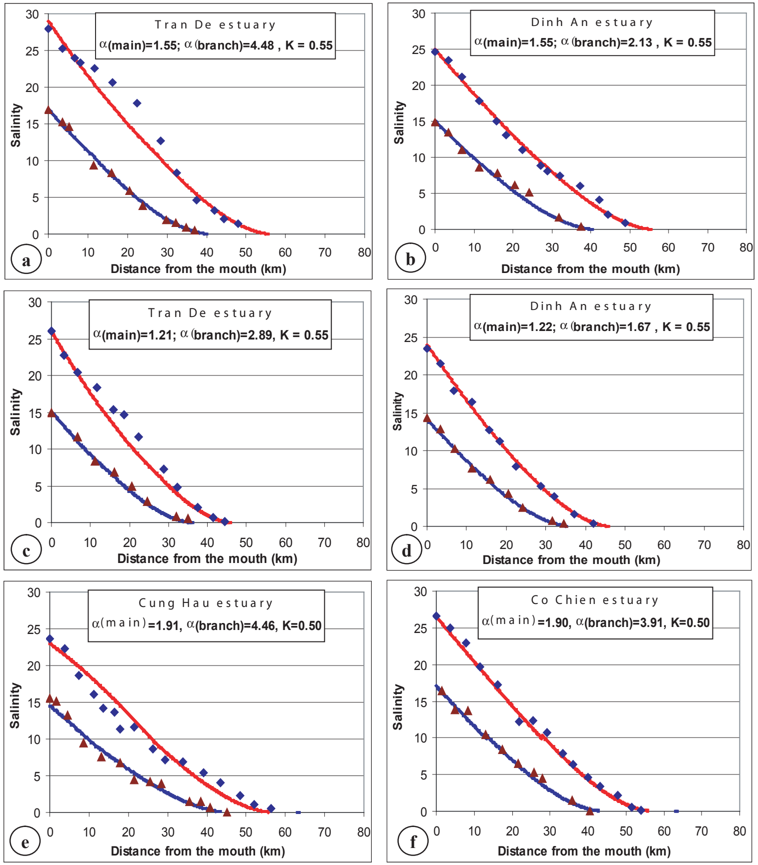

Fig. 5. Salinity distribution of individual branches: **(a)** Tran De on 8 April, **(b)** Dinh An on 9 April, **(c)** Tran De on 21 May, **(d)** Dinh An on 22 May, **(e)** Cung Hau on 21 April and **(f)** Co Chien on 22 April 2005, showing values of measured HWS (diamonds), measured LWS (triangles), calibrated HWS (red curve) and calibrated LWS (blue curve).

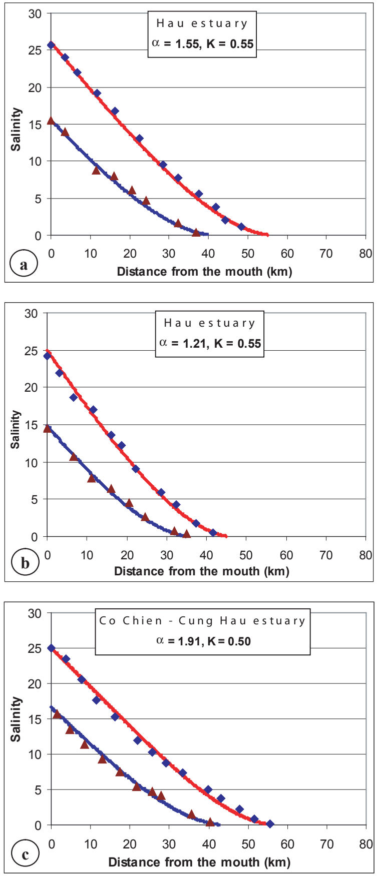

Fig. 6. Salinity distribution of **(a)** The combined Hau estuary (combination of Tran De and Dinh An branches) on 8 and 9 April, 2005; **(b)** The combined Hau estuary on 21 and 22 May, 2005; and **(c)** The combined Co Chien – Cung Hau estuary (combination of Cung Hau and Co Chien branches) on 21 and 22 April, 2005, showing values of measured HWS (diamonds), measured LWS (triangles), calibrated HWS (red curve) and calibrated LWS (blue curve).

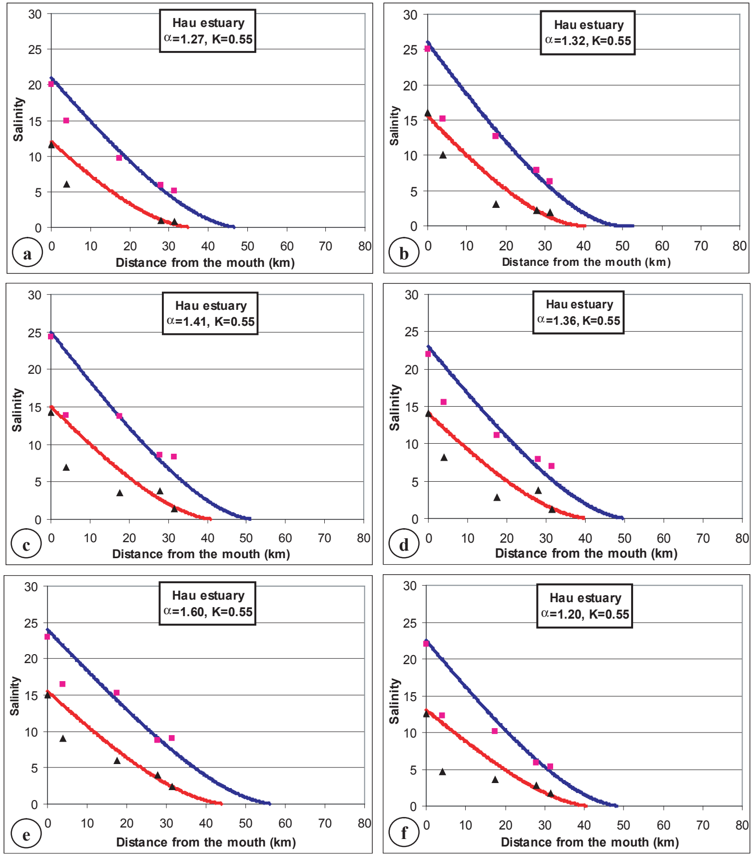

Fig. 7. Validation results of the Hau (combined Tran De and Dinh An) estuary: **(a)** on 01 March 1998; **(b)** 5 April 1998; **(c)** 7 April 1998; **(d)** 2 March 1999; **(e)** 20 March 1999 and **(f)** 16 April 1999, showing values of measured HWS (diamonds), measured LWS (triangles), calibrated HWS (blue curve) and calibrated LWS (red curve).

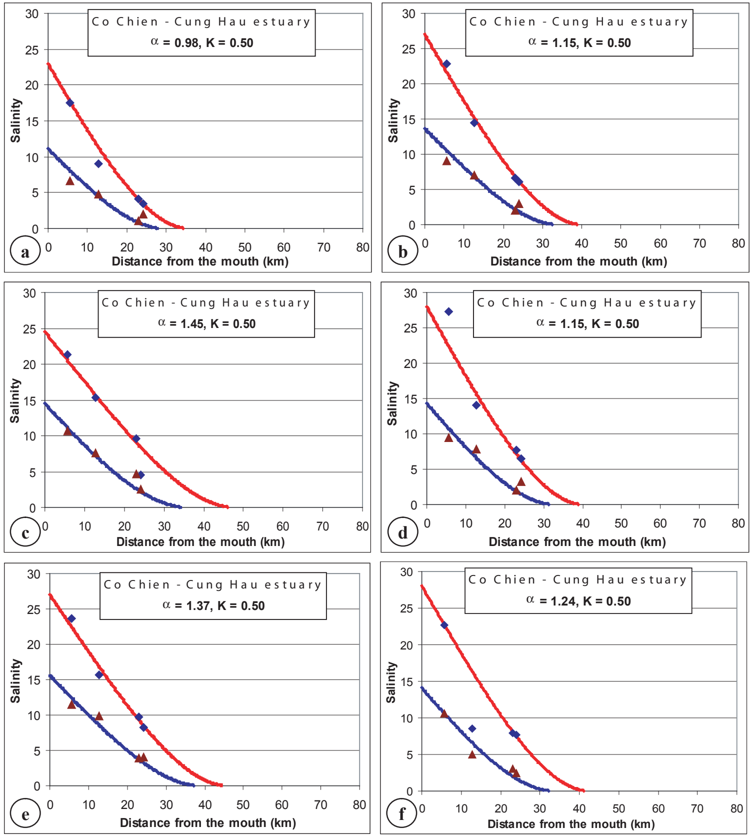

Fig. 8. Validation results of the Co Chien – Cung Hau (combined Cung Hau and Co Chien) estuary: **(a)** on 16 March 1998; **(b)** 2 April 1998; **(c)** 15 April 1998; **(d)** 2 March 1999; **(e)** 21 March 1999 and **(f)** 19 April 1999, showing values of measured HWS (diamonds), measured LWS (triangles), calibrated HWS (red curve) and calibrated LWS (blue curve).

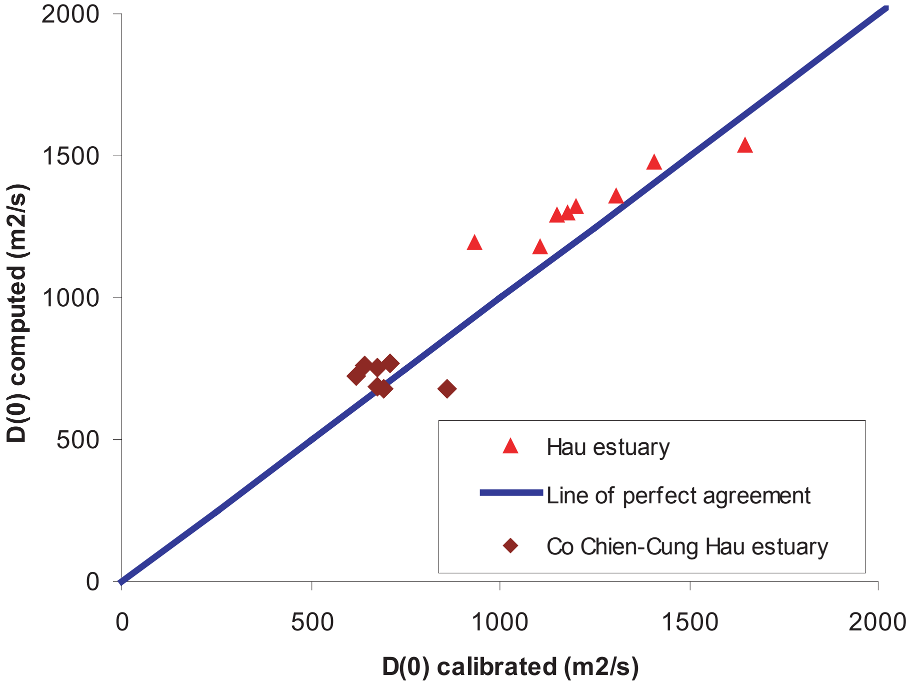

Fig. 9. Empirical relation for D_0^{HWS} for the Hau estuary and the Co Chien-Cung Hau estuary.

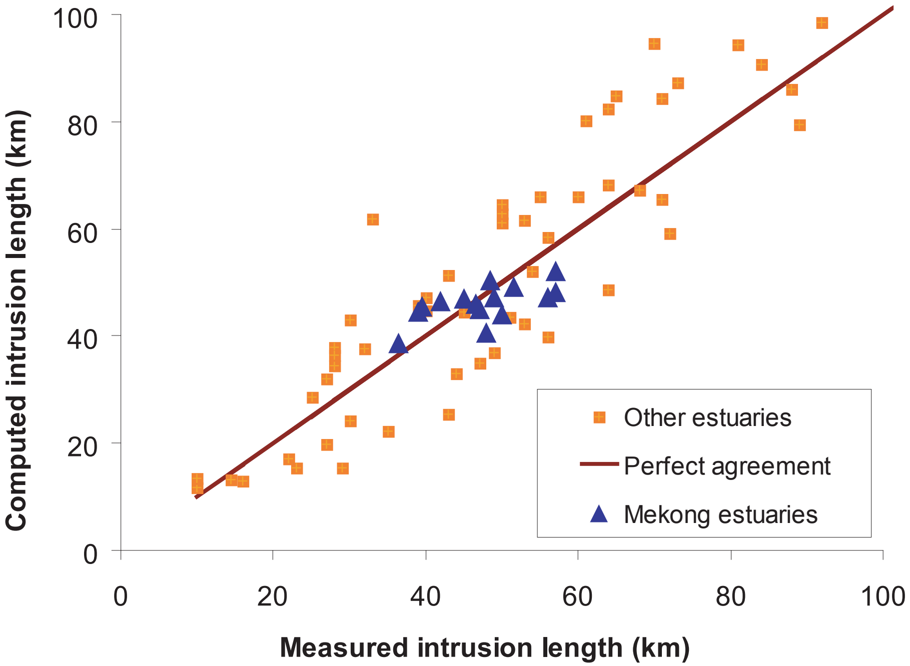

Fig. 10. Salt intrusion length at HWS according to the modified predictive model, applied to the Mekong and other estuaries described by Savenije (2005).