Noel Carbajal · Stephanie Piney · Jorge Gómez Rivera

A numerical study on the influence of geometry on the formation of sandbanks

Abstract Applying a two-dimensional, non-linear hydrodynamic numerical model in combination with a semiempirical equation for bedload sediment transport, the influence of geometry on the formation of sandbanks is investigated. In the first experiment, the formation of sandbanks in an ideal rectangular basin, resembling the Taylor's problem, was calculated. Sandbanks occur in a small area at the closed boundary. Similar experiments were carried out for a range of wavelengths of the incident Kelvin wave. The results reveal that large wavelengths favor the generation of sandbanks. In subsequent calculations, the basin was modified by introducing new geographical features like bays and peninsulas. The numerical experiments show that geometry is a fundamental factor to determine the position where groups of sandbanks appear. The results suggest that in regions where the Kelvin wave is diffracted, the formation of sandbanks occurs. An experiment, in which we applied an ideal geometric configuration representing that of the Southern Bight of the North Sea, generated sandbank patterns resembling those observed in the region.

Keywords Numerical modeling · Tides · Sandbanks · Taylor's problem

N. Carbajal (✉) · J. G. Rivera
Instituto Potosino de Investigación Científica y Tecnológica, Apdo Postal 3-74, Tangamanga, 78231 San Luis Potosí S L P, Mexico
E-mail: noelc@ipicyt.edu.mx
Tel.: +52-444-8335411
Fax: +52-444-8335412

S. Piney
Département de Génie Energétique et Environnement Domaine Scientifique de la Doua, Institut National des sciences Appliquées, Bâtiment Sadi Carnot 9, rue de la Physique, 69 100 Villeurbanne, France

1 Introduction

Quasi-periodic bed forms, often called linear sandbanks (Huthnance 1982) or sand ridges (Pattiaratchi and Collins 1987), have been observed in shelf seas like the North Sea, Colorado River Delta, Persian Gulf and Gulf of Korea among others (Off 1963; Carbajal and Montaño 2001). Sufficient sand availability and strong enough hydrodynamic processes are necessary to transport the sediments. To initiate the bedload transport of sediments, the flow should reach a critical velocity value of approximately 0.3 m/s. Sandbanks occur in a wide range of water depths, in mouths of estuaries, in the neighborhood of headlands and bays and in general on shelf regions. The analysis of physical features suggests that linear sandbanks originate in tide-dominated sea regions. Sand ridges are also observed in storm-dominated marine zones. Shoreface-connected ridges belong to a special class of sand ridges. They seem to be present in seas where tides and storms are both important (Van de Meene and van Rijn 2000a, b). Examples of shoreface-connected ridges are found along the Dutch coast in the North Sea. Important morphological properties of sandbanks in tide-dominated regions differ from that of sand ridges in storm-dominated areas. The orientation of tide-generated sandbanks is in direct dependence on the principal direction of tidal currents. The orientation of sand ridges is related to the coastline course. Tidal sandbanks are large, since they are up to 80 km long and reach heights of about 40 m and typical widths of several kilometers. Observed heights of sand ridges vary between 3 and 12 m and have lengths of about 20 km. The problem of understanding the origin, formation and maintenance of sandbanks is caused by the complexity of the processes occurring on the continental shelf and by the confusion of considering only the hydrodynamic context and not taking into account the geological origin and development (Dyer and Huntley 1999). From current measurements, important information can be obtained on the mechanisms associated to sandbank formation (Pattiaratchi and Harris 2002).

The morphodynamics of these bed forms has received much attention. There are a variety of theories and models that explain the formation of sandbanks and ridges. Two kinds of mathematical models can be distinguished: bed-instability models which describe the formation of sandbanks as a result of the interaction between tidal currents and the sea bottom (Van de Meene and van Rijn 2000a, b). Due to its periodicity, sandbanks can be interpreted as a kind of bed-form-free instability of a dynamic morphological system in which currents and sea bottom interact leading to the formation and evolution of the sandbanks (Hulscher et al. 1993). Huthnance (1982) was the first to explore this approach. His theory predicts the formation of sandbanks. Applying a morphological model which describes the interaction between a tidal flow and a sea bottom with sand availability, Hulscher et al. (1993) extended the theory to the estimation of sandbanks and sand waves. The scales of sandbanks observed in the Colorado River Delta and in other sea regions were explained satisfactorily applying Hulscher's theory (Carbajal and Montaño 1999, 2001). The application of a three-dimensional shallow water model, i.e., the inclusion of the vertical flow structure, allowed covering the formation of all existing scales of regular bed forms (Hulscher 1995). Walgreen (1999) studied the formation of shore-face-connected sand ridges. The morphological models simulate the evolution of sandbanks by calculating the sediment transport rates. Boczar-Karakiewicz and Bona (1986) explain the genesis of ridges with infragravity waves. Signell and Harris (1999) studied numerically the formation of sandbanks around headlands. The numerical modeling of the transport of sediments has been the subject of many investigations (Clark and Elliott 1998; Montaño 2003; Van de Meene and van Rijn 2000a, b; Zhu and Chang 2000).

The extension of Taylor's problem to the transport of sediments has been recently investigated in several research works. Applying different approaches, interesting aspects of transport of sediments could be studied. Mulder (2002) investigated the large-scale morphodynamics in an ideal rectangular basin representing the Southern Bight of the North Sea. His grid spacing of 9 km allowed calculating the transport of sediments for thousands of years. Erosion and accretion areas were generated along the basin. However, the instabilities leading to the formation of sandbanks could not be resolved. Van der Molen et al. (2004) carried out numerical simulations of transport of sediments for an ideal rectangular basin. They put emphasis on the seabed evolution at a basin scale, i.e., at a scale of hundreds of kilometers. Basically, they found two fundamental processes; a volume balance reveals a consistent deepening of the basin, i.e., it exports sediment. Secondly, the basin evolved to alternate accretion and erosion regions. The applied methodology of separating the hydrodynamic and morphodynamic processes allowed time steps of 100 years. They simulated the seabed evolution in geological time scales of 454,000 years. However, the more realistic non-linear interaction between flow and morphology at every time step was not considered. Gómez-Rivera (2003) investigated the Taylor's problem and the transport of sediments. The applied grid spacing allowed resolving the formation of sandbanks caused by this fundamental tidal flow. In this research work, a two-dimensional, non-linear hydrodynamic numerical model (Montaño 2003) in combination with a semiempirical equation for the bedload sediment transport is applied to study the influence of geometry on the formation of sandbanks.

2 The model

The model has been applied to study tides in the Gulf of California (Carbajal and Backhaus 1998), the transport of sediments in the Colorado River Delta (Montaño 2003) and to investigate the dynamics in coastal lagoons (Nuñes-Riboni 2002). We applied the vertically integrated equations of motion

$$
\begin{aligned}
\frac{\partial U}{\partial t} &+ \frac{U}{(H+\zeta)}\frac{\partial U}{\partial x} + \frac{V}{(H+\zeta)}\frac{\partial U}{\partial y} - fV \\
&= -g(H+\zeta)\frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial x}\left(A_H\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial U}{\partial y}\right) \\
&\quad - r\frac{U}{(H+\zeta)^2}\sqrt{U^2+V^2},
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\frac{\partial V}{\partial t} &+ \frac{U}{(H+\zeta)}\frac{\partial V}{\partial x} + \frac{V}{(H+\zeta)}\frac{\partial V}{\partial y} + fU \\
&= -g(H+\zeta)\frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial x}\left(A_H\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial V}{\partial y}\right) \\
&\quad - r\frac{V}{(H+\zeta)^2}\sqrt{U^2+V^2},
\end{aligned}
\tag{2}
$$

the equation of continuity

$$
\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0
\tag{3}
$$

and a conservation equation for the sediments

$$
\frac{\partial H}{\partial t} + \nabla \cdot \mathbf{S} = 0,
\tag{4}
$$

where

$$
\mathbf{S} = \alpha \frac{|\mathbf{v}|^b}{u_c^b}\left(\frac{\mathbf{v}}{|\mathbf{v}|} - k_*\nabla H\right)
\tag{5}
$$

is the volumetric sediment flux (m^2/s). In this system of equations, U and V (m^2/s) are the transports in the x and y directions, respectively, $\mathbf{v}$ the vector velocity (m/s), t the time (s), g the gravitational acceleration (m/s^2), H the water depth (m), ζ the sea surface elevation (m), $f = 2\Omega \sin\phi$ the Coriolis parameter (s^{-1}), Ω the angular velocity of the Earth (s^{-1}), ϕ the latitude, A_H the horizontal coefficient of eddy viscosity (m^2/s), $\alpha = 10^{-6}$ (m^2/s) a function of the sediment properties, $b = 3.0$ the potency

of the transport, $u_c = 0.3$ (m/s) the critical velocity for erosion and $k_* = 2.0$ a coefficient for the bed slope correction.

At the open boundary, the sea surface elevation is given by

$$\zeta(x, y, t) = A \cos (\omega t - \Phi),$$

where ω is the angular frequency of the tidal component. A and Φ are the observed amplitudes and phases, respectively. The boundary condition for the velocity vector, **v**, at the closed sides is

$$\mathbf{v} \cdot \mathbf{n} = 0,$$

where **n** is a unit vector normal to the coast. At the open side the condition is

$$\frac{\partial v_n}{\partial x_n} = 0,$$

where the velocity v_n and the coordinate x_n are perpendicular to the boundary. Similar boundary conditions were specified for the sediment flux **S**.

3 Results

We carried out several experiments to study the initial perturbations of a flat bottom caused by a tidal flow under different geometric configurations of a basin. It is important to mention that we are principally interested in the initial perturbations caused by a tidal flow. For this reason, we simulated the evolution of the seabed only for a few years. The simplest configuration is a rectangular basin representing Taylor's problem. It is known that the solution of Taylor's problem explains fundamental properties associated with the propagation of tidal waves in semienclosed basin. The principal aim of this calculation is to extend the Taylor's problem dynamics to the generation of sandbank patterns. For this, a numerical simulation was performed for a rectangular basin 500 km long, 250 km wide and an initial constant water depth of 40 m. Sandbanks observed in many sea regions show typical wavelengths varying between 5 and 10 km. To resolve these scales, we applied a grid spacing of 1 km in our calculation. The geographical position of this basin corresponds to that of the North Sea. The basin was forced at the open boundary by a M_2 tidal wave with amplitudes and phases corresponding to the open northern boundary of the North Sea (Zongwan et al. 1995). After a simulation of 5 years, the results reveal the formation of a group of sandbanks located in a small region at the closed boundary (Fig. 1). The distance between two crests is about 14 km. It is worth mentioning that these instabilities occur where the incident Kelvin wave is reflected. Near the open boundary there is also a perturbation process which is related to the boundary conditions applied in the calculation, i.e., a linear interpolation of amplitudes and phases observed on the eastern and western sides of the northern open boundary of the North Sea. A justification for this approximation is that the wavelength of a tidal signal propagating in the oceans reaches values of thousands of kilometers. When this signal reaches the open boundary of an adjacent sea, only a small section

Fig. 1 Quasi-periodic bed forms associated to the Taylor's problem after a simulation of 5 years
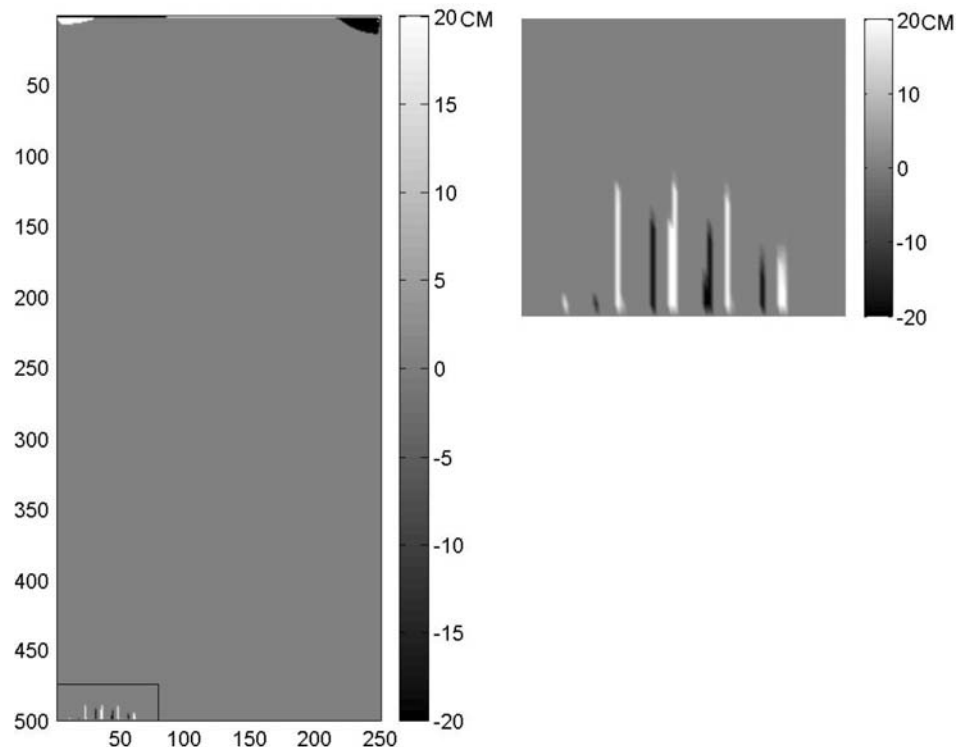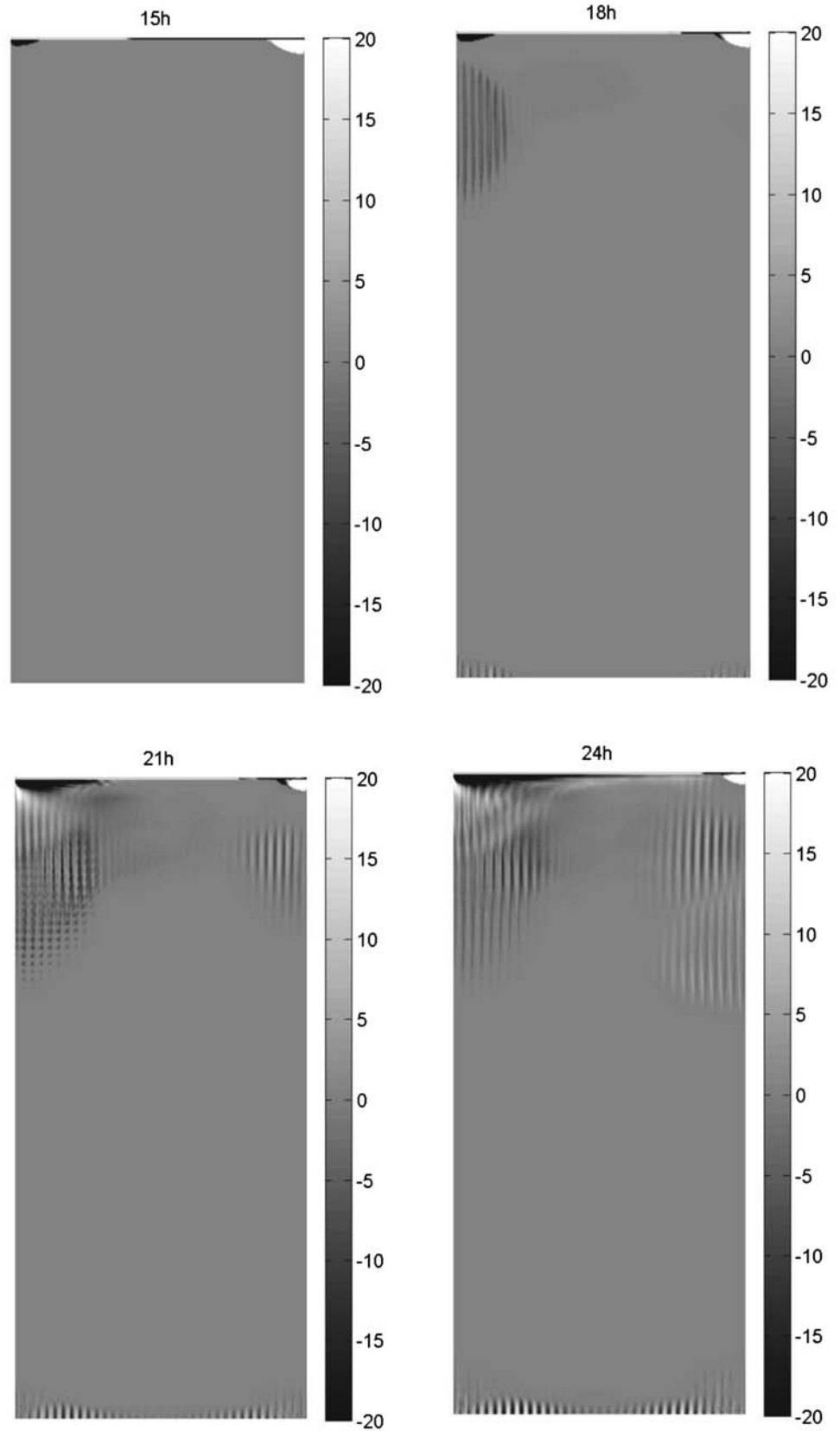
Fig. 2 The calculations were carried out for a basin 250 km wide, 500 km long, 30 m deep and for forcing signals with periods of 15, 18, 21 and 24 h. The observed perturbations have a wavelength of about 7 km. The scale is given in centimeter

of the wave interacts with the adjacent sea. In this process Poincaré waves are generated. As a first approximation, it can be considered as if the amplitudes and

phases vary linearly along the open boundary. These boundary conditions for the sea surface elevation differ slightly from an ideal sea surface elevation resulting

Fig. 3 We show the bathymetry of the North Sea and, schematically, the ideal rectangular basin applied in the calculations
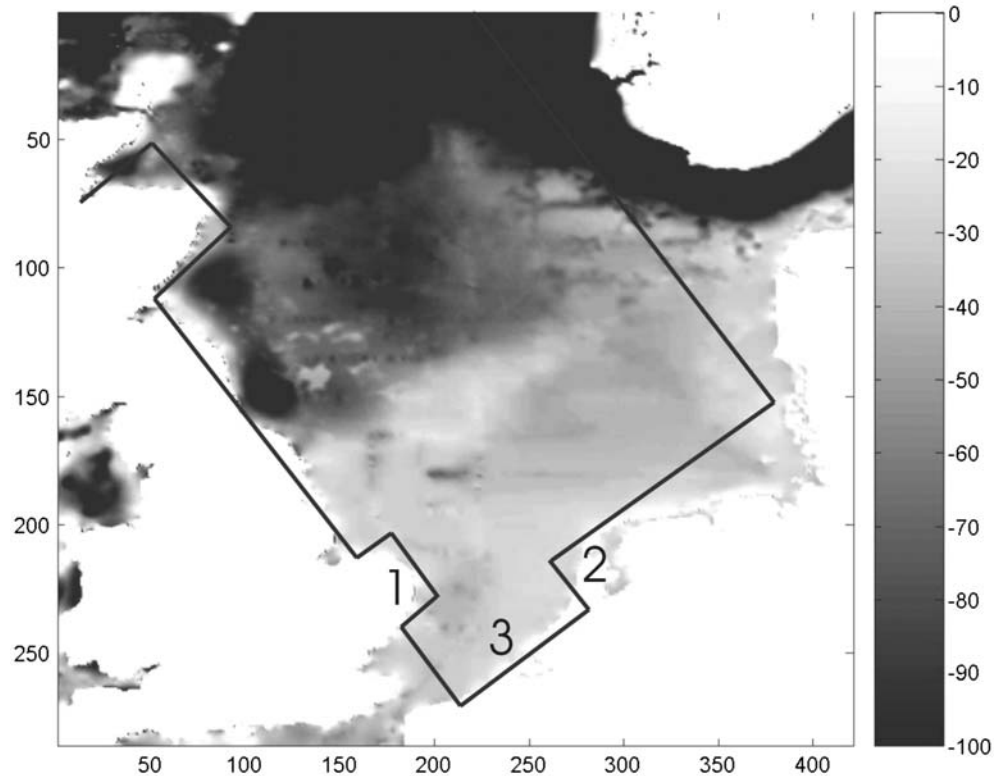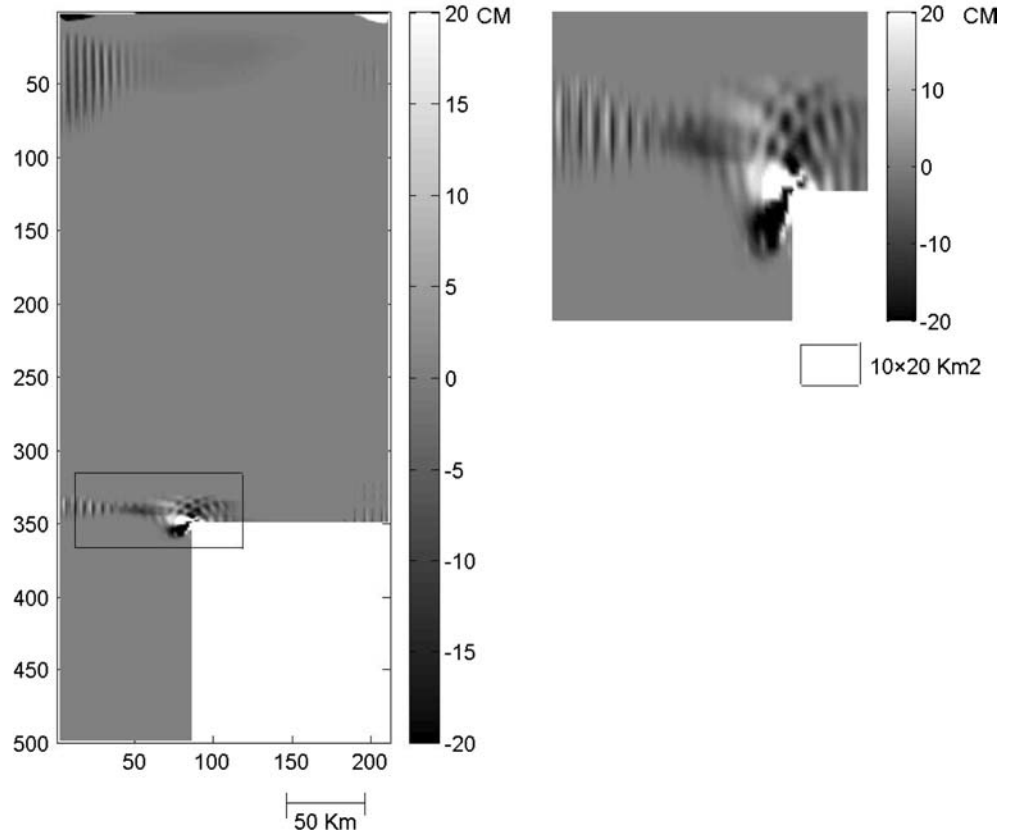

from the superposition of two Kelvin waves. The so-generated Poincaré waves explain the formation of sandbanks in the neighborhood of the open boundary.

Brown (1973) generalized the Taylor's problem by carrying out a series of calculations for a fixed rectangular basin, where the flow is forced by Kelvin waves of different frequencies. For large wavelengths, the Poincaré modes are trapped at the closed boundary of a semienclosed basin. However, they can propagate towards the open boundary as the wavelength of the incident Kelvin wave decreases. The energy is then radiated in the form of Kelvin and Poincaré waves and the flow pattern in the rectangular semienclosed basin varies in function of the frequency of the forcing Kelvin wave. One would expect that these different flow structures influence the generation of sandbanks. This aspect was investigated in a series of calculations. The basin was 250 km wide and 500 km long and had a constant water depth of 30 m. In all experiments, the simulated time was of 2 years. The amplitudes and the phases are the same as in the previous case. The sandbank patterns generated by Kelvin waves with periods of 15, 18, 21 and 24 h are depicted in Fig. 2. The results expose that for large periods, i.e., for waves with the largest wavelengths, the sandbanks are generated more easily. We observe, for example, that for the calculation of 24 h several groups of sandbanks are generated: two at the closed boundary and three near the open boundary. The wavelength of the observed sandbanks is about 7 km. The strength of the sandbanks diminishes as the period of the forcing Kelvin wave decreases.

In the following simulations, the rectangular basin was modified by introducing new geographical features like bays and peninsulas. To give an idea of why we have selected these geographic configurations, we show in Fig. 3 a plot of the geography and bathymetry of the North Sea. Additionally, a rectangular basin and rectangular peninsulas are superposed to indicate the geometrical simplifications we did. The principal geographic features of the North Sea considered in our calculations are numbered as follows: peninsula (1), land section (2) and bay (3). In the first calculation, we introduce a land section to configure the region of the Southern Bight of the North Sea. The basin is 500 km long, 225 km wide and the area representing the Southern Bight is 150 km long and 75 km wide. In Fig. 4 are displayed the results of a numerical simulation of 8 years. They suggest that in regions where the Kelvin wave is diffracted, periodic bed forms tend to occur. The distances between two crests are of the order of 7 km. It is also worth mentioning the tendency of the sandbanks to develop with crests forming a semicircle around the corner of the land section. At the closed boundary there is no sign of sandbanks like in the case of the Taylor's problem. Again, near the open boundary there are several groups of sandbanks.

A further complication in the geometry of the basin was introduced by adding a peninsula. For this new configuration, we carried out a series of calculation for different periods of the forcing Kelvin wave at the open boundary. The rectangular basin is 250 km wide, 500 km long and 30 m deep. The dimensions of the land

section are 175 km wide and 150 km long and of the peninsula 40 km wide and 40 km long. In all experiments, the simulated time was of 2 years. The periods of the forcing Kelvin wave varied between 3 and 15 h. In Fig. 5, we observe that for a period of 3 h, there are no signs of perturbations for the simulated time. In the calculation of 6 h, there are two slight perturbations at the corner of the land section and at the southern corner of the peninsula. In the 9 h forcing period, the two perturbations appear more developed and a small perturbation comes into view at the northern corner of the peninsula. In the simulation for a period of 12 h, the perturbation at the land section corner has now developed clearly as a transversal oscillating pattern of the seabed. This perturbation develops between the land section and the peninsula. The perturbation grows also to the right side of the land section corner. At the southern corner of the peninsula, there is a tendency for the development of oscillations. Finally, the oscillating pattern of the seabed is well developed in the 15 h simulation. It is also the most intense of all simulations. We interpret these oscillating structures as the formation of sandbanks. The estimated growth rates of these sandbanks would give a high of approximately 6.5 m in 500 years. Several regions are observed where bed form patterns develop: at the southern side of the peninsula and on the right side of the land section. From this series of calculations one can see that geometry is very important in generating groups of sandbanks. By comparing the results shown in Figs. 4 and 5, the calculations suggest that when the distance between the land section and the left closed boundary decreases, the development of bed forms increases.

4 Discussion

We performed a series of calculations for a perfect rectangular basin and for basins in which several geometric features were added. All experiments were carried out for an initial flat bottom. The seabed was perturbed by a tidal flow of different frequencies. In the model, we introduced a critical velocity u_c so that erosion occurs only for velocity values exceeding $u_c = 0.3$ m/s. The formation of sandbanks, i.e., perturbations of the seabed, occurs only in regions where the flow is relatively intense and where the geometry favors instabilities of the seabed. In the calculation resembling Taylor's problem, we found that sandbanks are generated only in a small region at the closed boundary (Fig. 1). Exactly at the same position and having the same form, in Mulder's (2002) calculations this region appears as a slight erosion area. The reason for this is that Mulder applied a grid spacing of 9 km, i.e., sandbanks are not resolved, only the global erosion and accretion processes. Although the intensity of velocities are almost the same across the area near the closed boundary, the generation of sandbanks takes place only on the side of the incident Kelvin wave.
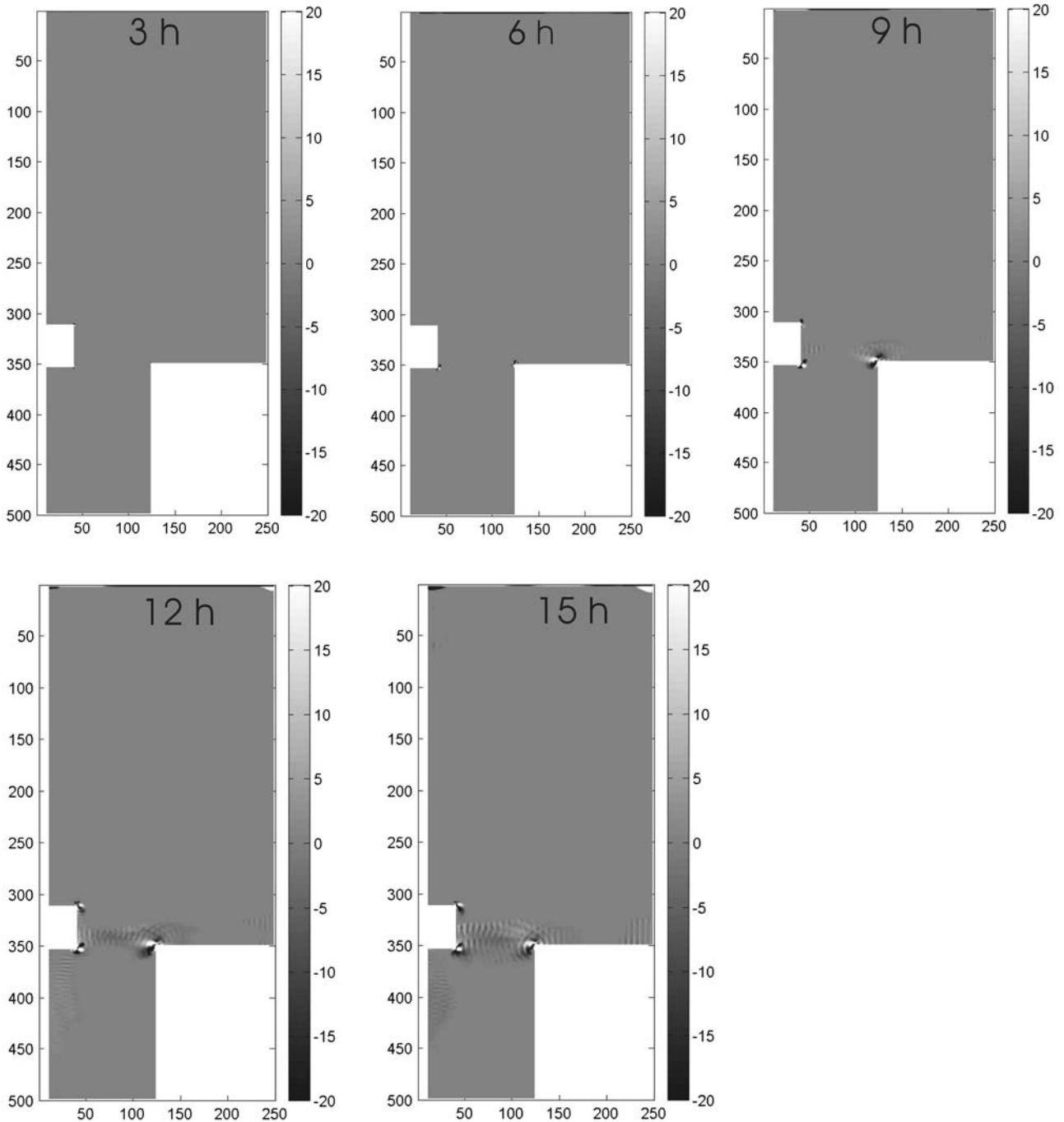
Fig. 5 Results of calculations for a basin with a configuration including a land section and a peninsula. In all calculations the simulated time was of 2 years

According to Taylor's theory, it is the zone where Poincaré waves are generated. An analysis of many sea regions where sandbanks are found indicates that this kind of seabed instabilities tend to happen more vigorously on the side of the incident Kelvin wave, for example, in the Colorado River Delta (Carbajal and Montaño 2001), the North Sea and the Gulf of Korea (Off 1963). We think that this subject is worth studying in more detail in future research works.

The calculations shown in Fig. 2 reveal that large wavelengths favor the formation of sandbanks in a rectangular basin. From Brown's theory, we know that for large wavelengths (compared with the width of the basin), the Poincaré waves, generated in the reflection process of Kelvin waves at the closed boundary, are evanescent, i.e., they vanish at some distance from the closed boundary (Fang et al. 1991). The larger the wavelengths are, the stronger the Poincaré modes are
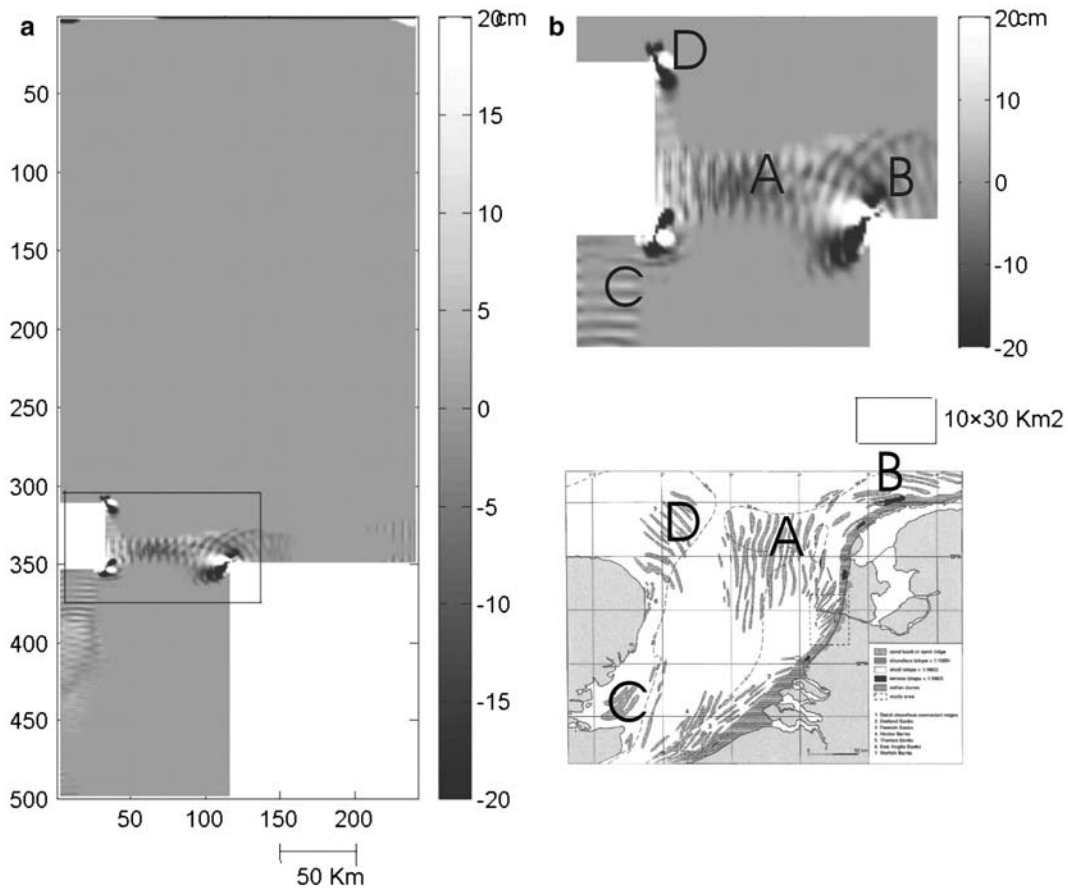
Fig. 6 Comparison between observed and calculated sandbank patterns in the area of the Southern Bight of the North Sea. The *plot on the right side below* was taken from Van de Meene and van Rijn (2000a, b)

trapped in an area near the closed boundary. It seems that this phenomenon plays a role in the growth rate of sandbanks. At the open boundary, we do not have information about the characteristics of the incident and reflected Kelvin waves. In these calculations, we applied a linear interpolation of the values of phases and amplitudes, observed on the eastern and western coasts of the North Sea. It has already been demonstrated that this kind of approximation leads to the generation of a family of Poincaré waves (Fang and Fang 1991; Carbajal 1997) in the vicinity of the open boundary. This explains the generation of sandbanks in that region. In Fig. 4, the rectangular basin was modified by introducing a land section. The influence of this geometric change is outstanding, since the area where instabilities in the seabed occur is displaced to the region where the basin becomes narrower. The growth rates of the sandbanks increase too. The perturbation extends across the basin between the corner of the land section and the eastern coast. The Kelvin wave is clearly diffracted in this area and Poincaré waves should be generated. The principal aim of this research work is to investigate the influence of geometry in the generation of sandbanks. For this reason we concentrate on the description of sandbanks. However, sandbank patterns should be analyzed in function of amphidromic systems of sea

surface elevation and tidal currents (Zongwan et al. 1995; Mulder 2002; Van der Molen et al. 2004). This will be done in another detailed numerical work on amphidromic systems and sandbanks formation. Figure 5 reveals important information on the grow rates of sandbanks. The introduction of a peninsula diminished the distance between the land section and the eastern coast. This had the effect of intensifying the generation of sandbanks. Another aspect of fundamental interest is to analyze how the perturbations are initiated. We can see in Fig. 5, for example, that the initial seabed instabilities show a rose-like structure, with alternated zones of erosion and accretion around the corner. These perturbations grow in a radial form until the sandbanks generation begins. These alternated erosion–accretion instabilities are also observed in theoretical calculations on the formation of sandbanks triggered by a bed subsidence (Roos and Hulscher 2002). It is of interest to mention that geometrical features induce the formation of sandbanks in their calculations as well as ours: a land section and a peninsula in our experiments and a subsidence in the seabed in their theoretical work.

Near the southern boundary of the North Sea, particularly in the area where the Southern Bight and the North Sea are connected, there are a lot of sandbanks and shoreface-connected sand ridges. Applying the

simple geometry of a rectangular basin, a rectangular land section and a rectangular peninsula to characterize the principal geographical features of the southern area of the North Sea, we carried out a 12 years calculation to investigate what kinds of sandbank pattern are generated under these conditions. The basin was 30 m deep and was forced at the open boundary with a Kelvin wave with a frequency of the M_2 tide. In Fig. 6, the results of our calculation are compared with sandbank patterns observed in the Southern Bight of the North Sea. For this, we have introduced in our plot a picture (Fig. 6c) of linear sandbanks, taken from Van de Meene and van Rijn (2000a, b). For a better comparison, we have designed capital letters to the different sandbank groups. In spite of the geometrical simplifications of our calculation, there are several similarities in the position of observed and calculated sandbank patterns. In our calculation, a group of sandbanks extends across the sea between the land section and the peninsula. The geometrical configuration of Fig. 6b and c suggests that this group can be identified as corresponding to the group A. Similarly, the inclined sandbank groups B in Fig. 6b and c can be related. The inspection of Fig. 6b and c reveals that the semicircular tendency in the orientation of the sandbanks observed in Fig. 6c has been reproduced to some extent in our calculation (Fig. 6b). It is worth mentioning that in Fig. 6b there is a superposition of two different groups of sandbanks. It looks like a superposition of gravitational water waves. If concepts like wave fronts and ray theory could be applied to the calculated oscillating sea bed pattern, then it would be of interest to investigate caustic points in sandbank patterns and see, for example, how the growth rates are at these points. Although not so obvious, the groups C in Fig. 6b and c, located at the southern side of the peninsulas, can also be identified as equivalent structures. The sandbanks observed in the group D, in Fig. 6c, are not well developed after 12 years of simulation in Fig. 6b. The group of sandbanks located to the east of C in Fig. 6c are probably related to the Poincaré waves generated in the region where the English Channel and the Southern Bight of the North Sea meet. This open boundary was not considered in our calculation. Finally, generation of sandbanks is also observed in an area on the right side of the land section. This would correspond to the formation of sandbanks in the German Bight.

We have showed that for the generation of sandbank patterns, the geometry plays an important role. The influence of the geometry was also investigated by Signell and Harris (1999). They studied numerically the formation of sandbanks around headlands. They found that symmetric sandbanks are formed and that, in this process, the shear stress and the instantaneous sediment fluxes are responsible for sandbanks' building. We have carried out all calculations for an initial flat bottom. In spite of this, the complex structure of sandbanks could be generated. Our results suggest that geographical features in combination with wavelengths of the incident Kelvin

wave may favor intensively the generation of sandbanks, i.e., it suggests a kind of optimal combination of geometry and wavelength of the incident Kelvin wave. Finally, we want to remark that the calculations show that sandbanks and shoreface- connected sand ridges are generated only by Kelvin waves forcing the system.

5 Conclusions

Applying a two-dimensional hydrodynamic numerical model and a semiempirical equation for the transport of sediments, we investigated the generation of sandbanks in ideal rectangular basins of initial flat bottom. Our experiments show that geometry is a fundamental factor in determining the position at which the formation of sandbanks occurs. A calculation resembling the Taylor's problem indicates that sandbanks occur on the side of the incident Kelvin wave. This phenomenon is observed in several sea regions. This experiment and others for different geometries suggest, in general, that instabilities are more susceptible to develop in regions where Kelvin waves are diffracted and where Poincaré modes are generated. Another important result is that large wavelengths favor the formation of sandbanks. Since we have applied in all calculations an initial flat bottom, the calculations highlight the importance of the geography in the generation of sandbanks. In spite of the simple geometry, a calculation applying a configuration resembling the area of the Southern Bight of the North Sea reproduced satisfactorily the complex patterns observed in that region.

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