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Restoring flow capacity in the Loire River bed

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Abstract:

During the 19th century oblique groynes were built in the bed of the Loire River, with the aim of channelling the river during low flow in order to maintain sufficient navigation conditions on a permanent basis. The long-term effect of these structures, in combination with massive sediment extraction over the past 50 years, has been to deepen the minor bed and aggrade old flood-prone areas. The goal of the present study was to restore the original flood conveyance properties of the river bed. The methodological approach combined refined flow modelling using the TELEMAC-2D program with traditional morphological expertise. Justifications for making this choice over alternative methods are given.

Constraints and objectives for site correction were determined by multidisciplinary analysis. In particular, this included an environmental analysis aimed at preserving the area's fauna and flora and at restoring its former ecological diversity. The analysis also concerned the hydromorphological behaviour of the system. Proposals for site corrections are described. These essentially involved modifying the structures and dredging in order to recover flow conditions whereby the secondary branches of the river bed would be self-maintaining. The main objective of lowering flood levels was thus achieved, together with some restoration of the ecological diversity of the river system. The study was an opportunity to compare a now well-established method for 1-D fluvial modelling with specific 2-D modelling aspects. It is an example of the progress that can be made by combining advanced modelling results with more traditional approaches. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS river morphology; sediment transport; Loire River; 2-D flow modelling

OBJECTIVES

Shipping on the Loire River in France has long been of great economic importance, but in the past it was threatened by the irregular flow regime and, in particular, by severe droughts. Many spots along the river were equipped during the 19th century with oblique groynes with a view to maintaining a single bed and sufficient depth conditions during the low-flow season. Nowadays, these groynes, known as 'chevrettes', are part of the landscape, but their presence, combined with massive extraction of bed material during the last 50 years, has led to a transformation of the river bed. The minor bed has deepened as expected, but secondary branches and wide floodable areas have been overgrown, resulting in a severe reduction of flow capacity during floods and local elevation of flood water levels. The structures themselves, which were made of masonry, are often in bad shape, sometimes partly destroyed, and sometimes covered by trees. Deposition and plant growth near these structures has built up islands within the river bed, the height and effect of which on flood conveyance are often greater than those of the structures themselves.

One of these sites is located a few kilometres downstream of the confluence with the river Allier, 530 km

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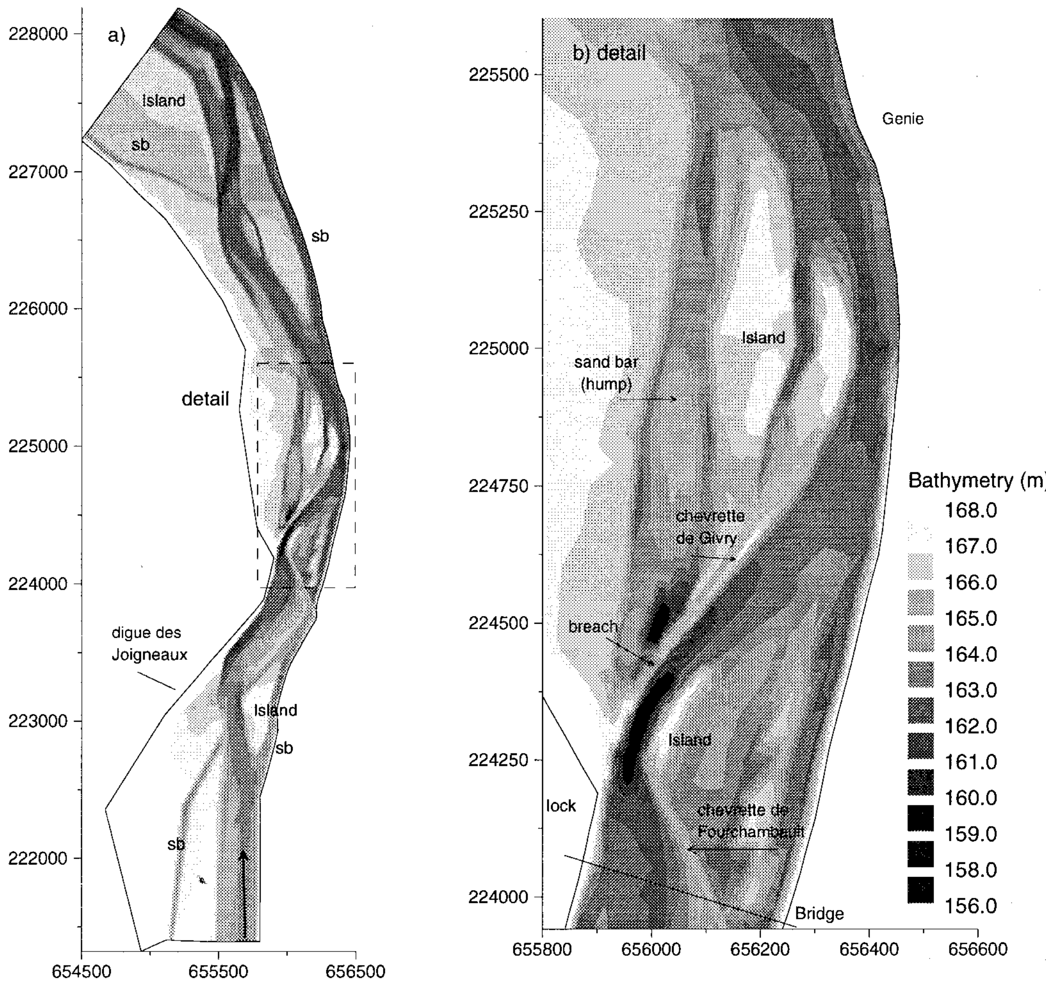

Figure 1. Site description and topography (plan views are referred to Lambert III Projection System in metres. (a) Full site, (b) detail of the central area

upstream from the river mouth. Figure 1 shows the site from upstream (lower part of the picture) to downstream. Important points to note are:

1. a dike on the left bank, 'la digue des Joigneaux', which forces flow into a narrow section under Fourchambault bridge;
2. a first oblique groyne, 'la chevrette de Fourchambault', anchored on the right bank, which in low flow conditions forces the river towards the left bank;
3. a second oblique groyne, 'la chevrette de Givry', and the extremity of the 'chevrette de Fourchambault' makes a channel toward the right bank — the reason for creating such a strange flow pattern was the need to enable shipping from Givry lock, on the left bank, to old iron plants on the right bank ('Genie').

In 1996, the Laboratoire d'Hydraulique de France, a subsidiary of SOGREAH, was commissioned by the Regional Environmental Agency (DIREN Centre) to carry out a study aimed at restoring the river's original flow capacity, in connection with the maintenance of these old navigation structures.

METHODOLOGICAL ALTERNATIVES

Complete changes in methodological practice are currently taking place in most fields of engineering, mainly driven by the rapid changes in economic conditions and also by the development of informatics. Our domain, river engineering, provides good examples of such trends. If one reviews the recent history of morphological and sediment studies, this paper could be considered as a complement to another paper that we devoted to the history of sediment modelling (Belleudy, 1994):

Up until the last 10 years, river morphology was considered as such a complex subject that relevant questions were put only to so-called 'experts', i.e. specialists with long experience and a good grasp of physical realities. Also, because of the complexity of the subject, caution was certainly not a fault, and technically speaking reasonable work was done.

Mathematical modelling has achieved a high level of refinement in the description of physical processes. In the domain of river morphology in particular, extending the possibilities offered by computers led to high ambitions, e.g. 1-D sediment transport models taking account of unsteady flow, with coupled calculation of the transport of sediment mixtures, development of sand dunes, separation of bedload and suspended load, etc. (see e.g. Belleudy, 1992). A great numerical challenge was thus overcome but methodological questions arose. Many of these questions concerned the validity of bringing together in a single model several theories that originally were developed to describe a single process. Other questions related to methods and data for calibrating such models, their initialization (Belleudy and Schuttrumpf, 1994) and the assessment of the validity of the results. Initial experience has demonstrated that such modelling requires a great understanding of physical processes and their formulation.

The physical processes involved in the present study included 2-D flow, unsteady transport of graded sediment, and sometimes 3-D flow over structures. Three options were therefore available for developing the methodological approach:

1. To take the opportunity of carrying out a demonstrative hi-tech study, i.e. in a word an innovative 2-D river model, including calculation of sediment transport and deposition. Such an option can be seen as a 2-D extension of the questions and uncertainties of sedimentation modelling. This would be an interesting scientific challenge on the one hand and a novel demonstration on the other, but ultimately a little hazardous in the context of an engineering study that calls for practical conclusions.
2. A second option, although still remaining innovative, would be to use 2-D river modelling for flow field calculation as an input to more traditional expertise. The advantage here would be that a definite answer could be found to the question. This option is also challenging for the expert because it provides his/her expertise with some additional tools. It is also a good opportunity for passing on such expertise with the prospect of improving modelling methodologies. This is the option that was chosen.
3. Being less ambitious, that is sticking to traditional methods (with or without the aid of 'the expert'). Economically, this is the safest option. The risk is that only a partial answer will be given to the questions raised by the project. This last option was discarded, as it was without question the least challenging and least exciting.

THE DIFFERENT STAGES OF THE STUDY

Environmental analysis

The 'Plan Loire Grandeur Nature' is a development and protection programme, the main concern of which is the full restoration of the flow capacity of the Loire valley, with the aim of reducing flood risks. Such a comprehensive objective involves local flood protection, preservation and restoration of the ecological qualities of the river, and lastly the acceptance or preferably the support of the people living along the river, always bearing in mind their local needs and concerns.

As the general objective of lowering flood levels and giving a better flood conveyance capability to the river bed is well defined, a refined analysis of the local ecological characteristics had to be carried out. This reach of the Loire River is a particularly rich one. The region is a refuge for migrating birds. The underwater ecology is also very rich, as the project areas provide some of the most valuable spawning grounds for pike (*esox lucius*) along the entire river. Sociological concerns and demands, especially with respect to heritage conservation, also needed to be analysed as a preamble of the study. Picturesque landscapes and historic navigation structures could be valuable assets for tourism. Such analysis defined the various project constraints. Preserving the ecological qualities depends mainly upon maintaining these very particular areas near the mean water level, which are frequently submerged. The current need not be very strong but there must be sufficient bed mobility to prevent trees from colonizing the area.

Sediment transport characteristics

A remarkable constant of the Loire River is the distribution of its sediment material (Babonaux, 1970). The minor bed is generally covered with pebbles with diameters ranging from 0·005 m to 0·010 m. The material forming the sand bars is a degree finer (mean diameter $d_m = 0{\cdot}002$ m). Such areas are submerged by small floods and are subject to considerable exchange of material, giving the Loire the characteristics of a wild, natural river. Higher parts of the bed (often between embankments) are made of fine sands ($d_m = 0{\cdot}0006$ m), which are transported during very high floods (frequency > 5 years). Initiation of sediment transport and deposition thus takes place at very distinct discharge ranges for the different parts of the river bed.

Considerable quantities of sediment were extracted from the Loire, especially in the middle of its course, in the period 1945–1980. It is commonly acknowledged that the equivalent of 400 years of bedload transport was removed from the bed during these 35 years. As a result of this deficit of material, the natural slope of the river ($S_0 = 0{\cdot}00045$) has been reduced and the sand banks are less mobile, thus allowing vegetation to develop. The secondary branches of the braided channel have even tended to disappear as a consequence of plant growth. At the same time agricultural and human uses of the river banks have changed. Bushes and forests have developed on the highest parts of the bed and on the islands between the different channels, which previously were maintained as pasture land. The ancient practice of 'essartage', that is cutting firewood from the river bed, has disappeared. The result is a 'channelling' of the river bed, with a certain deepening of the minor bed but with an overall diminution of conveyance during floods. Examples of such secondary branches can be seen in the topography (sb on Figure 1) away from the central area.

Impact of flow navigation structures

Navigation structures were efficient for the purpose for which they were designed, i.e. improving navigation conditions during low flow seasons, but they considerably upset the bed morphology. The particular flow pattern during floods was responsible for sedimentation behind the structures at points where the flow lines bend. As these areas were submerged less frequently (because of the deepening of the main channel) vegetation developed and retained sediment more easily during floods. As a consequence of this process, wooded islands higher than the dike itself developed. A comparison of the present situation with pictures taken in the 1950s shows that the same process is taking place in the central area behind the 'chevrette de Fourchambault' (at which point it is the result of lowering of the friction slope produced by the higher downstream water level during floods).

Previously, little sediment crossed the 'chevrettes' and a secondary channel could develop behind, along the bank. This secondary channel was of great importance, because it helped to convey flow during floods. It was also of great ecological value because of its normally quiet waters with, generally, a deep scoured area just behind the 'chevrette'. An important feature is a breach in the 'chevrette de Givry' near its connection to the left bank (a result of bombing during World War II). High sediment load passing through the breach (at the worst location on the bend) was not balanced by a sufficient discharge. This sediment settled within the secondary channel, and has built the large mound that can be seen on Figures 1 and 2.

The main objective of the project was to lower flood levels upstream:

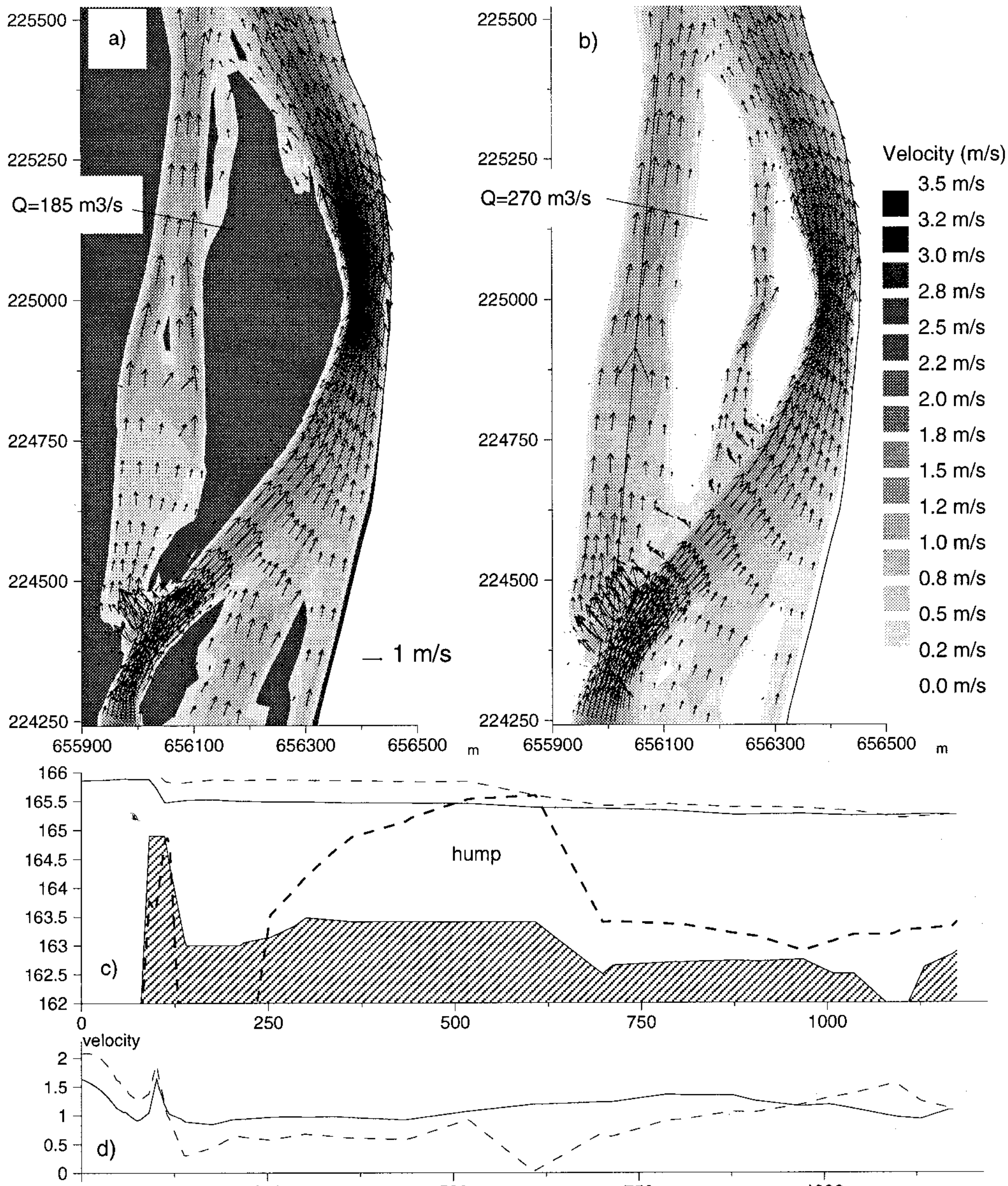

Figure 2. 'Chevrette de Givry' total discharge = 884 $m^3 s^{-1}$. (a) Present flow pattern; (b) after proposed modifications; (c) bottom and flow profiles (dotted lines: present; solid lines: proposed); (d) velocity profiles

1. in order to reduce flooding risks, in particular above the bank at Joigneaux;
2. to increase the friction slope in the secondary branches in the upstream part of the area, enabling them to be maintained naturally by restoring sediment transport (a condition for preventing plant development).

An analysis of flow patterns showed that head loss occured downstream of areas of high velocity (greater than 3·5 m s^{-1} in certain areas). Such high velocities are also responsible for scour and the deepening of the minor bed, and for weakening structures such as the 'chevrettes', but also bridges and embankments.

A better distribution of flood discharge is a prerequisite for reducing head losses. The conveyance capability of the secondary branches must be increased during floods. The resulting redistribution of flood discharges will help to reduce velocities within the main channel. For ecological and economic reasons the necessary increase of conveyance capacity in the secondary branches must be achieved with minimum artificial dredging. A more regular velocity and friction slope distribution is therefore essential to prevent further sand deposition. Moreover, regular flushing of sediment or at least removal of the coarsest material must occur at least once a year in order to prevent vegetation (willow trees, *Salix alba*) from developing and colonizing the area.

The modification that has taken place in the bed morphology is too great to be reversed. Complete elimination of the structures is not desired. In particular, it would be inefficient to remove the islands that have developed behind the structures and this could even lead to a situation worse than present conditions. However, the present situation is no more acceptable, because the current tendency is towards the complete elimination of the secondary branches, with a consequent worsening of flood levels, and a great loss of biodiversity. Moreover, the present conditions, which are characterized by high flow velocities and the development of trees near, or within, the structures, accelerates their decay and destruction.

Proposals and expected results

Final options for site correction were defined after a series of simulations. The most characteristic features are detailed hereafter with special emphasis on the contribution made by TELEMAC-2D modelling. Changes in the bed occur during floods. However, morphological stability has to be assessed on the basis of annual flow patterns and flood frequency. Typical steady flow conditions were therefore selected. The corresponding discharges are $Q = 884\ m^3\ s^{-1}$, $1920\ m^3\ s^{-1}$, $3000\ m^3\ s^{-1}$.

1. $884\ m^3\ s^{-1}$ is approximately the discharge of the largest annual sediment flux. At this stage there is considerable flow over the oblique groynes, and such conditions are representative of those which cause the present deposition behind these structures.
2. $1920\ m^3\ s^{-1}$ is the peak discharge of the annual flood. Comparatively, structures are less of an obstacle to flow than sediment deposits. In these areas, conditions for sediment mobility must be satisfied in order to avoid colonization by vegetation.
3. $3000\ m^3\ s^{-1}$ is the peak discharge of the 10-year flood. Flooding of the entire bed occurs. The final objective of the study was to ensure a significant lowering of the water level for such flood discharges.

Observed flow conditions at $Q = 884\ m^3\ s^{-1}$ and $Q = 1920\ m^3\ s^{-1}$ were actually used for validation of the model. The proposals were also checked in low and medium flow conditions ($60\ m^3\ s^{-1}$ and $350\ m^3\ s^{-1}$), where a higher flow level should favour ecological diversity and fish spawning.

'Chevrette de Givry'. The first priority was to repair the damage resulting from the breach in the dike. The objective here was to increase discharge behind the groyne during floods in order to flush out sand deposits or at least to maintain sufficient shear conditions for a secondary channel to be self-maintaining. This could be achieved by repairing the breach, and by lowering the crest elevation of the dike by almost 1 m. Minimum artificial dredging homogenizes the flow velocity pattern (Figure 2c), thus creating self-dredging conditions, which can be checked on the longitudinal profile of scalar velocity along the secondary channel (Figure 2d). Lowering the crest elevation and selective cutting of the vegetation ensures that floods will continue to spill over the groyne. The discharge through the secondary branch is raised from $185\ m^3\ s^{-1}$ to $270\ m^3\ s^{-1}$. Present and future flow patterns are displayed in Figures 2a and 2b, with a significant reduction in flood levels ($-0{\cdot}30$ m for $Q = 884\ m^3\ s^{-1}$) in the downstream part of the main channel.

'Chevrette de Fourchambault' and upstream. Because of the increase in friction slope, a lowering of the flood water level ensures automatic self-dredging of the sand bars downstream of the 'chevrette'. A negative

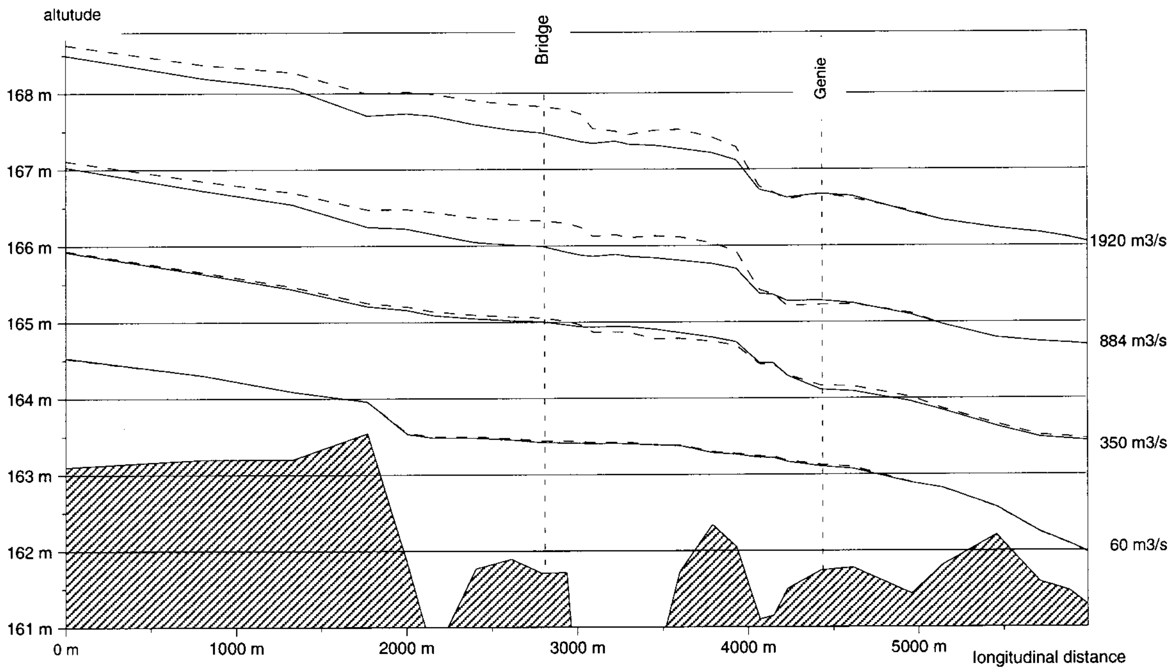

Figure 3. Flow lines along main channel (dotted lines: present–solid lines: proposed)

effect, however, is an increase in flow velocities at the most critical area near the left bank anchor of the lower groyne ('chevrette de Givry').

The second important corrective measure was aimed at increasing the flow cross-sectional area. The elimination of the extremity of the upper groyne and the small island that has developed on it was proposed to achieve this. The modifications are partially described in Figure 4 (section A). However, lowering flow velocity (maximum velocity for discharge 884 $m^3 s^{-1}$ at present is 3·5 m s^{-1} and this will become 2·8 m s^{-1}) will bring about a significant reduction in the head loss and thus an effective lowering of flood levels in the upstream part of the area (see flow lines on Figure 3). An additional measure was therefore to initiate self-dredging conditions in the secondary channel in the upstream part of the study area, with a view to decreasing flow velocity along the left bank dike and taking advantage of water level reductions upstream of the area under study.

Dumping of dredged material. Corrective measures to restore flow diversity and the ecological properties of the site involved the elimination or displacement of materials from the bed. The total amount of dredging was minimized and conceived only as a way to initiate self-dredging flow conditions. However, a total volume of approximately 160 000 m^3 is involved, consisting mainly of intermediate sand material (mean diameter $d_m = 0{\cdot}5$ mm). A coarser mixture is also expected whenever the structures are modified, as their constituent material after the stone masonry is removed.

Sand extraction from river beds is now restricted by law in France. In order to prevent river engineering from becoming a pretext for removing material, any material derived from such corrections must be released within the river bed itself. The project therefore faced additional challenges:

1. to minimise distance, and optimise transportation for economic reasons;
2. to minimise ecological disturbance, in particular with respect to fish;

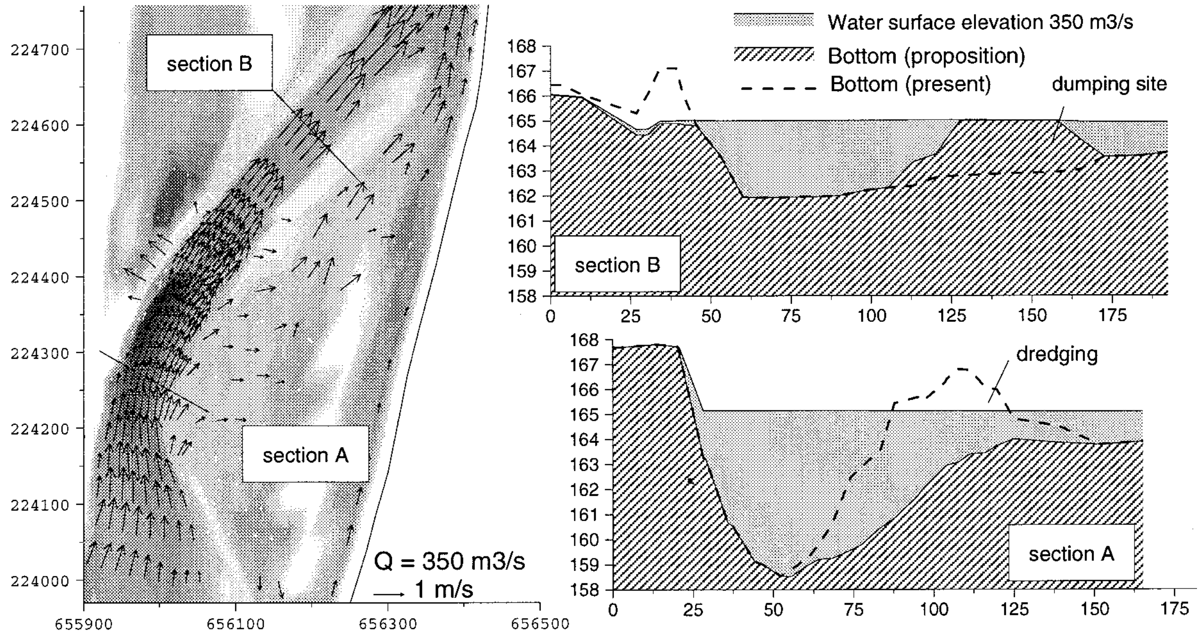

Figure 4. 'Chevrette de Fourchambault': (a) Flow pattern; (b) cross section A, rectification and dredging upstream; (c) cross section B, dumping of dredged material

3. to not create significant new head losses, and in particular to avoid the stabilization of such dumping areas which could have the same effect as the corresponding material in the present situation.

Direct dumping of these materials into the low flow bed, in high velocity areas, where there is also deep scour, would produce a large amount of suspended load, especially if the works are carried out during low flow conditions. This would have a great ecological impact on a long reach of the river, in particular because of the few possibilities for fish to escape to shelter in less disturbed areas. Such direct dumping was therefore ruled out.

The 'strategy' was to dump this material on sand bars to allow it to be carried away progressively during small floods, with a high probability of total elimination within 1 year after they have been dumped and no risk of stabilization by armouring or vegetation. The current sediment deficit of the Loire River will probably encourage such a process, which will restore some of the old mobility of the river downstream of the study area, at least for some years.

The coarsest sediment ($d > 20$ mm) derived mainly from the groyne structures will be dumped in areas within the river bed, but which do not really participate in flood conveyance. Such areas were investigated with the aid of the mathematical model, and the variety of analysis tools available in TELEMAC and RUBENS. The detailed operations for designing and sizing the intermediate dumping area are illustrated in Figure 4. This area receives fine sediment from rectification work on the end of the upstream groyne (approximately 50 000 m^3). Material is transported 200 m on average and dumped on the sand bar along the low flow channel. The deposit builds a 200 m long by 50 m wide mound, the elevation of which is limited to the water level corresponding to average flow conditions (350 $m^3\ s^{-1}$ exceeded on average 140 days a year). The total volume of the deposit (34 000 m^3, calculated by the RUBENS post-processor) is sufficient for the estimated volume of fine sediment resulting from correction of the groyne.

CHARACTERISTICS OF THE MODEL

The TELEMAC-2D modelling system was used for the study. Its characteristics and main features are described in several papers (e.g. Hervouet and Moulin, 1994; LHF, 1997). Topographic data included 15 'traditional' cross-sections (transverse profiles) of the river bed, with the distance between profiles ranging from 500 m to 150 m in the central area. Additional levelling of the structures was also undertaken in order to construct the model. Topographic data used for the model were levelled entirely during the year preceding the study. Figure 5 displays the 2410 node by 4625 mesh computational grid of the model. Mesh sizes vary from a metre in sensitive areas, e.g. where strong velocity gradients were expected or in the case of strong bathymetric gradients, to 50 m in flood-prone areas not directly connected to the central area, where less precision in the results was required. More elongated meshes were designed within the minor bed and wherever the flow direction was known in advance, in order to reduce the computational cost.

The Strickler roughness coefficient was defined according to vegetation cover or surface characteristics (from 12 for woody areas to 37 for the minor bed and 45 for sand banks). Such coefficients were adjusted as part of a minimal calibration of the model. Adjustments were made in order to obtain a good reproduction of the water level measured at various points of the site and for different flow regimes. The calibration also attempted to reproduce a number of representative measurements of the discharge in secondary branches. As confirmed by our experience in river modelling, the Strickler value is in general higher by a factor of 1·3 than it would have been for a 1-D model.

Groynes were described with their real geometry, and overspilling is computed by the same de-Saint-Venant equations as for the river meshes of the model. This is not the usual way and deserves more comment.

Flow through structures is usually computed by classical head-loss formulations, which are relationships between discharge and water surface elevation on each side of the structure. A discharge (or head-loss coefficient) is given to the structure according to its shape and is often calibrated by comparing the calculation with measurements. Using such formulations, it is not easy to take account of the velocity upstream of the structure. Moreover, classical head-loss formulations are designed for cases where the structure is perpendicular to the direction of flow, or else parallel to it, as in the case of lateral weirs.

In the present case, the flow direction during overspilling is oblique and it is impossible to define in advance the angle between the flow line and the centre line of the structure, i.e. to define where the upstream and downstream points of the flow line are for the calculation. The computational grid had thus to be refined near the groynes (see details on Figure 5), but computation times were kept within reasonable limits. The validity of this option for groyne modelling was confirmed both by comparison with scale model test cases performed at the Laboratoire National d'Hydraulique, and by comparing the results with measurements made on site.

CONCLUSIONS

Confirming our experience

Two-dimensional river modelling, and especially its applications to river bed morphology, can be considered as a relatively new technique. At the present stage, every new study produces new questions, or at least a piece of experience that deserves some analysis. The most significant results in the present case concern (i) requirements and specifications for topographic data, (ii) assessment of the validity of the modelling and (iii) indicators for morphological analysis.

Topographic data. It is obvious that such 2-D river modelling, which gives a more detailed description of flow than traditional 1-D modelling, requires an additional degree of precision in the description of the topography. Whereas 1-D modelling requires the input of user expertise in determining appropriate cross section spacing because of the importance of schematization, this need is (relatively) minimized in 2-D modelling and counterbalanced by the need for a precise topographical description.

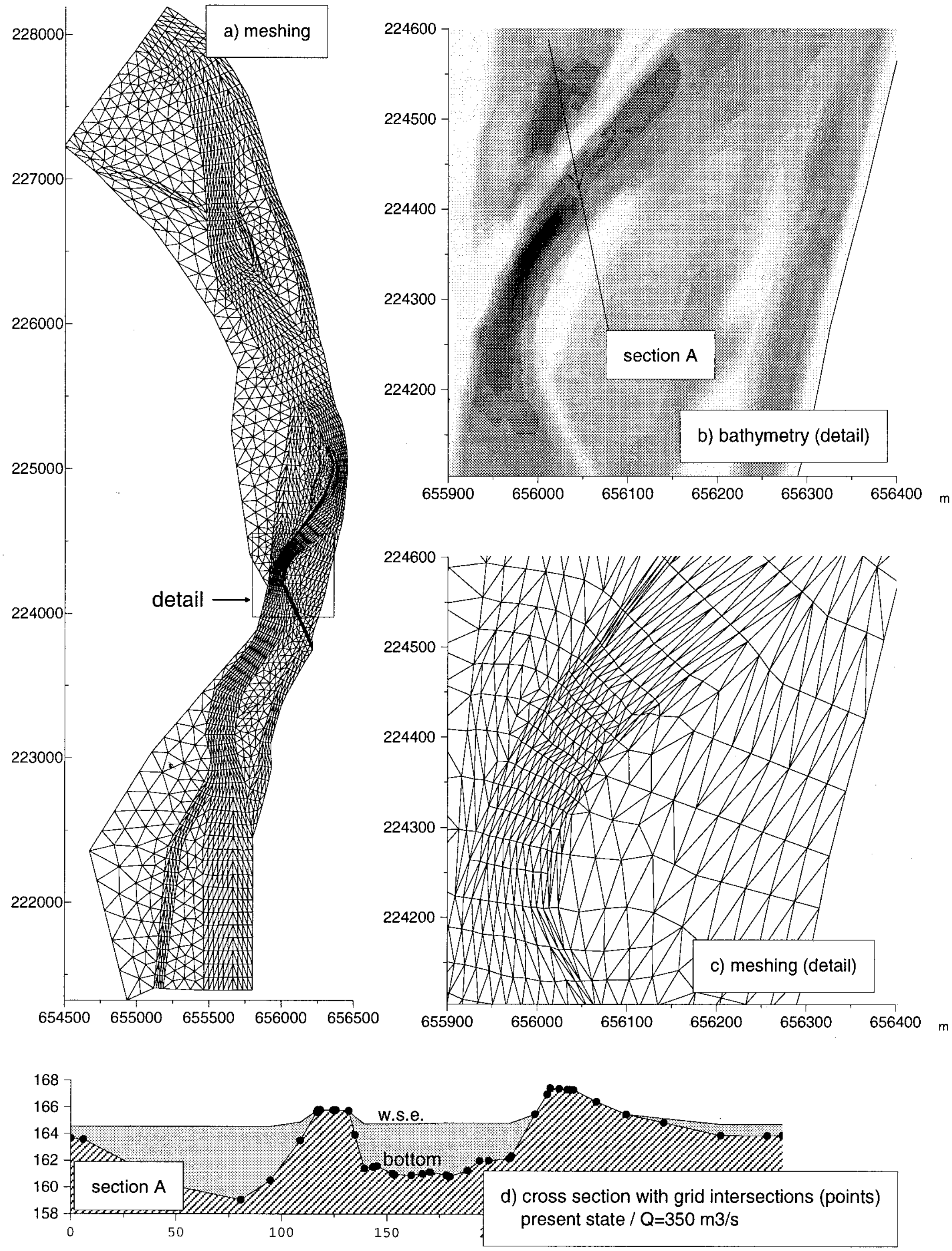

Figure 5. The computational grid of the model

An illustration can be given of two different cases:

1. One-dimensional river flow modelling is based upon a good reproduction of the wetted area and wetted perimeter. It nevertheless tolerates some imprecision with regard to the detailed geometry, which would not be acceptable for a 2-D model. On the other hand, the 1-D modeller is often confronted with serious difficulties when building a model to be used for a large range of flow conditions, especially in the case of confluences, that are not encountered by the 2-D modeller.
2. Where a digitized elevation model is required for 2-D floodplain modelling, a much simpler description of available storage (volume versus elevation) and the characteristics of exchanges (e.g. bank elevation) is necessary with a cell-based modelling system (of the CARIMA or ISIS type, for instance). In the former case, however, the modeller must make a reasonable a priori estimation of the flow pattern within the floodplain when designing the model (the cells and their connections).

Further steps are undoubtedly needed in this direction, for example in the specification of more complete topographic data requirements for 2-D river models.

Validity of flow modelling. Although the author has confidence in the management recommendations that were made, he is nevertheless conscious of the poor justifications given for the validity of the modelling itself. At least two items should be discussed, i.e. (i) roughness/head losses and (ii) the requirements for the validation of the modelling.

The Manning–Strickler coefficient for regular head losses is a lumped or global measure that not only includes grain and form roughness but even variations in shape and size of the channel cross-section, obstructions, vegetation or meandering (Cowan, 1956; cited by Ven Te Chow, 1959). The methods for the evaluation of global head-loss relationships in compound channels are still under debate in the abundant literature that is produced on this subject. Engineers familiar with 1-D river modelling rapidly acquire a certain skill in the determination of global head-loss coefficients. As a matter of fact, 1-D modelling, which used to be the only practical possibility 10 years ago (with or without cells), should now be replaced by 2-D modelling as standard engineering practice whenever domain complexity and precision demand it. A smoother Manning–Strickler coefficient (factor of 1·3 already noted) is then required because momentum exchanges within the cross-section are part of the system of equations. Another question concerns the validity of the Manning–Strickler relationship for the description of regular head losses when vegetation height is of the same order of magnitude as the water depth:

$$q = k_{str} h^{5/3} \sqrt{S_f}$$

where q is the discharge per unit width, k_{str} is the Strickler coefficient, h is the water depth, and S_f the friction slope.

For example, according to Lefort, a Borda type head-loss expression also could be considered, which would result in a similar formulation but with an exponent of 1 for h

$$q = \frac{1}{\lambda} h \sqrt{S_f}$$

where λ is a head loss coefficient [dimension L^{-1} T].

Specifications for validation data

A good reproduction of water level measurements is generally accepted as a good criterion for assessment of the validity of a hydraulic model. This is particularly true where water levels are the pertinent parameter (e.g. for flood calculation). We were able to confirm that the model developed in this study was able to achieve such a prediction because measurements of the water level were immediately available. However, this is certainly not sufficient for simulations of sediment transport and stability as these are dependent on other characteristics of flow. In our case, some measurements of discharges in secondary branches were undertaken, which could be used to confirm that the mechanism of flow within the braided system was well reproduced by the model. Ideally, more precise descriptors, e.g. a flow velocity field, should be used for validation of such models. Further investigations should also be conducted to enable specification of measurements and procedures that are sufficient for assessment of the validity of the morphological modelling but are also optimized, economically and technically speaking, in the context of engineering studies.

Indicators for morphological stability. During the study, our main indicator was the scalar value of flow velocity, because it enabled both morphological stability assessment and analysis of head loss reduction. Such an indicator was considered despite the relatively incomplete description of sediment mobility conditions that it can give, because priority was given to human expertise in every stage of our study, and also because it could be calculated immediately by TELEMAC and because of the need to use easily understood concepts when describing the study and its results.

A further step will be made to involve 2-D mathematical modelling in analysing more complete indicators of the shear conditions that are responsible for sediment transport. Naturally, those investigations are limited to bed surfaces that are neither cohesive, nor covered by any vegetation. Some attempts were made during the study, and are presented in this section.

Figure 6 displays for the same flow conditions (a) the flow velocity field, (b) the scalar value of velocity V, (c) the scalar value of the friction slope S_f, and (d) the shear velocity U^* typically considered in studies of sediment mobility. Shear velocity was calculated as

$$U^* = \sqrt{ghS_f}$$

where g is acceleration of gravity, h is depth of water, and $S_f = q|q|/K^2$ is friction slope, with q the discharge per unit width and K the conveyance per unit width.

Comparison of scalar velocity and shear velocity shows little difference and validates our choice. A great difference is noticed at the groynes (where flow conditions are nearly critical at such a discharge), or in the case of high velocities combined with subsequent major scouring when morphological equilibrium is reached (area A). Such scour could not happen in area B because of the fact that rock outcrops protect the bed. A great difference can be noted between friction slope and shear velocity in the case of shallow depths.

Another attempt was made to check the mobility of dumped material during annual flood discharges by calculating the dimensionless shear stress

$$\tau^* = \frac{hS_f}{[(\rho_s - \rho_w/\rho_w]d}$$

where ρ_s is sediment density, ρ_w is water density and d is the characteristic dimension of the sediment.

Figure 7a shows dimensionless shear stress τ^* for annual flood discharge conditions and for mean diameter dumped sediment. The threshold value, as given by Meyer-Peter ($\tau_c = 0{\cdot}047$), confirms the mobility of the dumped material for such a discharge. Another illustration is given on Figure 7b, where, in the same flow conditions and with the same threshold value, sediment mobility is expressed in terms of the 'maximum size of transported sediment'.

A step towards safe, physically sound modelling

As the current trends are to endorse modelling for solving even our most complex problems, or worse to anaesthetize our critical senses and judgement with so-called 'coloured hydraulics' (i.e. brilliant screens with little physical meaning), the benefits that traditional engineering and expertize can derive from modelling have been demonstrated in this study.

One-dimensional modelling can also take advantage of such experience with 2-D schemes, for instance in flow modelling, where comparisons between 1-D and 2-D models may help to determine the techniques and

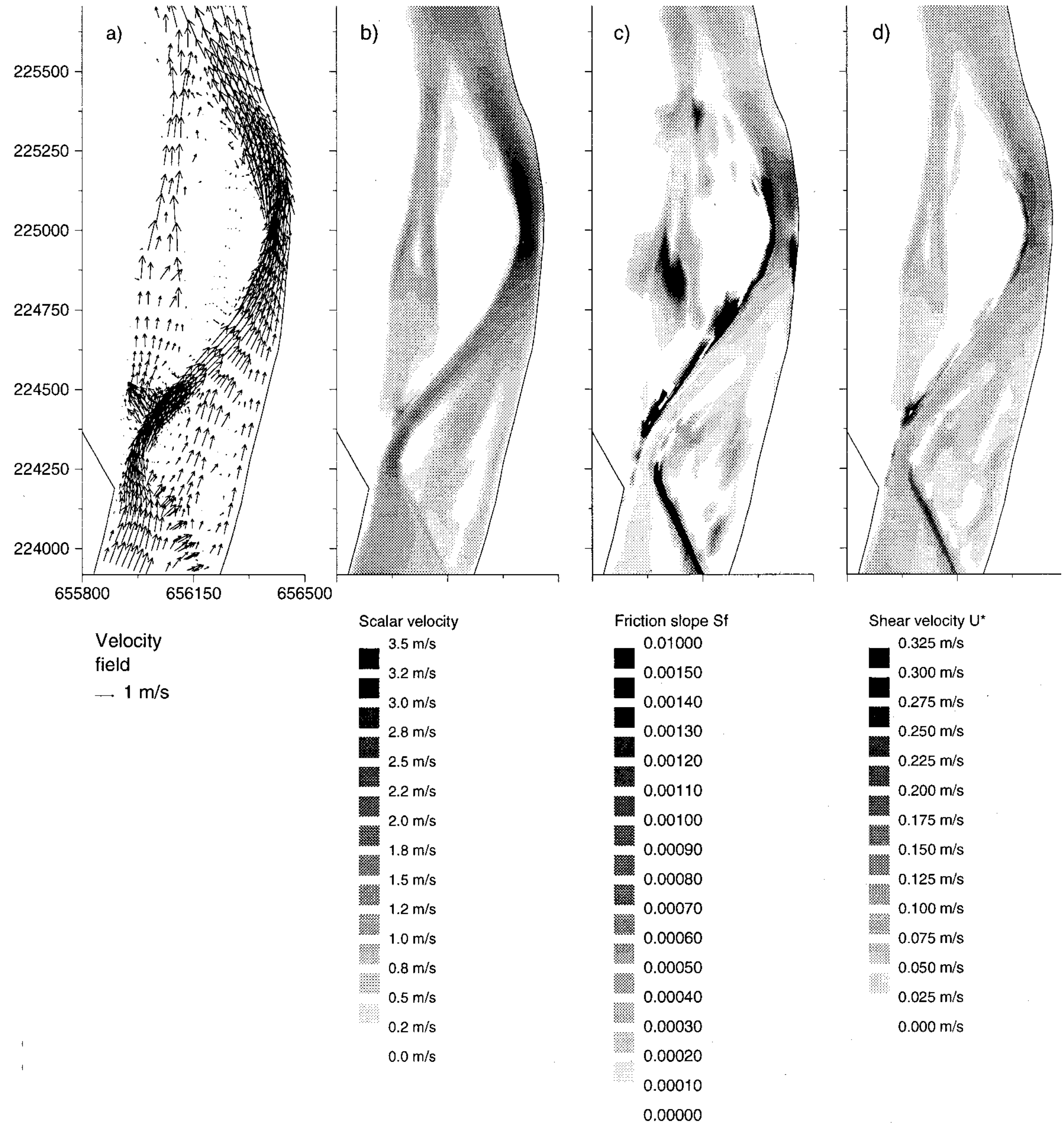

Figure 6. Indicators for morphological stability assessment. (a) Flow velocity field; (b) scalar value of velocity V; (c) scalar value of the friction slope S_f; (d) shear velocity U^*

limits of schematization, or in sediment modelling, for example as a guide for modelling bank erosion or non-uniform cross-section erosion. This raises the symmetrical question: how far can we go with 2-D in the case of 3-D processes? Where are the limits and how can they be treated? The final conclusion is to point out what we consider to be one of the greatest challenges in river morphology, i.e. the interactions between vegetation, hydrology and river sedimentation.

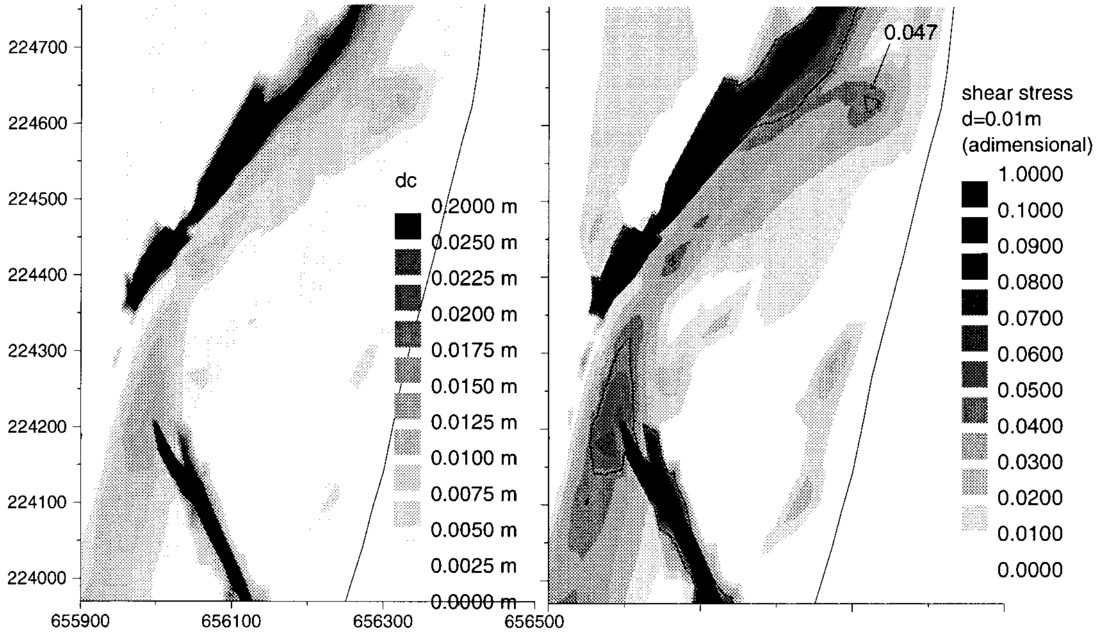

Figure 7. Indicators for morphological stability assessment. (a) Dimensionless shear stress; (b) critical sediment size

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