IMPACT OF DREDGING AND DUMPING ON THE STABILITY OF EBB-FLOOD CHANNEL SYSTEMS

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ABSTRACT: The impact of dredging and dumping activities on the morphological development of ebb-flood channel systems in an estuary is investigated by stability analysis. The same method for analysing the stability of river bifurcation's is applied. The equations describing the morphological development of the channels are extended with a source/sink term representing dredging and dumping activities. The analysis shows that a naturally stable ebb-flood channel system can become unstable and turn into a single-channel system, when the intensity of dredging-dumping activities exceeds a critical level. The critical level of the dredging and/or dumping amount is expressed as a fraction of the total sediment transport capacity of the system. If only dumping is carried out in the flood channel then the critical level is about 10% of the total transport capacity of the system. This critical level may be considered as a dumping capacity of the system and can play an important role for the manager of the estuary in planning/judging dredging and dumping activities.

1 INTRODUCTION

The Western Scheldt estuary is one of the last remaining natural estuaries in north-west Europe. An important morphological feature of the Western Scheldt is the occurrence of ebb-flood channel systems. An ebb-flood channel system consists of a ebb-dominating channel, a flood-dominating channel and in between an inter-tidal shoal. A stable multi-channel character is an important natural feature of large estuaries.

In the estuary large dredging operations are needed to maintain the shipping channel to the harbour of Antwerp. This harbour is one of the major harbours in the region and it is located about 60 km inland from the estuary mouth near Vlissingen in the Netherlands. The dredging and dumping activities have increased from less than 0.5 Mm^3/year in 1950 to over 15 Mm^3/year in the 1975 [1]. After a first deepening in the period 1970-1975, a new deepening program was negotiated between the Dutch and Belgium authorities in 1995, called the 48'/43'-deepening. This means that the minimal water depth should increase from 14,5 m to 16,0 m below N.A.P. (Dutch ordnance level ≈ mean sea level) so that large vessels can enter the harbour of Antwerp. This deepening program started in 1997 and is concentrated on the sills in the estuary. For the deepening as well as for the maintenance of the navigation channel, the deeper ebb channels are deepened by dredging, and the dredged material is

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dumped in the shallower flood channels. Questions have been raised how far the dredging-dumping activities can continue without damaging the natural multi-channel character of the estuary.

In this paper the impact of dredging and dumping activities on the morphological development of ebb-flood channel systems in an estuary is investigated by a stability analysis. The same method for analysing the stability of river bifurcations [2,3] is applied. The equations describing the morphological development of the channels are extended with a source/sink term representing the dredging dumping activities.

2 SCHEMATISATION OF A EBB-FLOOD CHANNEL SYSTEM

In the accompanying paper [4] the ebb-flood channel systems in the Western Scheldt is described in detail. It is shown that the estuary can be schematised as of a chain of morphological cells. Each of these cells is an ebb-flood channel system consisting of an ebb-channel, a flood channel and an inter-tidal flat in between. The stability of such a single cell is considered here.

The morphological development of the two channels in the system is driven by tidal flow, i.e. ebb flow as well as flood flow. During the ebb phase, the land side of the cell forms a bifurcation and the sea side of the cell forms a confluence, and during the flood phase vice versa (Fig.1). During both the ebb and the flood phase, the system looks similar to a river bifurcation case (Fig.2), or the case of two river branches with an island in between. It is important to realise that such a system has at least three physically realistic equilibrium states: one with both branches open and two with one of the branches closed. The system will tend to one of these equilibrium states, which is a stability problem.

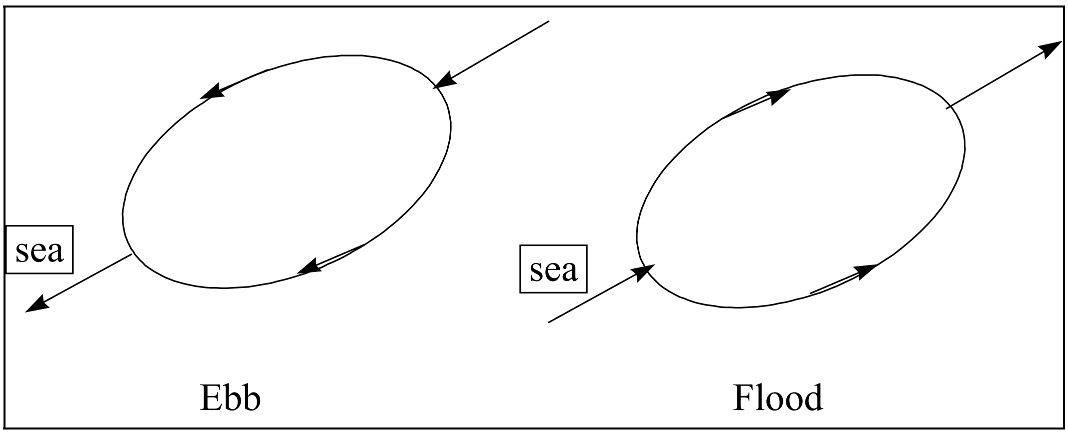

Fig.1: Sketch of a single morphological cell

For river cases this stability problem has already been analysed [3, 4]. It appears that the nodal point relation, describing the distribution of the sediment transport into the two bifurcating branches, is crucial for the stability of the bifurcation. Physically, this distribution is determined by the local three-dimensional flow situation at the bifurcation. Based on field and laboratory data, and based on the behaviour of 1D network models, the following nodal point relation is recommended [3]:

$$\frac{S_1}{S_2} = \left(\frac{B_1}{B_2}\right)^{1-k} \left(\frac{Q_1}{Q_2}\right)^{k} \quad (1)$$

Herein

S_1, S_2	=	sediment transport to branch 1 and 2,
B_1, B_2	=	widths of the two branches,
Q_1, Q_2	=	discharges through the two branches.

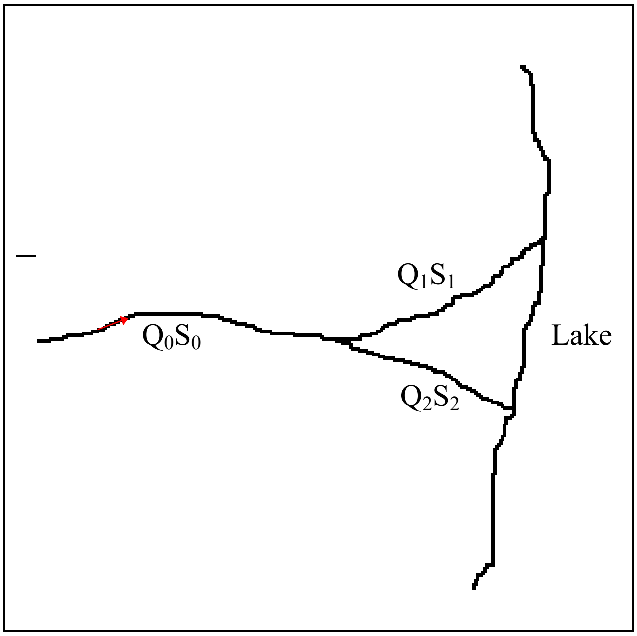

Fig.2 River bifurcation

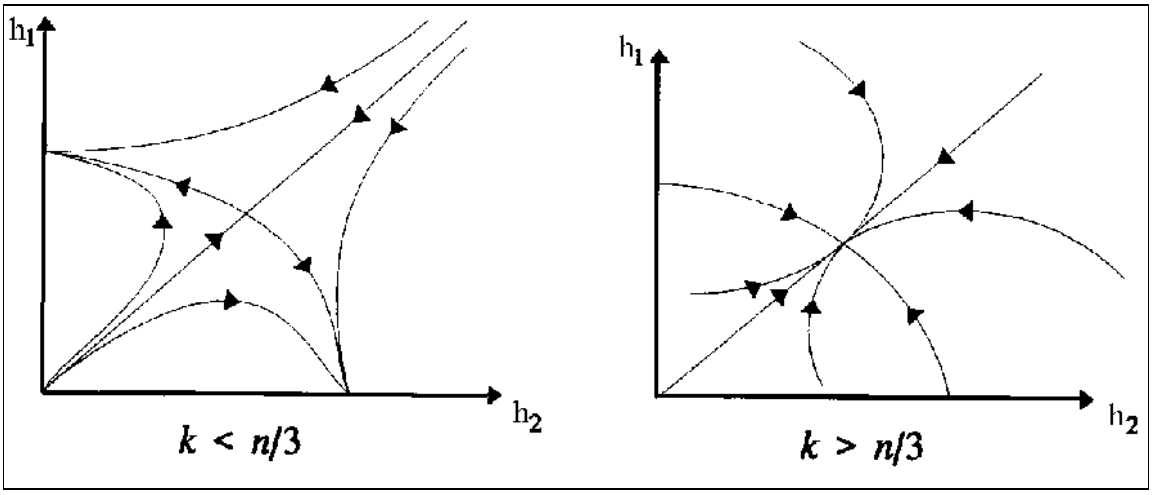

Fig.3 Phase diagram indicating the stability of the three equilibrium's
(h_1 and h_2 are the water depths of the two branches)

If Eq. (1) is used as nodal point relation the stability of the bifurcation is determined by the parameter *k.* For large values of *k* the bifurcation is stable, i.e. both branches tend to remain open. For small values of *k* the bifurcation is unstable, i.e. one of the branches tend to be closed (Fig.3). The critical value of the parameter depends on the sediment transport formula.

In case the sediment transport is proportional to power n of the flow velocity (n=5 for Engelund-Hansen) the critical value is n/3 (Fig.3). Numerical simulations with a 1D network model for an ebb-flood channel system have shown that the same conclusions also apply for the tidal flow case [5, see also 6].

In the following, the same stability analysis is repeated but then extended by taking into account the dredging and dumping activities. The objective of the analysis is to study if the dredging-dumping activities influence the stability of the multi-channel system, and if so, what is the critical level of activities turning a stable system into an unstable system. Strictly speaking, the analysis applies to the steady flow river case. To translate the conclusions to the unsteady tidal flow case, it is assumed that the total sediment transport capacity in the tidal flow system should be comparable to the transport capacity in the river case. The total sediment transport capacity through the system in equilibrium state is defined as follows:

$$S_{cap} = \frac{1}{T}\int_0^T |S_0| \,\mathrm{dt} = \frac{1}{T}\int_0^T \left(|S_1| + |S_2|\right) \mathrm{dt} \qquad (2)$$

The arguments for this assumption are that it is the sediment transport that determines morphological developments and that it is the total transport rather than the residual sediment transport that determines the stability of the system, since the ebb-flood channel can also remain stable if the residual transport through the system is zero when there is sufficient transport capacity in both channels.

3 MORPHODYNAMIC MODEL AND STABILITY ANALYSIS OF A CELL

Consider the two-channel system and take the water depth of the two channels (h_1 and h_2) as morphological state variables. The following equations apply for the mass-balance of sediment:

$$\frac{dh_1}{dt} = \frac{S_{1e} - S_{1i} - I_1}{B_1 L_1}$$
$$\frac{dh_2}{dt} = \frac{S_{2e} - S_{2i} - I_2}{B_2 L_2} \qquad (3)$$

Herein

S = sediment transport, subscript $_e$ means export at the end (the confluence side) and $_i$ means import at the upstream side (the bifurcation side),

I = interference (dumping is positive and dredging is negative),

L = length of the branches.

The import transports between the two branches are determined by the nodal point relation Eq.(1) and the continuity equation for sediment:

$$S_{i1} + S_{i2} = S_0 \qquad (4)$$

The export transports at the end of the branches are equal tot the sediment transport capacity that is dependent of the flow velocity in the corresponding branch *Q/(Bh).* The exact form of these equations depend on the applied sediment transport formula.

The discharge distribution into the two branches depends on the geometric parameters (*h, B* en *L*) en de roughness coefficient e.g. the Chezy coefficient *C*:

$$
\begin{aligned}
Q_1 &= \frac{\beta_1 h_1^{\frac{3}{2}}}{\beta_1 h_1^{\frac{3}{2}} + \beta_2 h_2^{\frac{3}{2}}} Q_0 \\
Q_2 &= \frac{\beta_1 h_2^{\frac{3}{2}}}{\beta_1 h_1^{\frac{3}{2}} + \beta_2 h_2^{\frac{3}{2}}} Q_0
\end{aligned}
\tag{5}
$$

Herein $\beta_j = B_j C_j L_j^{-1/2}$, $j=1,2$. Substituting all these equations into Eq. (3) yields a system of two first order ordinary differential equations for the variables h_1 and h_2:

$$
\begin{aligned}
\frac{dh_1}{dt} &= f_1(h_1, h_2) \\
\frac{dh_2}{dt} &= f_2(h_1, h_2)
\end{aligned}
\tag{6}
$$

The equilibrium states are represented by the combinations of h_1 and h_2 for which $f_1=f_2=0$. Mathematically, the stability of an equilibrium state is determined by the signs of the eigenvalues of the Jacobian matrix at the equilibrium point. The equilibrium is stable if both eigenvalues are negative, or if they both have negative real parts in case they are complex. Otherwise the equilibrium is unstable. For the case that the relatively simple sediment transport formula of Engelund-Hansen is applied, and without any dredging and dumping activity, the eigenvalues have been determined analytically [1]. However, for cases that a more complex sediment transport formula is chosen, or dredging and dumping activities are taken into account, the analytical solution of the stability problem is not always possible. Therefore the phase diagram is determined numerically. This is done by evaluating the functions f_1 and f_2 for a large number of combinations of h_1 and h_2. Then, with the help of a graphical presentation program, the iso-lines $f_1=0$ and $f_2=0$ are drawn. The cross-points of the two lines represent the equilibrium state of the system. The stability of these equilibrium states is indicated by depicting the direction of the vector (f_1, f_2).

As an example the impact of various dredging and dumping scenario's on the stability of a particular system is shown in Fig.4 through Fig.8. Figure 4 depicts the basic case, i.e. without any dredging or dumping. It concerns a symmetric case: both channels have a length of 10 km and a width of 1250 m. The sediment transport formula of Engelund-Hansen is used. The hydrodynamic and sediment transport parameters are chosen such that the equilibrium water depth in the two branches is 22 m for the case that both branches are open. The used *k* value for the nodal point relation (Eq.1) is 2.2. The numerical phase diagram (Fig.4) shows that the equilibrium state with both branches open is stable and the other two equilibrium states are unstable, which is in agreement with analytical results.

Figure 5 shows the case in which 5% of the total sediment transport capacity of the system is dumped in branch 2. As can be be observed from the phase diagram, there are now 4 equilibrium states. Compared with the basic case there is now an extra equilibrium state with both branches open. This extra equilibrium is unstable. The old equilibrium with both branches open is moved such that branch 2 becomes shallower, but it remains stable. The equilibrium with only branch 2 open remains unstable, but the one with only branch 1 open becomes now stable. If the initial state is the old equilibrium, with both branches open, the system will develop to the stable equilibrium with both branches open. This means that the two channel system will be preserved, i.e. the critical level of interference is not reached yet.

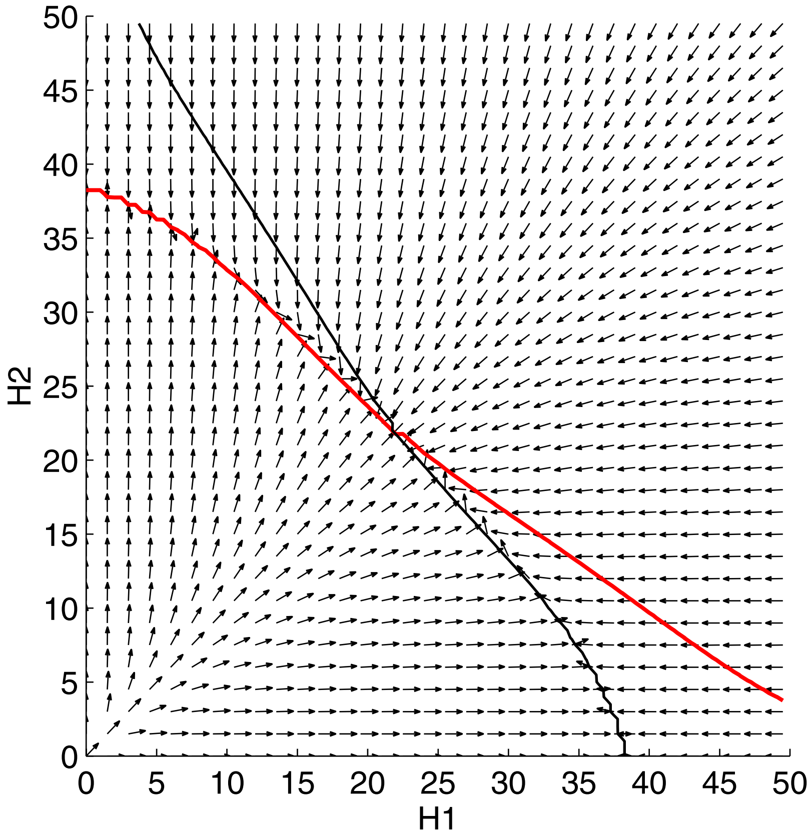

Fig.4 No interference

Figure 6 shows the case that 10% of the total transport capacity is dumped in branch 2. Now there are only two equilibrium states left, both with only one branch open. There is no more equilibrium with both branches open. This means that branch 2 will be closed and only branch 1 will remain open. The originally two-channel system will turn into a single channel system. Apparently 10% dumping will exceed the critical level of interference.

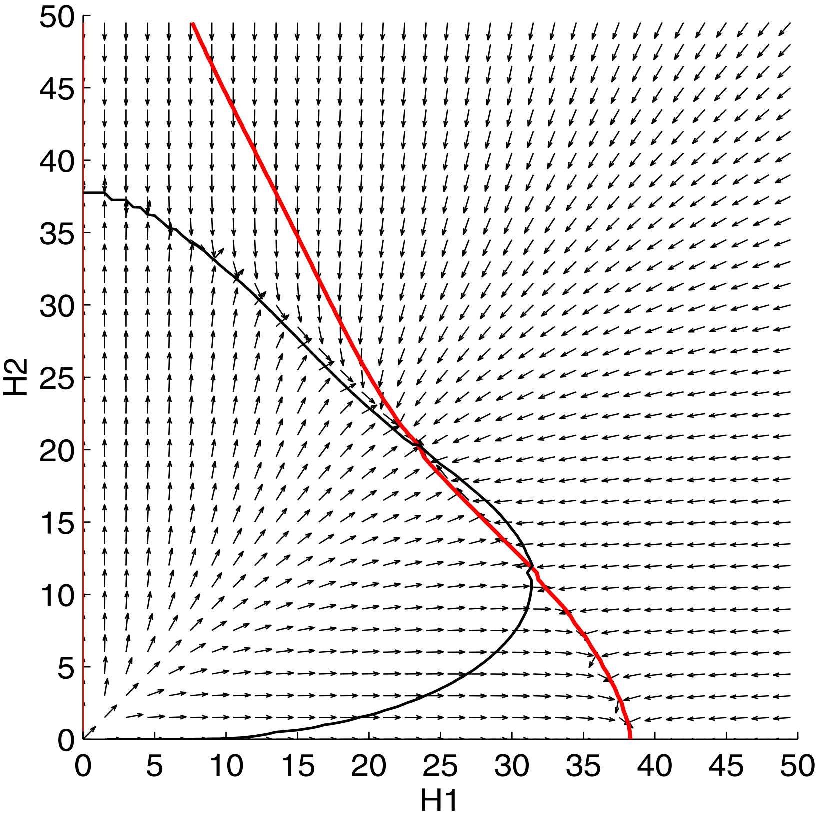

Fig.5 The same as Fig.4, but with 5% dumping in branch 2

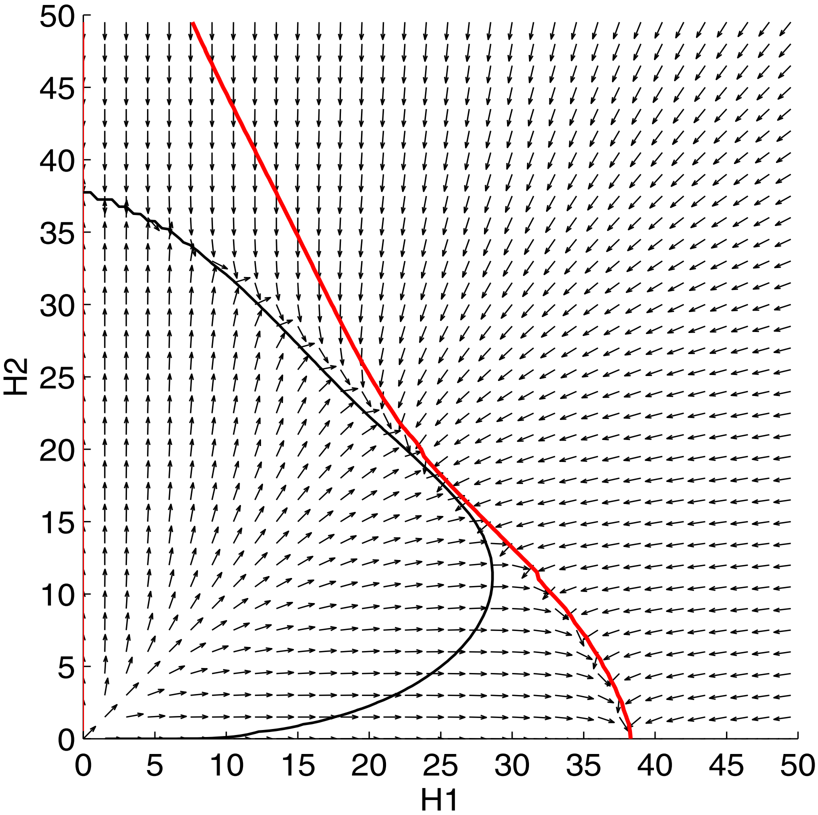

Fig.6 10% dumping in branch 2

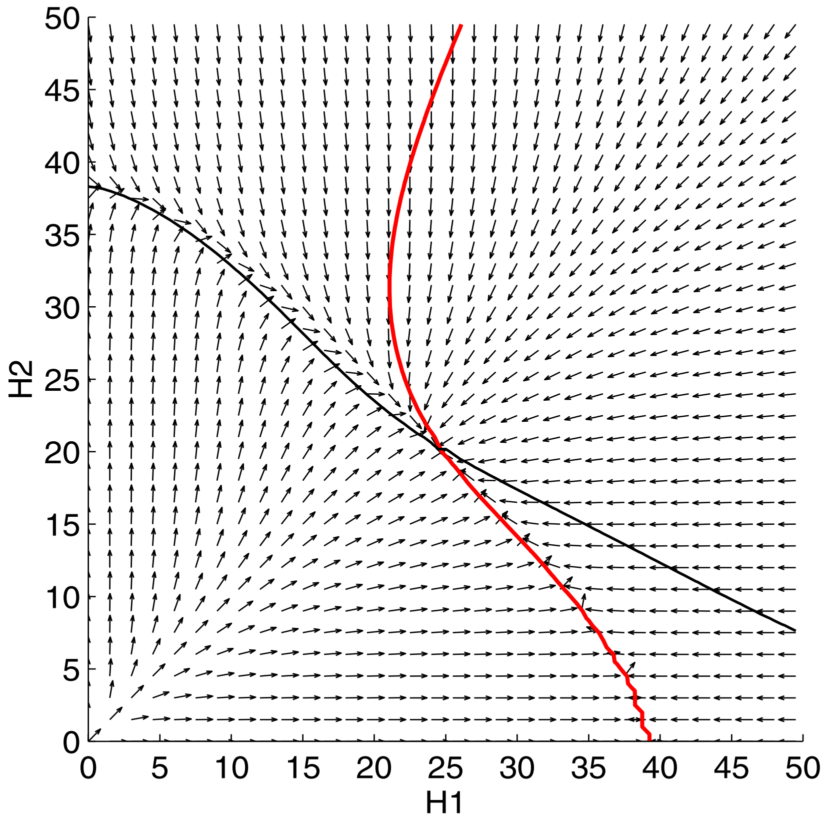

Fig.7 10% dredging in branch 1

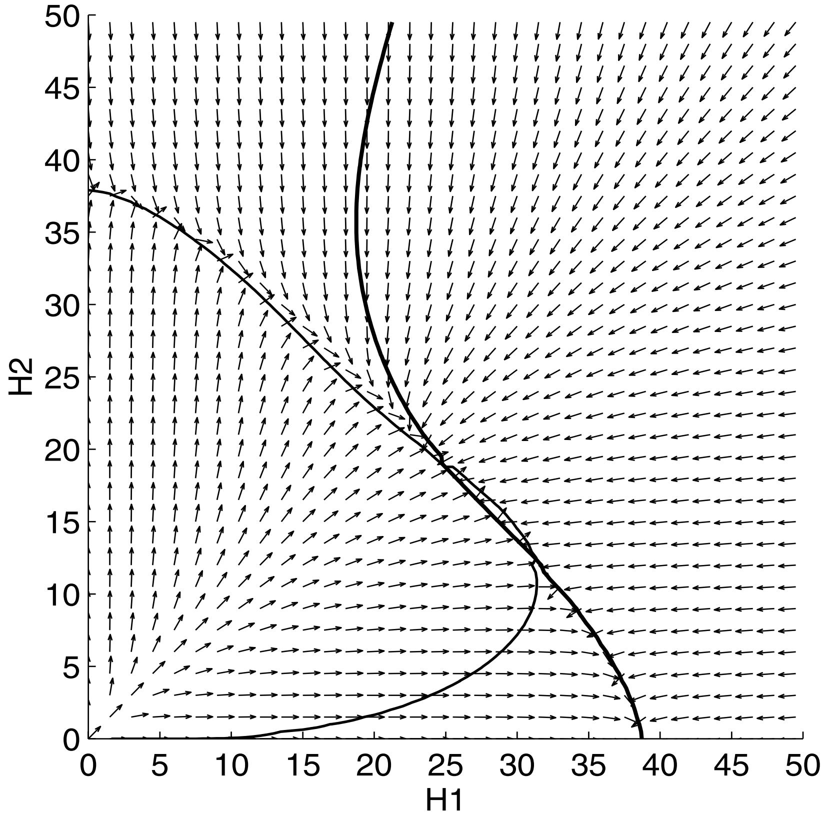

Fig.8 5% dumping in branch 2 and 5% dredging in branch 1

Figure 7 shows the case that 10% of the total transport capacity is dredged in branch 1. In contrast to the case of dumping (Fig.6) the phase diagram shows the same behaviour as the basic case (Fig.4). The equilibrium with both branches open remains stable. Only its position is moved. Apparently dredging alone does not influence the stability of the two-channel system. However, dredging combined with dumping in another branch does influence the stability of the system, as shown in Fig.8. Compared with Fig.5, it is clear that, in combination with 5% of the transport capacity dredging in the other channel, the 5% dumping brings the system closer to the limit of instability than dumping of 5% alone.

A disadvantage of the numerical approach, as presented in this example, is that the results do not give decisive conclusions about the general case. The conclusions may change if the geometric, hydrodynamic and sediment transport parameters change. However, the results of a series of many numerical experiments show the following consistent conclusions:

- Dumping influences the stability of a two-channel system. There is a critical level for the amount of dumping, above which the two channel-system becomes unstable.
- The critical level of dumping in one of the branches is about 10% of the total transport capacity of the system. Of course, the exact figure of this critical level depends on the particular situation and the parameters used in the model (especially the value of k). However, the discrepancies are small compared to e.g. errors in the dredging and dumping data, so for the application purposes it is sufficient to consider this 10% as the critical level.
- Also when its amount is below the critical level, dumping has influence on the behaviour of a two-channel system. First, the stable equilibrium with both branches open will change due to dumping. Second, the single-channel equilibrium, with the branch where sediment is dumped is closed, becomes stable instead of unstable.
- Dredging alone in one of the branches does not influence the stability behaviour of the two-channel system. However, in combination with dumping in the other branch it does have a negative influence on the stability of the two-channel system. In the worst case it can halve the critical level of the dumping amount, i.e. it becomes 5% instead of 10% of the total transport capacity.

4 DISCUSSION AND CONCLUSIONS

The stability analysis of the two channel system under influence of dredging and dumping shows that a naturally stable ebb-flood system can become unstable and tends to turn into a single-channel system, when the intensity of the dredging-dumping activities exceeds a critical level. As the multi-channel character of an estuary like the Western Scheldt is considered to be very important for the various management aspects of the estuary, this critical level is of great practical importance for the manager of the estuary in planning and judging dredging and dumping activities. For this reason the conclusion drawn from the presented analysis requires verification using field data.

Analysis of the historical data on the dredging-dumping activities and morphological development show indeed that channels receive too much dumping for a long time indeed tend to be closed [4]. In practice this means that dumping in such a channel then becomes impossible. Comparing the observed critical level of dredging and dumping with the calculated total sediment transport capacity using a 2DH model based on Delft3D-MOR shows that the 10% criterion derived from the analysis is a good estimate for the critical level of dumping intensity.

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