ELSEVIER

Limnologica 34, 65–74 (2004)
http://www.elsevier.de/limno

LIMNOLOGICA

The use of soft shore protection measures in shallow lakes: Research methodology and case study

Selim M. Sayah*, Jean-Louis Boillat, Anton Schleiss

Laboratory of Hydraulic Constructions, Swiss Federal Institute of Technology, Lausanne, Switzerland

Abstract

Shore protection in lakes is an issue of major importance in Switzerland where several big lakes in plains suffer from a pronounced bank erosion. For the moment, in shallow lakes, soft and biotechnical protection measures proved their reliability. Unfortunately, the scientific basis for the design of such techniques does not exist in some cases or not appropriate enough in order to have an optimized effect. Therefore, the aim of an on-going research project is to study, on the basis of physical and numerical modeling, the impact of such measures on the shores regarding bank erosion, and to establish the main basis for their dimensioning. A 2-D numerical model was used to simulate the eroded beach of Préverenges on the North coast of Lake Geneva. Hence, this case study allowed a better understanding of the numerical capacities of the program by modelling wave effect on bedload sediment transport and shore erosion as well as wind role in the generation of littoral currents.

Key words: Soft shore protection – numerical modelling – beach erosion

Introduction

The process of shore erosion in lakes and the design of well-adapted soft shore protection techniques are topics where further systematic research remains a need. Unfortunately, the scientific basis for the design of such techniques is mostly unknown. Thus, the actual practice in shore protection overestimates the design of structures which could be detrimental to maintain the natural coastal aspect.

In order to thwart any eventual landscape degradation, pioneer soft designs are being constructed in Lake Biel in Switzerland. Since 1985, the "Association for the Protection of Lake Biel" has developed several soft techniques for the protection of reed bed and thwarting bank erosion (see Fig. 1) as brushwood fences or wooden piles both used as groynes or breakwaters, or gravel embankment and reed plantations used as soil shore consolidation agent (ISELI 1995).

The main goal of the ongoing research project EROSEE is to study the interactions of these soft protection techniques with the incident waves in the lake, in order to evaluate their effect on the sediment transport. Physical and numerical modelling is used in order to establish the required scientific design basis. Field measurement campaigns will be carried out in Lake Biel by the Berne University of Applied Sciences for the validation of the theoretical and experimental results.

Shore protection measures

The most recent history of banks in Lake Biel (see Fig. 2) goes up to the end of the 19th century period dur-

***Corresponding author:** Selim M. Sayah, Laboratory of Hydraulic Constructions, Swiss Federal Institute of Technology, CH - 1015 Lausanne, Switzerland. E-mail: selim.sayah@epfl.ch, E-mail of co-authors: jean-louis.boillat@epfl.ch and anton.schleiss@epfl.ch

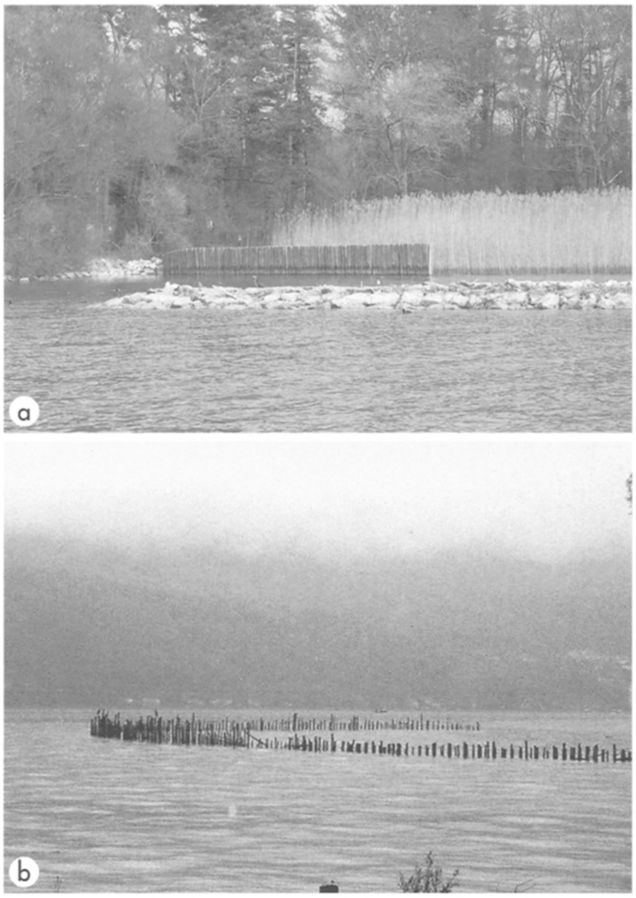

Fig. 1. (**a**) Combined bank protection measures in Lake Biel, using breakwaters and palisades (wooden piles) to protect natural reeds on the beach. (**b**) Brushwood fences used in Lake Biel for shore protection against erosion.

ing which the first correction of rivers and lakes in the Jura plain was carried out. The diversion of the Aar river in Lake Biel modified the natural dynamic equilibrium of the latter leading to a gradual and constant growth of different vegetal species including plants and reed formation along the banks of the lake. Unfortunately, rigid constructions related to human activity brought some harmful impact on the shore stability (OSTENDORP et al. 1995). Thus, since the late thirties of the past century, an increase in erosive forces clearly appeared in the 60% remaining natural shore of the lake.

In order to stop shore erosion, the use of protection measures must be applied with respect to the surrounding landscape of Lake Biel. Hence, soft measures most adapted to shallow lakes were applied during past decades as *brushwood fences* in Ipsach, Sutz, and Mörigen, and *palisades* in Ipsach, Lüscherz, and Erlach.

Scientific and technical goals

Fig. 3 shows the need for further systematic research to investigate the interaction between the shore protection measures, the hydrodynamics of a specific site, and the bedload sediment transport and bank erosion. The numerical modelling is based on physical tests carried out in the wave tank of the laboratory. The latter are used as a tool to calibrate the basic numerical model.

The main goal of the multidisciplinary research project EROSEE is therefore to remediate to shore erosion using well-adapted measures for shallow lake conditions. Their behavior will be evaluated on short, middle and long-term conditions. The research will provide the necessary tools for the design which will take into consideration the envi-

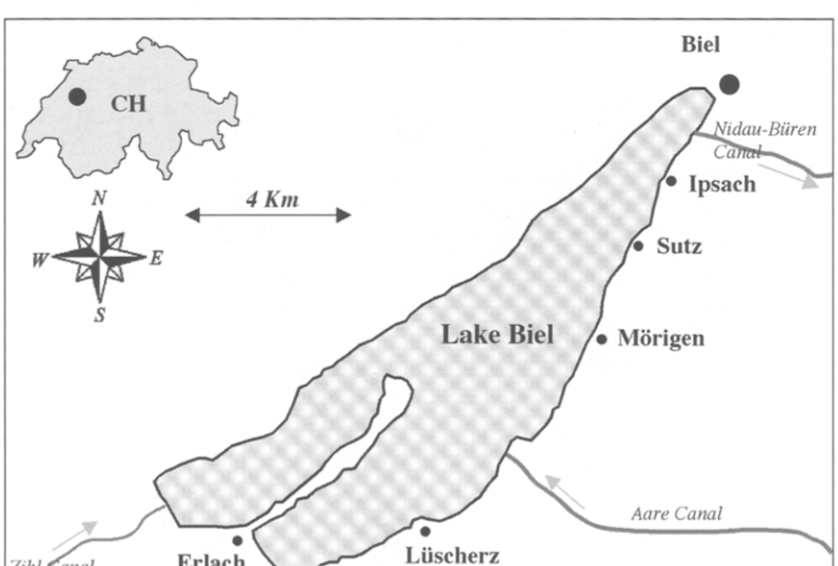

Fig. 2. Lake Biel, Switzerland.

ronmental impact on the landscape and the shore, the criteria that influence their lifetime and any eventual maintenance. Finally the conditions for using these measures in some other shallow lakes will also be analyzed.

It is to me mentioned that Hannover University studied, on the basis of physical and numerical models, the interaction of waves and the brushwood fences (MATHEJA et al. 2000).

Proposed methodology

The methodology of the research project is subdivided into three phases (see Fig. 4) as follows:

- *Phase 1* concerns the adjustment of the numerical model on the basis of the test results of the physical model, using the 2-D free-surface software *MIKE 21* (DHI 2001).

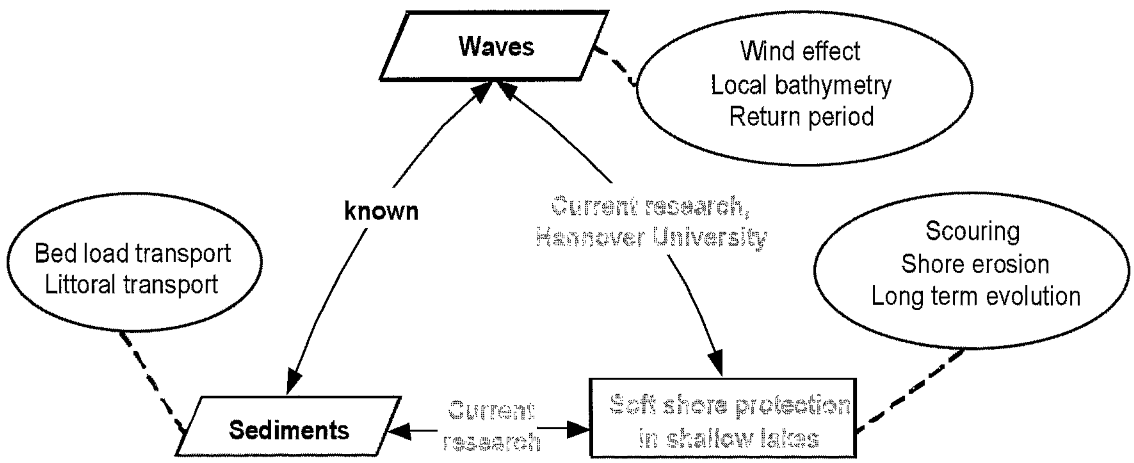

Fig. 3. Further research is needed to understand the interaction of the soft shore protection measures in shallow lakes with waves and sediment transport.

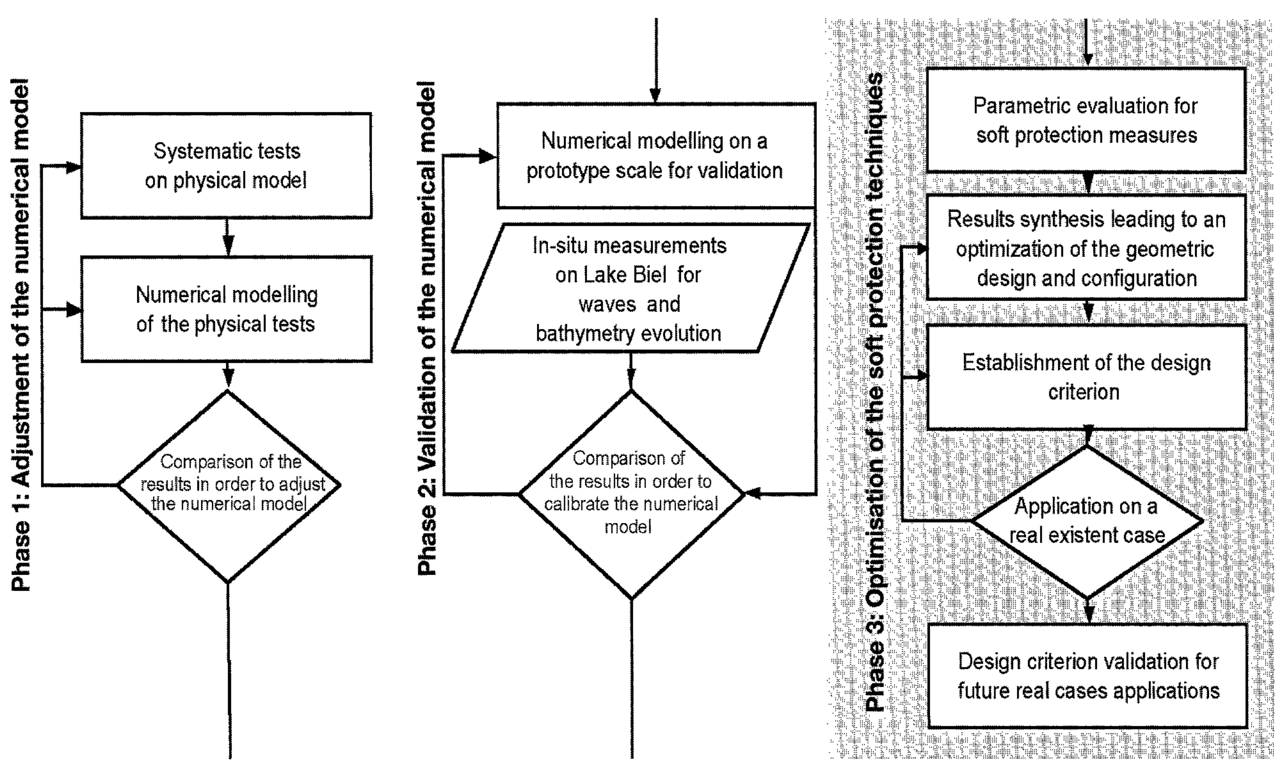

Fig. 4. Detailed methodology for the research project EROSEE.

- *Phase 2* provides the basis for the validation of the model adjustment done in phase 1, being based on the measurement campaigns of the sediment transport by bedload in the lake and the wind generated waves. The validation will be based on a full scale real numerical model that simulates real conditions in Lake Biel.
- *Phase 3* will establish the scientific basis and design criteria of the shore protection measures with the purpose to optimize the effect against bank erosion. When the numerical model is validated on the basis of prototype results, it is used to carry out a parametric study.

Case study: Beach erosion on the North shore of Lake Geneva

Near the end of the 1980's, the people of Préverenges (see Fig. 5) a small village situated in the north region of Lake Geneva, showed serious concern about the increased erosion of their beach.

The latter is well known for water sports because of its ideal wind conditions. In order to stop the erosion process, four groynes were built along the beach, perpendicular to the shoreline. After many years of monitoring, the groynes solution appeared to be not efficient. They were unable to attenuate refracted waves that propagate perpendicularly to the shoreline.

Historical analysis

Many old photos revealed that the beach of Préverenges was wider than its actual configuration. In the summer of 1935, the beach was 15 m wide (see Fig. 6a). Moreover, the Lake Geneva is at its highest level during summer following the water level regulation principles of the lake, established at the beginning of the 20th century. Comparing the situation of 1935 to the actual beach morphology (see Fig. 6b), it can be confirmed that the latter has suffered an increased erosion process during the last decades which narrowed the beach to a maximum 2 m width during the same period of the year.

It appears also that the actual configuration of the trees is different than the one shown on Fig. 6a. The actual plantation level is higher than the old one. In fact, the level of the beach road was also lower in the past. Investigations confirmed that filling up the land behind the beach has heightened the road and tree level. It possibly occurred in the sixties, during construction of the motorway between Geneva and Lausanne.

Hence, it is very likely that the changes of the shore level have generated an increase in the hydrodynamic forces due to wave breaking. With a higher shore level, the incident waves appear to break more frequently and brutally in comparison to a breaking on gently growing beach slope pushing the shoreline in the landward direction.

Considering the vegetation on the shore, their action differs depending on the wave attack angle and beach material properties. In several places, the roots of the trees are bare, proving the inefficiency of the trees very near to the shoreline in soil consolidation. In other places, where the shore is more or less well protected against severe hydrodynamic forces, reeds appear to play a very efficient role in keeping the beach in its natural condition while providing a good protection against erosion.

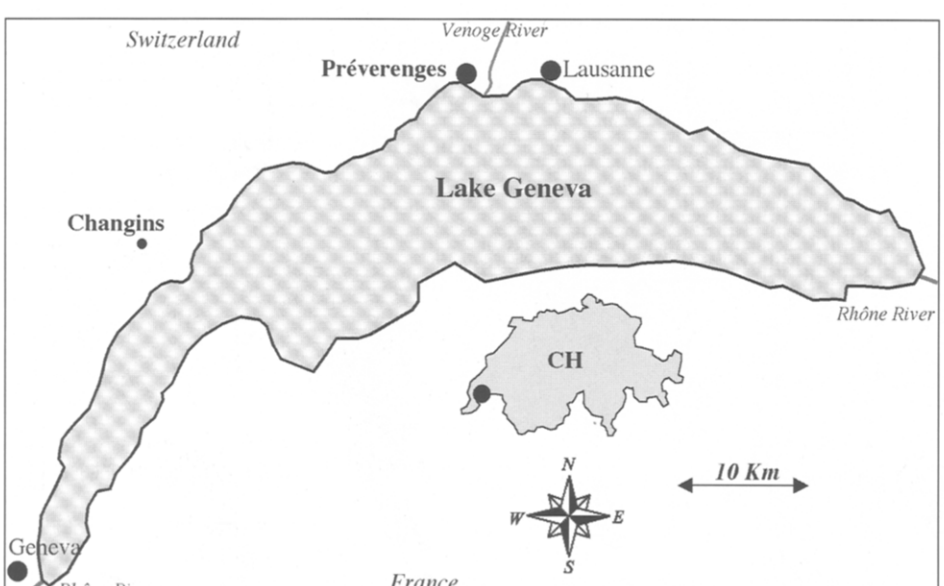

Fig. 5. Préverenges, situated on the North coast of Lake Geneva, Switzerland.

The on-site technical investigation proved that both in *Wind* (southwestern wind) and *Bise* (northeastern wind) regimes, nearshore littoral currents are being generated. Due to the shoreline orientation, the *Bise* regime does not generate waves in the littoral zone of the beach. Waves are therefore only generated during the *Wind* regime.

Anemometric and hydrodynamic site conditions

The short waves (having typically a period less than 20s) attacking the nearshore zone of Préverenges are essentially wind waves. Taking into consideration the wind rose that is most representative of local wind in the region (meteorological station Changins, at 30 km distance from Préverenges), it appears that the southwestern wind (called *Wind*) is the most frequent and will mainly influence the hydrodynamic conditions, considering the orientation of the shoreline. Since the beach is oriented perpendicularly to the northeastern wind (called *Bise*), the influence of the latter on the hydrodynamic conditions in the nearshore zone of Préverenges is considered negligible.

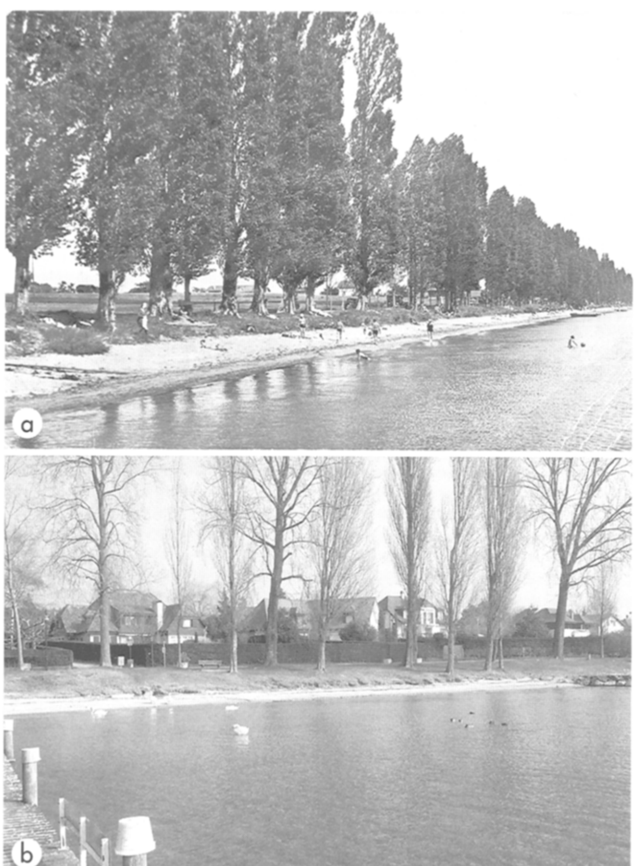

Fig. 6. Photos showing the beach of Préverenges; (**a**) was taken in the summer of 1935, and (**b**) was taken in winter 2003 (when the water level of the lake is at its lowest value) providing a clear idea of its width that has suffered an increased erosion process through the last decades.

Changins measures the *Wind* blowing 33.5% over 23 years wind measurements duration (data used start from the year 1979 and end in 2002, on the basis of 10 minutes-mean-wind-velocity) (LASEN 2001). These data are the basis for a statistical analysis of the *Wind* in the region of Préverenges, whose results are used to calculate its corresponding wind generated waves. Since a general evolution of the beach due to the erosion process is needed, a long-term statistical analysis will be considered. Short-term analysis refers to analysis of winds that occur during one wind surge within one storm. This phenomenon is not always sufficient to produce well established wind-waves (KAMPHIUS 2000). Fig. 7 shows the intensity-duration-frequency graph resulting from the wind velocity analysis which gives the corresponding return period for every wind velocity at Changins wind station, and a selected wind blowing duration.

As mentioned before, the wave characteristics are calculated using wind data. Parametric wave hindcasting determines wave height and period from fetch, storm duration and depth of water in the generating area. In the present study, the generating area is considered as deep water. Hence the depth of water has no effect on the wind wave generated parameters.

The method used for wave hindcasting is based on the method developed called Jonswap (HASSELMANN et al. 1973). This method is generally used for wave hindcasting based on wind data. It is applicable to a relatively small body of water like Lake Geneva, as well as on larger bodies of water like seas.

Fig. 8 shows the wind wave heights and periods for different return periods. It is to be mentioned that return periods are directly related to wind speed through the graph of Fig. 7, and waves characteristics are then derived using Jonswap method (for a 22 km fetch length).

Waves generated by boats are being efficiently dissipated by the wide nearshore region. Furthermore, large boats navigate hundreds of meters away from the shore.

Beach erosion analysis

The hydrodynamic loadings due to wave attack will result in movement and transport of the sediment (e.g. sand in the present case) in beach profile. This is referred to as *littoral transport processes* (MANGOR 2001) and is the subject of this section.

The main sediment transport process, responsible for strong erosion, occurring in the beach of Préverenges is due to wave generated *rip currents*. They are directed away from the shore, bringing the surplus water carried over the bars in the breaking process, back into deep

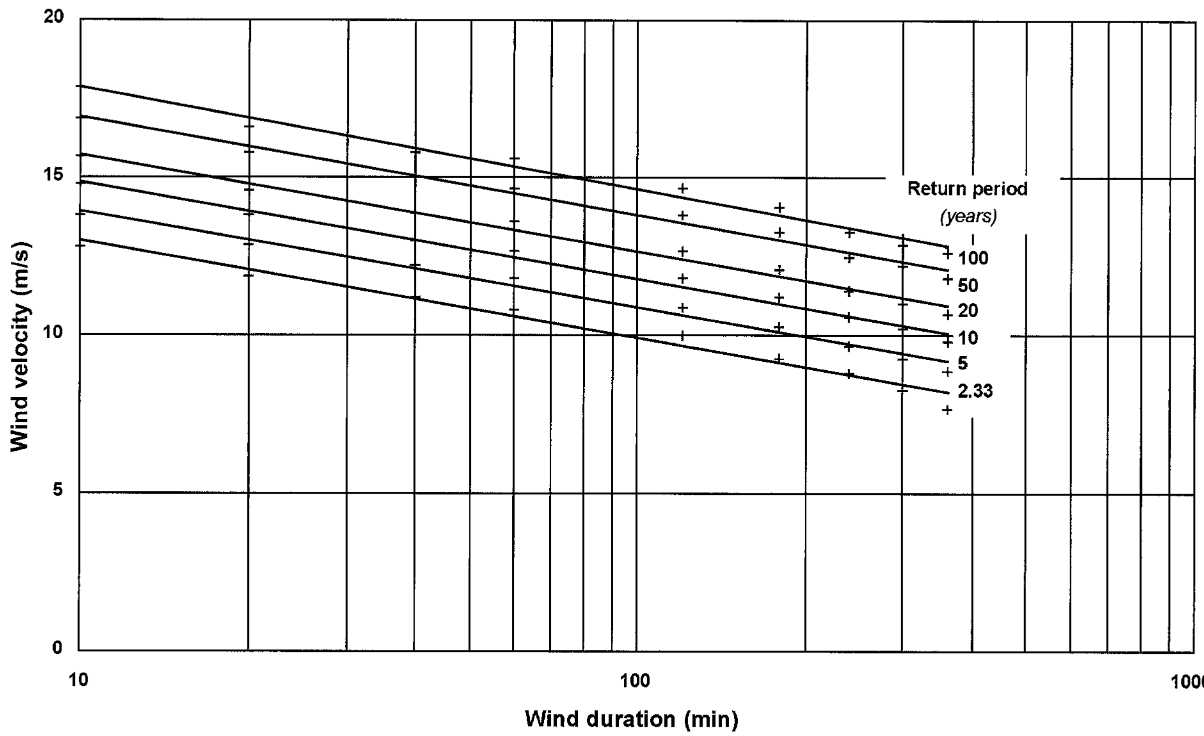

Fig. 7. Wind velocity at Changins wind station in the sector [225°± 15], in function of wind blowing duration for different return periods.

water. While rip opening travels slowly downstream, sediments are transported to a region less exposed to large forces or large shear stresses by water movements. After deposition, they induce *bar* formation. Bars are longshore submerged deposits in or near the surf zone parallel or oblique (in this case parallel) to the coast. The wave generated rip currents produce flows that engender variable shear stresses applied on the sandy bottom. When the flows exceed the threshold of motion defined by the sediment granulometry, an initially flat bed may deform into various types of bed features, ranging in size from small ripples up to major sandbanks. BONNEFILLE (1992) defines sediment transport regimes using the dimensionless parameters D_* related to sediment diameter and Reynolds number of particles R_*. This leads to:

- Ripples formation only when $D_* < 15$
- Dunes formation only when $R_* > 15$

for

$$D_* = \left[\frac{(s-1)\cdot g}{\nu^2}\right]^{1/3} \cdot d_{50} \qquad (1)$$

$$R_* = \frac{u_* D}{\upsilon} \qquad (2)$$

$$u_* = 2.2 \cdot \left[\frac{\upsilon H^2}{T^3 \sinh^2 2\pi \frac{d}{L}}\right]^{\frac{1}{4}} \qquad (3)$$

where s is the ratio of densities of grain and water, d_{50} the median grain diameter (m), g the accélération due to gravity = 9.81 m/s², ν the kinematic viscosity of water (m²/s), u_* the bottom friction velocity due to wave generated orbital currents (m/s), H the wave height (m), T the wave period (s), L the wave length (m), d the water depth u_* (m) applied.

Table 1 shows the different possible regimes in Préverenges for different sediments found along the beach.

It is clear that the main regime for sediment transport essentially generates ripples formation in the region of Préverenges since the finer sand is located in the nearshore region. The coarser sand being deposited on the beach. Some aerial photos show big dunes (estimated average length = 100 to 200 m; estimated wavelength = 15 to 20 m) parallel to the shore. Hence, it is very probable that during big storms, when high incident waves are generated, strong flows applied on the bottom increase R_*. This may generate changes on the coastal profile.

Numerical modelling

The hydrodynamic and sediment transport related phenomena are simulated numerically using the 2D free-surface numerical model *MIKE 21*. The results of the modeling process are divided into two issues:

- *Hydrodynamics:* After using the module *MIKE 21 NSW (wind-wave generation)* to calculate the refrac-

Table 1. Various sediment transport regimes in Préverenges for different sediment diameters.

d_{50} (mm)	D_* (–)	R_* (–)	Regime
0.2	4.06	1.83	ripples
0.25	5.08	2.52	ripples
2	40.63	44.3	dunes

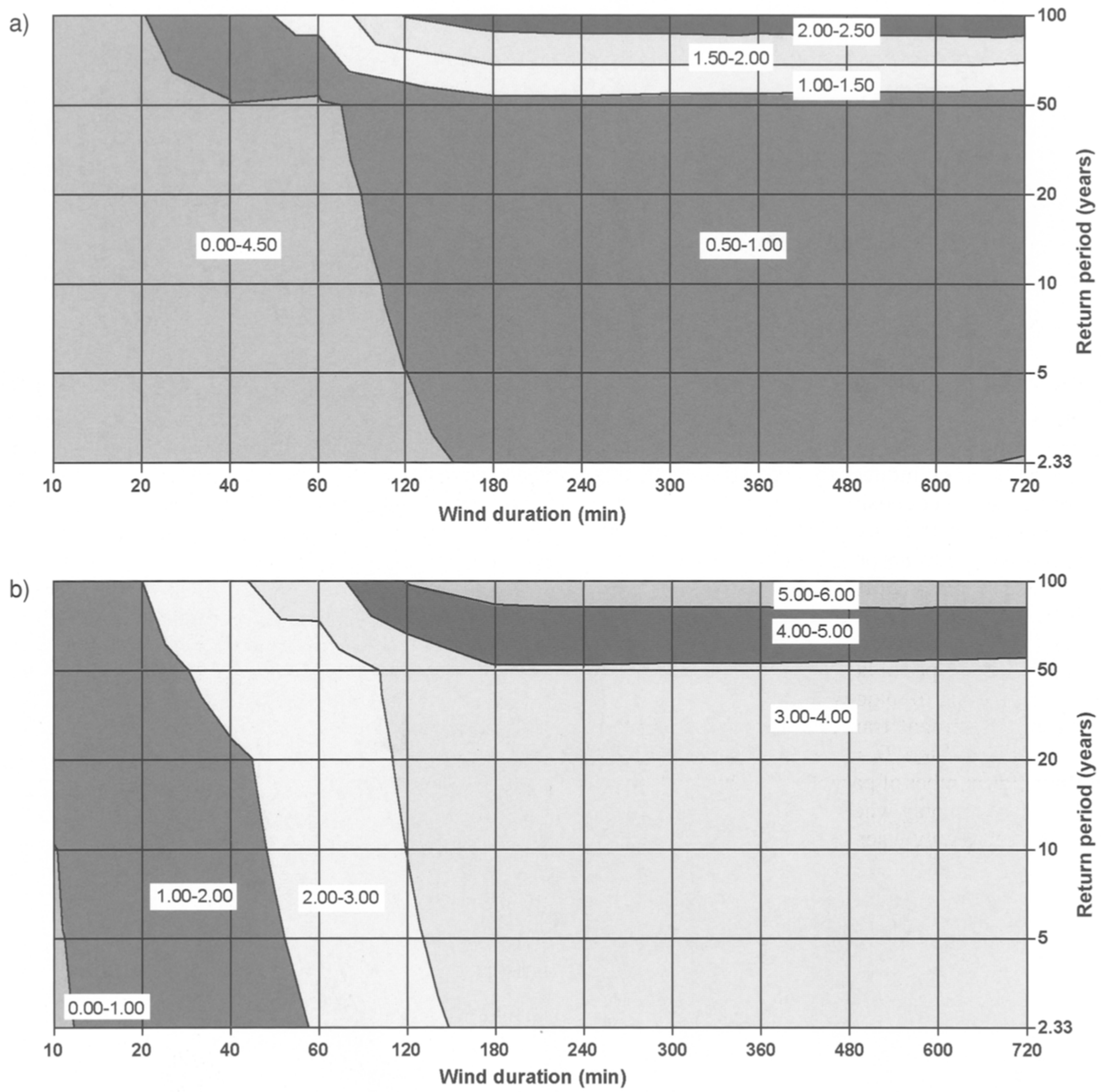

Fig. 8. (**a**) Energy-based significant wave heights H_{m0}, calculated in deep water for the fetch of Préverenges for different return periods. (**b**) Wave periods T_p(s), calculated in deep water for the fetch of Préverenges at different return periods.

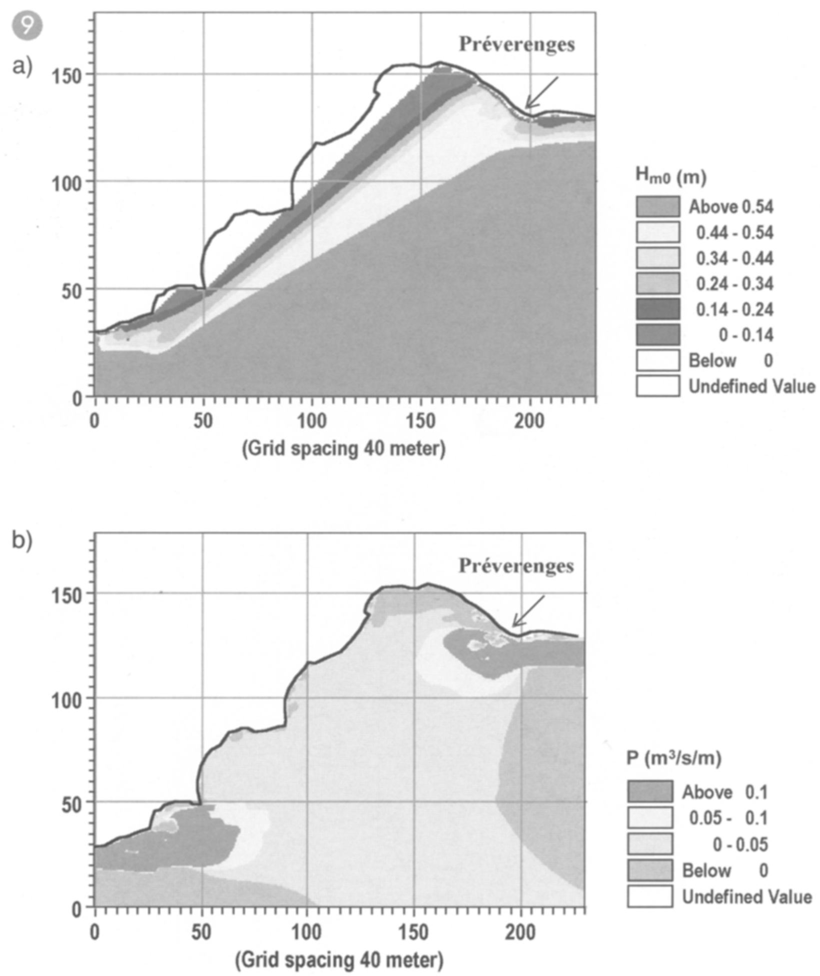

Fig. 9. Results issued from the *MIKE 21* simulation; (**a**) Wave heights H_{m0} (in metres) given by *MIKE 21 NSW* for *Tr = 50 years*. (**b**) Horizontal component of the wave generated currents *P* (in the x direction, given in m³/s/m), corresponding to the same return period (arrows indicate the Venoge mouth location).

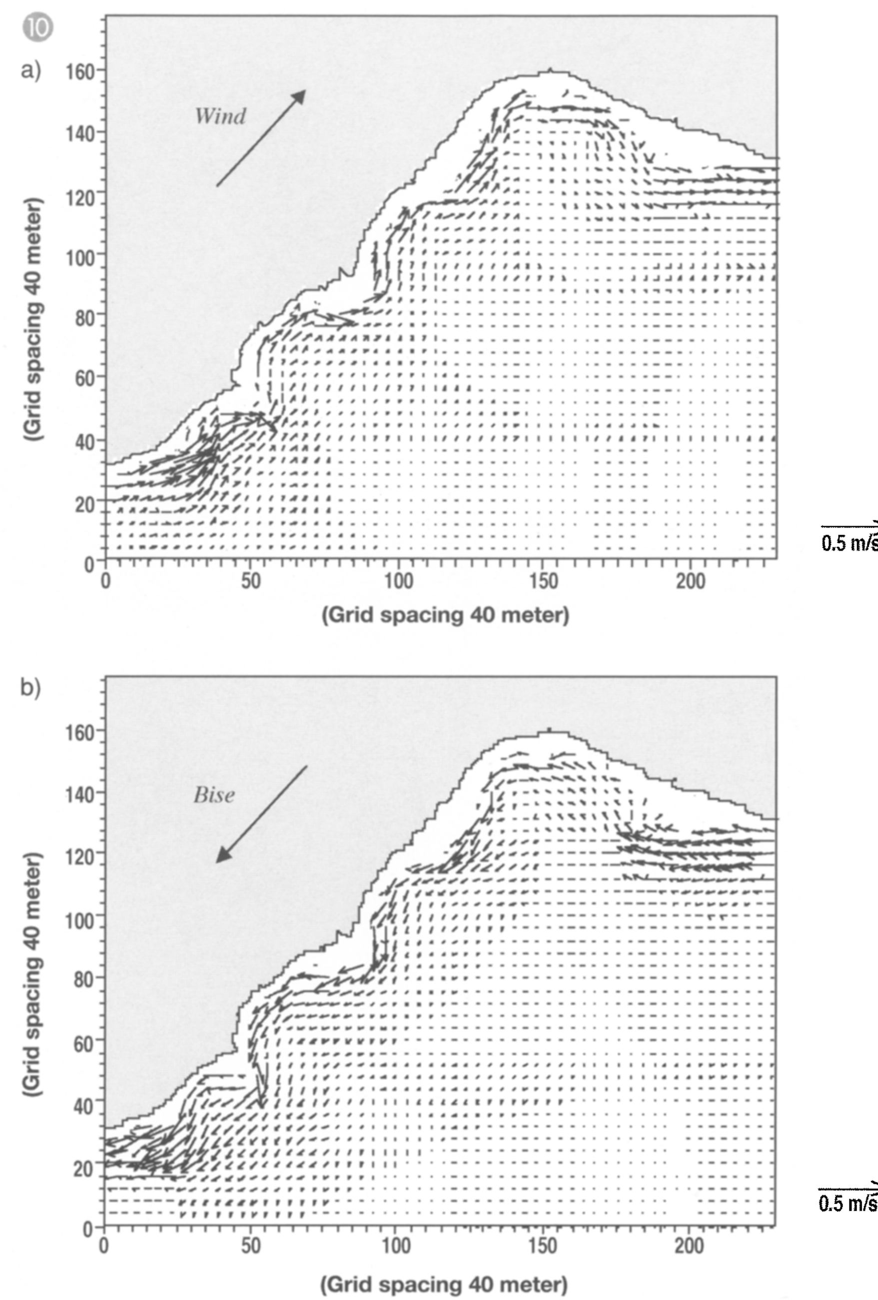

Fig. 10. (**a**) Drift currents generated by the *Wind* in the region of Préverenges with a wind velocity of 7.5 m/s. (**b**) Drift currents generated by the *Bise* in the region of Préverenges for a wind velocity of 7.5 m/s (arrows indicate wind directions).

tion and shoaling of the incident waves (using the values calculated previously), the results are used as boundary conditions in order to generate flows due to waves, in the module *MIKE 21 HD (hydrodynamic)*.

- *Sediment Transport:* The results of *MIKE 21 HD* are then used to generate the bedload sediment flows in the *x* and y directions. The module *MIKE 21 ST (sediment transport)* is used for that propose.

The numerical model of the region is based on a 40 m rectangular grid. This width is based on the average width of the delta of the Venoge river, located next to the beach to the East of Préverenges.

In order to obtain a good comparison between short and long term results, the return periods of waves considered for calculation are as follows: *Tr = 2.33, 10, 20, 50 years* (USACE 2001). The numerical calculations are also based on the simulation of single events. It means that every simulation considers only constant wave characteristics as boundary condition, related to its return period, attacking the beach during a defined duration. Since the 4 hours duration for each return period gives the highest wave, this same duration is considered for each event simulation.

Fig. 9a proves that the incident waves in the nearshore of the beach of Préverenges are already refracted by the shallow bathymetry in the South of the Préverenges region that helps to reduce the energy of the incoming waves generated in the deep water of the lake by decreasing the wave height due to the orbital friction on the bottom.

Afterwards, the module *MIKE 21 HD* calculates the wave generated orbital currents *P* and *Q* respectively in the *x* and *y* directions. Fig. 9 shows the current in the x direction for a return period of *50 years*. These values are the result of 3 hours simulation for which flows reach a steady-state condition.

Furthermore, the *P* currents reach their highest positive values (see the dark region on the upper-left of Fig. 9b) in the delta of the *Venoge*. Since every river is in principle charged with sediment in suspension, this phenomenon proves that when the beach of Préverenges is attacked by *Wind* generated waves, there is no possible nourishment of the beach due to the *Venoge* since the currents are generated in the opposite direction, i.e. towards the East.

Regardless of the wave generated currents, drift currents are also generated by *Wind* and *Bise* friction on the surface of water. In order to have a good estimation of the size and direction on these currents, and to evaluate their effect on the littoral currents, a numerical model is built using *MIKE 21 HD* without introducing any waves. An average velocity of *Wind* and *Bise* of 7.5 m/s is considered. Fig. 10 highlights their effect on two phenomena:

- *Effect on the delta of the Venoge:* The *Wind* as well as the *Bise* create drift currents in the delta of the *Venoge* that cannot contribute by any means in nourishing of the beach of Préverenges with the suspended sediment in the river flow. While the *Wind* creates currents directed towards the East, in the opposite direction to the beach, the *Bise* generates currents directed towards the South-West, very far from the beach.
- *Generation of littoral currents in the nearshore of the beach:* The *Wind* as well as the *Bise* generate littoral currents both in the seaward direction that can engen-

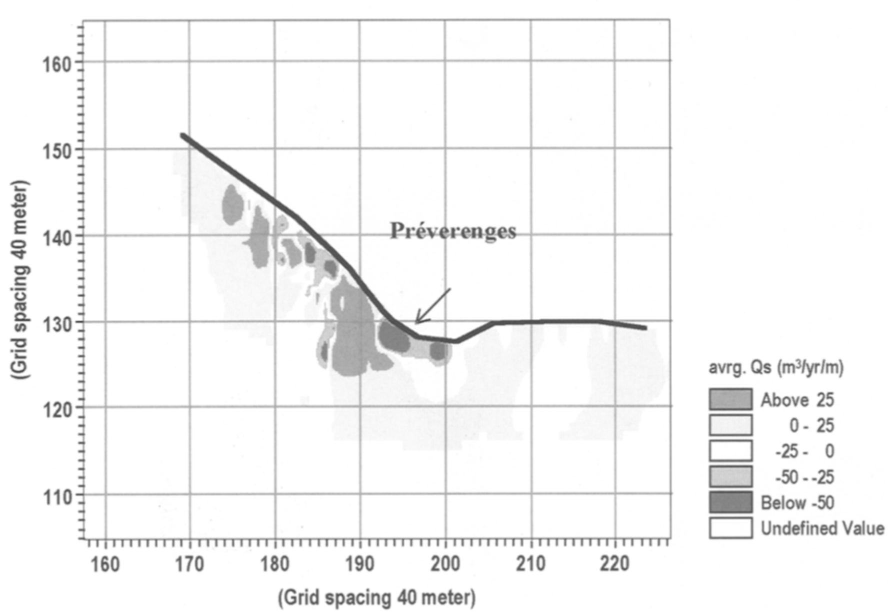

Fig. 11. Average sediment transport rate *Qs* (m^3/yr/m) in the nearshore region of Préverenges in the y direction over one entire year. The waves considered correspond to a return period of 50 years.

der a littoral transport similar to *rip currents*. These currents are also unfavorable for the beach accretion.

MIKE 21 ST is used to evaluate the bottom sediment transport rate. Since these values are very small for a *4 hour* duration event, a long term evaluation is provided by multiplying the result by the number equal period over one year. This would highlight the sediment transport evolution due to wave attack. Fig. 11 gives the average sediment transport rate over one full year in the *y* direction.

While comparing the erosion (negative values) and deposition (positive values) regions in Fig. 11 it appears that the sediment transport regime is clearly in the seawards direction due to rip currents.

Discussion

The embankment on the shore of Préverenges has modified its morphodynamic equilibrium and results in increased erosion due to wave breaking. Furthermore, *rip currents* promote sediment migration away from the shore. The bedload sediment transport promotes the formation of ripples and, during storms, when waves are high, the increase of bottom shear stresses induces sediment transport changes towards dune regime. In addition, the beach is not by any means nourished by the suspended sediments from the Venoge river. Hence, any structural protection against erosion will not restore the eroded beach. A beach nourishment project will therefore be more compatible for beach restoration.

References

BONNEFILLE, R. (1992): Cours d'hydraulique maritime, pp. 75–101. Paris.

DHI (Danish Hydraulic Institute) (2001): MIKE 21 Manual. 5–1; pp. 16–67.

HASSELMANN, K., BARNETT, T. P., BOUWS, E., CARLSON, H., CARTWRIGHT, D.E., ENKE, K., EWING, J. A., GIENAPP, H., HASSELMANN, D.E., KRUSEMAN, P., MEERBURG, A., MÜLLER, P., OLBERS, D.J., RICHTER, K., SELL, W. & WALDEN, H. (1973): Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project. Deutsches Hydrographisches Institut, Hamburg.

ISELI, C. (1995): Zehn Jahre Schilf- und Uferschutzmassnahmen am Bielersee. Schriftenreihe Verein Bielerseeschutz **4**.

KAMPHIUS, J. W. (2000): Introduction to coastal engineering and management, pp. 81–116. Singapore.

LASEN (2001): Vents à Changins (VD). Laboratory of Energy Systems (LASEN) – Swiss Federal Institue of Technology Lasuanne (EPFL). Lausanne (unpublished).

MANGOR, K. (2001): Shoreline management guidelines. Denmark.

MATHEJA, A., SCHWARZE, H. & ZIMMERMANN, C. (2000): Simulation von Sedimentation und Erosion in Lahnungsfeldern. Franzius-Intitute for Hydraulic, Waterways and Coastal Engineering, University of Hannover, pp. 1–21.

OSTENDORP, W., ISELI, C., KRAUSS, M., KRUMSCHEID-PLANKERT, P., MORET, J.-L., ROLLIER, M. & SCHANZ, F. (1995): Lake shore deterioration, reed management and bank restoration in some Central European lakes. Ecological Engineering **5**: 51–75.

USACE (2001): Coastal Engineering Manual. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C.