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Hydroinformatics support to flood forecasting and flood management

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Abstract This keynote paper describes state-of-the-art hydroinformatics support to the water sector. A few examples are worked out in some detail, whereas for other examples the reader is guided to recent literature. The focus is on flood forecasting and flood management, with a brief description of the potential of changing technologies that support studies and facilities in this area. Examples are: new data collection methods; data mining from these extensive new sources of information, e.g. the use of genetic programming; data driven modelling techniques, e.g. artificial neural networks; decision support systems; and the provision of a hydroinformatics platform for flood forecasting. Particular attention is given to advances in numerical flood modelling. Over recent years the robustness of numerical models has increased substantially, solving for example, the flooding and drying problem of flood plains and the computation of supercritical flows. In addition, the emergence of hybrid 1D2D models is discussed with their different options for linking model components of flood prone areas.

Key words data mining; flood forecasting; flood management; flow resistance; flood simulation modelling; hydroinformatics; Open MI; open source; proprietary software; unsteady flow modelling

INTRODUCTION

Hydroinformatics covers the application of information technology to the water sector in the widest sense. The continuously increasing speed of computers and increased density of information storage, the increased communication potential through the Internet, and the creative power of scientists have brought us rapid progress in the way in which water related studies can be executed; they are currently based upon a much better understanding of underlying processes and their description than some decades ago. For a better awareness of what is being opened up with these developments, participation in the biannual Hydroinformatics conferences (e.g. Nice, 2006; http://www.hic06.org) is recommended. This paper refers to contributions published in the proceedings of the 2004 Hydroinformatics Conference (Singapore). Other recent sources of information are the contributions related to hydroinformatics published in the *Encyclopaedia of Hydrological Sciences*, e.g. Werner *et al*. (2005), Minns & Hall (2005), Stelling & Verwey (2005). Here we give an outline of various interesting developments and treat, on a selective basis and in more detail, some specific issues in relation to flood forecasting and flood management.

HYDROINFORMATICS TOOLS

The focus on hydroinformatics emerged from the field of computational hydraulics when it was realized and felt desirable that, around the modelling systems developed in the last three decades of the last century, a complete infrastructure of informatics support existed and that its potential had to be explored and expanded to improve service to society. Hydroinformatics comprises data acquisition and data management techniques; new simulation techniques based upon cognitive sciences and pattern recognition, such as artificial neural networks; data mining and knowledge discovery techniques; evolutionary algorithms; decision support and management systems; forecasting and data assimilation methods; fuzzy logic; cellular automata; integration of systems and technologies; and emerging internet based technologies. A state-of-the-art description of new technologies applied in the area of ecohydraulics was given by Mynett (2004). Historically, balance equations or empirical relationships were developed by scientists, e.g. Newton, Navier, Poisson, de Saint Venant, Stokes, Darcy, de Chézy, Strickler and Manning, by trying to define fundamental relationships between various system state variables on the basis of observations and by setting up balance principles, partly based upon the empirical relationships found. A thorough presentation of the role of various scientists is included in the work of Chanson (1999). Hydroinformatics can now be seen as providing an extension to these developments, partly by using computer power to guide and process new and massive data collection techniques, and partly by leaving it to computational power to establish best fitting new relationships, often in areas which could not be explored before. The change that hydroinformatics really brings is a change in the role of scientists, from those who establish laws to those who guide the establishment of laws and relationships by mobilizing computer power.

A good example is the use of artificial neural networks (ANN), which can be seen as an extension of the traditional use of regression techniques, e.g. Minns & Hall (2005). However, whereas in regression techniques formulae have to be prescribed and parameters calibrated, ANN provides the additional flexibility that the relationships between state variables, or the formulae, are left open, in fact never defined, as all the relationships established are based upon signals passed on through a sequence of (neural) cells with weightings established by the so-called learning process through numerous trials. Compared with the human mind, only one thing is missing: the ability to extrapolate the knowledge outside the range where the learning process took place, but even many humans have difficulties with such extrapolations. Although ANNs have opened up the way to new simulation techniques, the learning process shows clearly their limitation, for example in rainfall–runoff modelling, where physically-based balance models, equipped with appropriate limiters, can be used more trustfully in extreme situations that go beyond earlier observations.

A step beyond ANN is the employment of sets of data to establish empirical relationships in the form of mathematical expressions by using evolutionary algorithms. Unlike ANNs, where the development process of knowledge in the human brain serves as an example for computer-based knowledge development, evolutionary algorithms take the biological reproduction process as the blueprint for the derivation of mathematical relationships. By seeing state variables, operators and parameters as components of DNA strings, recombinations of substrings, together with the process of mutation leads, in a learning process, to continuously better matching of mathematical relationships in a “survival of the fittest” process. A recent example that serves flood modelling is given by Baptist *et al.* (2005). For a number of years, Baptist (2005) has been working on the development of empirical relationships defining the resistance of flow, expressed as a de Chézy value as a function of flow depth and height and type of vegetation. For submerged vegetation, Baptist derived the relationship:

$$C_r = \sqrt{\frac{1}{C_b^{-2} + \frac{C_D m D k}{2g}} + \frac{(h-k)^{3/2}\,\frac{\sqrt{g}}{\kappa}\ln\left(\frac{h-k}{e z_0}\right)}{h^{3/2}}} \tag{1}$$

where C_r is the depth dependent Chézy coefficient [$\mathrm{m}^{1/2}\ \mathrm{s}^{-1}$], C_b is Chézy value for the bottom friction alone [$\mathrm{m}^{1/2}\ \mathrm{s}^{-1}$]; C_D is drag coefficient for flow around the vegetation stems [–]; m is vegetation density [m^{-2}]; D is representative stem diameter [m]; g is acceleration due to gravity [$\mathrm{m\ s}^{-1}$]; k is representative vegetation height [m]; κ is von Kármán’s constant [–]; e is base of the natural logarithm [–] and z_0 = roughness height of the top of the vegetation [m]. The equation was checked on a set of 990 results obtained with a 1-DV (1-Dimensional in the vertical) model based upon the Delft3D code, including a description of turbulence developed around the stems of vegetation.

Rodriguez Uthurburu (2004) and Baptist *et al.* (2007) used the same set of data to train a genetic programming code, and came up with the equation:

$$\frac{C_r}{\sqrt{g}} = \sqrt{\frac{2}{c_D m D k}} + \ln\left\{\left(\frac{h}{k}\right)^2\right\} \tag{2}$$

Figure 1 shows the scatter plots for both equations. Also, based upon RMSE values for both sets: 1.30 for equation (1) and 0.97 for equation (2), it can be concluded that the data-driven discovery process has led to a better fitting equation than the equation derived on the basis of existing theoretical knowledge.

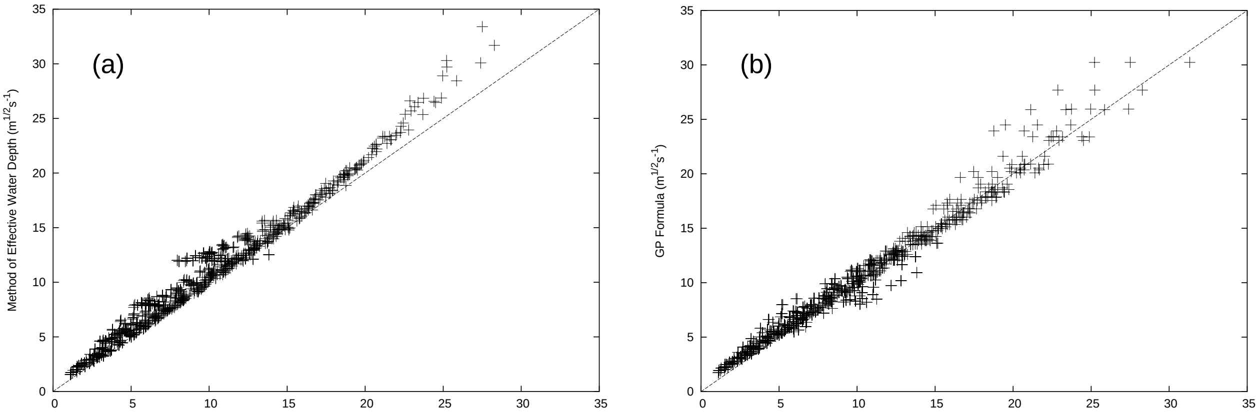

Fig. 1 Scatter plots for the two equations compared with 1-DV data: (a) method of effective water depth, equation (1); (b) original Genetic Programming formula, equation (2).

In a next step, and further analysing the descriptive nature of equations (1) and (2), it was decided to impose the first term of the right hand side of equation (1) and add in the data-mining process the von Kármán's constant κ to the set of parameters. Genetic programming then came up with:

$$C_r = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{1}{2g} C_D m D k}} + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{k}\right) \tag{3}$$

which had an RMSE value of 1.21, between those for equations (1) and (2), but believed to have a wider range of applicability than equation (2). Results were also tested against 177 experimental runs based on laboratory flume experiments from 10 independent sources. In this case the RMSE values are higher, as expected. However, they are still good enough to confirm the usefulness of the data-driven equation development.

The above experiment shows that computer-based technologies provide us with a better means of exploring relationships in nature, either based upon large sets of measured data or upon data generated with very fine grid numerical simulations based upon existing theories. The experiment also shows that the application of these technologies merely provides an extension of our scientific minds and certainly not a replacement. With the current floods of data collected with remote sensing, for example, there must be many ways in which data-mining will assist us in deriving relationships in such complex areas as environmental process description, ecology and unsaturated groundwater zone analysis.

OPEN SOURCE *vs* PROPRIETARY SOFTWARE

When dealing with hydroinformatics, a point of continuous discussion is the question of open source *vs* proprietary software, which is generally provided in the form of compiled executables. This form also implies that the software codes cannot be modified by staff other than those of the software vendors. Discussions on open source software come down to the question of how water resources agencies are best served and how providers of hydroinformatics services are stimulated to provide the best tools. The point of view of the agency is extensively described by Khatibi *et al.* (2004), with inputs from hydroinformatics tool providers. A number of aspects will be presented briefly here. For water resources agencies, interested only in the use of software, the following aspects are of interest:

(a) economical comprehensive solutions for their hydroinformatics infrastructure, e.g. the overall costs for the development of a flood forecasting system, including the forecasting platform, costs for underlying software, costs for model development and calibration, etc.;

(b) reliability of the software products, through good development practices and maintenance of the codes, based upon extensive testing procedures;

(c) openness of the software, enabling the coupling of various components;

(d) reproducibility of results through good version management;

(e) state-of-the-art scientific bases for the methods implemented in the software;
(f) quick response to development needs.

Most of these requirements also apply to vendors of hydroinformatics software, as it is in their interest to provide good service to clients, and this in a competitive environment. Open source is definitely not in the interest of this group, unless special factors play, such as market penetration for other services (e.g. consultancy), name branding and free co-developments by third parties. This last interest sometimes leads to adoption of the concept of "open source in closed community", based upon co-development of codes by a limited group of participating organizations and the right for one or more of these partners to distribute the code commercially.

Here is not the place to draw definite conclusions on what is best practice. With a common sense approach to advantages and disadvantages, the best solution can be found for each case. However, regarding point (c) the difference between open and closed source will be reduced in the near future. Water management agencies, in general, have a strong interest in the openness of software, so that various components can be linked without the need to contract the original developers of such software components. This service is now being developed through the European OpenMI (Open Modelling Interface) concept, which facilitates coupling both of open source and proprietary software components.

OPEN MI

When dealing with water authorities, their own staff and different consultants are continuously implementing bits and pieces of software and often there is neither a contractual obligation nor the means to embed these new service tools into a consistent hydroinformatics infrastructure for the organization. For this reason, the concept of OpenMI (Open Modelling Interface) was developed through the European HarmonIT project, initiated by the Ministry of Transport, Public Works and Water Management in The Netherlands as an important stakeholder. OpenMI has been designed as a generic set of communication rules for linking all kinds of software components available to the water sector. For example, OpenMI facilitates the transfer of data in a generic way and at any moment in time, from one model, e.g. a rainfall–runoff model, to another model, such as a hydrodynamic model, and *vice versa*. More generally, OpenMI facilitates the flexible linking of a wide variety of simulation models, generic modelling systems, databases, GIS, decision support systems, web-based services, etc. (Gijsbers, 2004).

OpenMI is primarily a set of rules on how to exchange data in a pre-defined way. Ideally, within an organization, all software tools should be linkable through a common platform. With the current trend of developing integrated models of hydraulic, hydrological and environmental systems, the development of such platforms becomes even more desirable. Currently, the definition stage of the OpenMI standard has been completed (http://www.harmonit.org) and it is expected that this initiative will lead to a European standard on data exchange. In addition, the HarmonIT project is finalizing a utility library, which is available as public domain software on http://www.OpenMI.org. This library will facilitate application builders with the responsibility of connecting various software codes via OpenMI standards. The various organizations in the HarmonIT project are also composing additional tool sets, such as event loggers and data visualizers, which will remain their own proprietary software.

In order to improve the integration of software systems, various groups have to contribute. Fortune (2004) identifies the following OpenMI user groups: non-specialist end user, specialist end user, model integrator, model builder, model coder, application builder and tool coder. In particular, it is important that the demand for better communication between hydroinformatics components is enforced in contracts. As an example, recently the Bundesanstalt für Wasserbau (BAW) in Germany demanded OpenMI compliance for the delivery of the generic Delft3D modelling system of WL | Delft Hydraulics. There is a clear trend now that the principal participants in the HarmonIT project, such as DHI, Wallingford Software and WL | Delft Hydraulics are opening up their standard software packages with OpenMI communication links. In principle, all existing modelling systems can be made OpenMI compliant. Fast connections can only be made if the source code is available. The adaptation is relatively easy if the code has been programmed in an object oriented way. Executables can be made OpenMI compliant by encapsulating them within a wrapper, a communication layer which transfers data that are accessible through the standard input- and output routines of the code. This, however, may lead to slower communication links.

The advantages of OpenMI were recently explored by Solomon (2005) for the application of ensemble Kalman filtering to reduce uncertainties in the outputs of a rainfall–runoff model. For the ensemble Kalman filtering, the EnKF code developed by WL | Delft Hydraulics was used. For the rainfall–runoff model, use was made of the five parameter, five state variable modelling system HYMOD on an existing model of the 1944 km^2 catchment of the Leaf River watershed, Mississippi, USA (Vrugt *et al.*, 2003). A comparison was made of connecting both software components via batch files and via OpenMI calls. The objectives of this exercise were the comparison of the results obtained with both methods and the analysis of execution speed differences. It was found that both methods of coupling gave nearly the same results, whereas the OpenMI coupling proved to be 40% faster than a batch file connection, for a simulation with updates of state variables based upon 30 ensembles (see Fig. 2).

No effort was made to test the speed of a direct implementation of the ensemble Kalman filtering code inside HYMOD. This would go against the trend of designing modelling systems in a modular way by developing different functionalities in separate executables. However, other experiments with OpenMI have revealed that the speed difference between simulation with a fully integrated code and with separate codes in a modular design with exchange of data based upon OpenMI data exchange is not very significant.

FLOOD FORECASTING PLATFORM

Quoting Fortune (2004): *Perhaps the most advanced approach to flexible model integration is taken for flood forecasting applications*. This is, indeed, the area where the need for coupling of the components of hydroinformatics systems is most

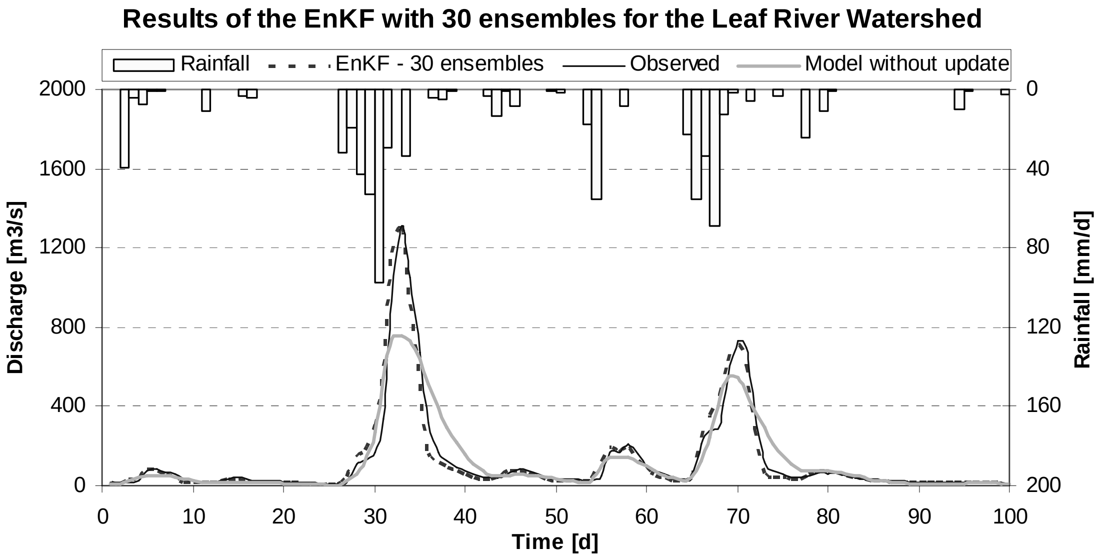

Fig. 2 Observed, modelled and updated discharges for the OpenMI connection between EnKF and HYMOD.

pronounced. As shown in the following, flood forecasting requires many operations between a wide variety of components to be orchestrated in a short time. This leads to the explicit need to create a generic flood forecasting platform, where existing components can be connected and new components be added in a flexible manner. With this objective, the Delft-FEWS (Flood Early Warning System) was developed and implemented in various places in the world.

The Delft-FEWS system takes care of executing the following tasks:

(a) import of external sources of data, such as meteorological forecasts, including those based upon numerical weather models, radar data, rainfall, discharge and water level time series from telemetric systems, and data from external databases;

(b) validation and interpolation of incoming data, using extensive data validation options with gap filling and hierarchy rules to allow alternative data sources to be used as a fallback for ensuring continuity in the forecasting process;

(c) data transformation in order to prepare the required inputs for reporting and for the forecasting models, such as weighting of precipitation from distributed point sources, from radar and from numerical weather models, as input to rainfall–runoff modelling;

(d) execution of the hydrological and hydraulic forecasting models. These models may be provided by various suppliers and cover a wide range of methods, from simple regression analysis, lumped hydrological models, spatially distributed hydrological models, artificial neural networks, hydrological routing models to 1D and integrated 1D-2D hydrodynamic models;

(e) updating the state of the models through a feedback mechanism to minimize the gap between observed and forecast data. Delft-FEWS provides some of the possible data assimilation models, such as the ARMA error correction method and ensemble Kalman filtering. Delft-FEWS also facilitates the implementation of other updating techniques;

(f) visualization of results on maps, which can be imported from various sources, such as GIS, aerial photographs, etc. including geographic navigation on these maps;

(g) dissemination of forecasts through maps and HTML formatted reports, allowing easy communication to the relevant authorities and public through intranet systems and the Internet.

An example of the typical requirements of a forecasting agency is described by Werner *et al.* (2004). In 2002, the Environment Agency in the UK commissioned WL | Delft Hydraulics and Tessella Scientific for the development of the National Flood Forecasting System (NFFS) as a flood forecasting platform for the complete area of England and Wales. A requirement given was the openness of the system to allow the continued use of various calibrated models which were already operational in flood forecasting systems for a number of river catchments in the area. So far, the calibrated models include the rainfall–runoff models based upon PDM, MRCM, TCM and NAM, the hydrologic routing models based upon DODO and KW, and the hydrodynamic modelling systems ISIS and Mike11. Currently, Delft-FEWS also has links to the rainfall–runoff software HBV, Sacramento, PRMS and VFlo, and the hydrodynamic modelling system SOBEK.

NFFS replaces, among others, the earlier FFS2 system developed for the UK Midlands region (Dobson & Davies, 1990). It comprises the MCRM lumped conceptual rainfall–runoff model and the DODO two layer Muskingum routing model, both equipped with updating techniques. These models had to be retained, as they have been extensively calibrated over the past years. The existing telemetry system was equipped with 124 meteorological gauges, 147 hydrological gauges and 272 forecasting points that may or may not coincide with gauge locations. The whole system represents a substantial asset value, of which many components are of great value in the newly installed Delft-FEWS. Once the new system is operational, component models can be replaced by better options if and when these are acquired.

An immediate advantage of the new system is that forecast lead times increase through the link to more advanced weather forecasting, which is part of the overall platform. A longer term advantage is that gradually the hydrological and hydraulic models can be replaced by state-of-the-art products, without being bound to one single manufacturer. Similarly, with the overall platform in place, the Environment Agency can gradually increase the number of catchments where forecasting is provided.

EXAMPLE OF A FLOOD MANAGEMENT DECISION SUPPORT SYSTEM

Decision support systems aim at facilitating the societal, political and managerial decision making processes with sound engineering knowledge. An interesting example is the Planning Kit, developed for supporting the decision making process of improved flood management along the Rhine branches in The Netherlands (de Vriend & Dijkman, 2003). Due to climatic and land-use changes and the increased awareness of their effects, triggered by the 1993 and 1995 flood situation along the Rhine, the design discharge for the Rhine Branches has been increased by about 7%. At the same time, a policy change was accepted by the Dutch Parliament to no longer rely on heightening dykes. The new policy is to provide “room for the river”, with dyke

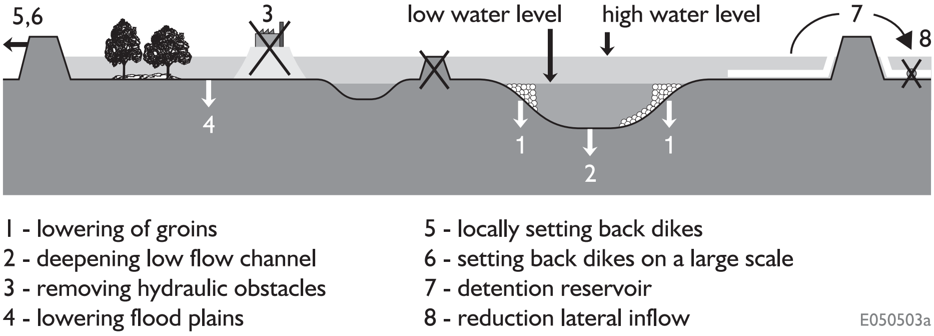

Fig. 3 Flood control measures in the river bed (from Silva *et al*., 2000). Courtesy Ministry of Transport, Public Works and Water Management in The Netherlands.

heightening only as a last resort. As a result, various measures have to be taken to achieve safety against flooding for these new criteria. In a recent study, *Room for Rivers*, many alternatives for flood protection were presented as an alternative to the earlier solutions of a continued raising of dyke levels. Examples of such measures are presented in Fig. 3.

Many of these measures can be taken to simultaneously enrich the ecological state of the flood plain. Most of these measures, however, also have a negative impact on the population living along the rivers. This leads to a complex decision-making process with many actors and stakeholders, both public and private. After an extensive investigation of possible measures, including the creative inputs provided by stakeholders and local authorities, a set of some 700 potential measures along the Lower Rhine branches emerged. The objective of the Planning Kit has been the visualization of the effects of these measures to facilitate the participation and planning process. As a first step, these measures were implemented in a GIS environment.

Limiting ourselves here to the flood level aspects, GIS was used to compute the changes in flood conveyance. These changes were introduced in a 2D depth-averaged hydrodynamic model of the entire Lower Rhine system. Subsequently, submodels were run to study the impacts of local measures on the surrounding flood levels. These impacts were stored in a database as water level changes along the river, compared to the reference situation. During public hearings and meetings with local authorities, the measures could be discussed on the basis of the presentations in GIS, combined with other database information, such as photos, visualization of the area with and without the measures, and the scores of individual measures on more than 50 criteria (costs, ecological effects, etc.). The use of the database enabled the instantaneous visualization of the superimposed effect of any selected combination of measures on the maximum flood levels along the river. This selection could be made by just clicking on the map, in the list of measures, or on a graph. Such effects could not be produced during the actual meetings by using real models. This would simply take far too much time. With the Planning Kit, a preferred set of actions could be defined by the public and decision makers who cannot be expected to have an in-depth knowledge of river hydraulics.

The question arises whether the superposition principle of measures is justified, as the hydrodynamic process is nonlinear. Such justification is based upon the evaluation of measures in a relatively narrow range of water level variations around the design flood level. In addition it can be stated that rating curves, though by definition non-linear, show up as monotonically rising and rather smooth functions at these levels.

Obviously, after reaching agreement on a set of measures using the Planning Kit, a 2D calculation with all measures implemented is realized to check the combined water level effect. Figure 4 appears to justify the use of the Planning Kit, by showing that a combination of 40 measures along the Rhine Branch Waal provides water level effects which differ by not more than 10 cm from those obtained with a full 2D hydrodynamic model.

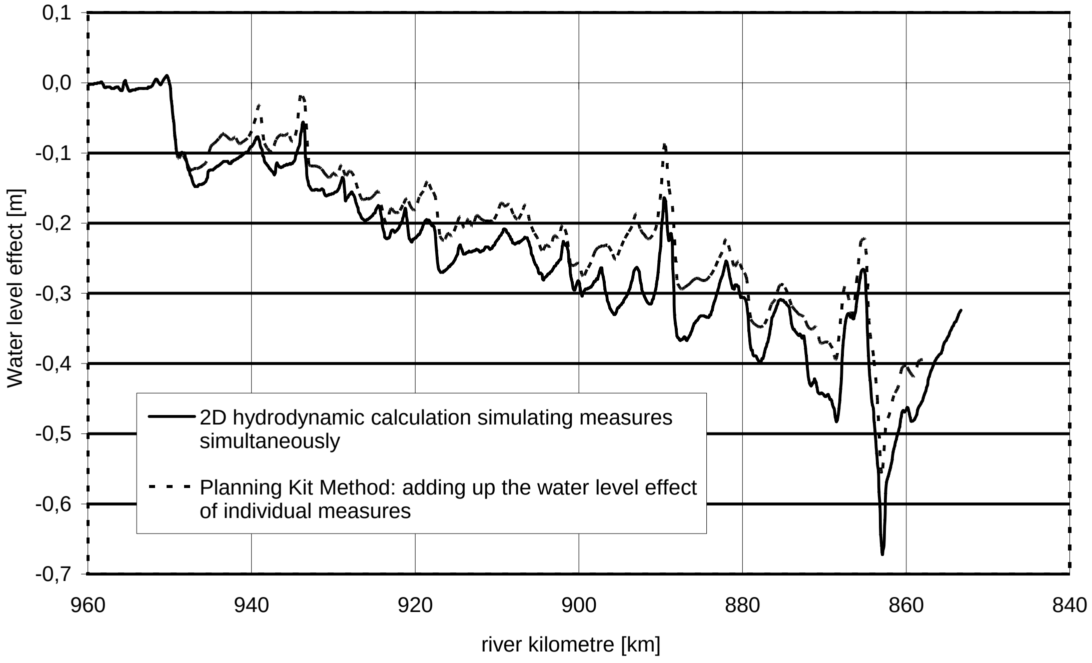

Fig. 4 Water level effect of 40 measures along the Rhine Branch Waal under design flood conditions as calculated with a 2D model simulating all measures (solid line) and as a result of the Planning Kit method, in which results for individual measures are simply added up. The reference level is formed by existing dyke heights.

All in all, the strength of the Planning Kit is that all stakeholders have rapid access to a common and uniform set of information on all potential measures. This provides clarity and avoids confusion, while it serves as a rapid learning tool for decision makers.

NUMERICAL FLOOD MODELS

Hydroinformatics platforms, such as a flood forecasting system and a decision support system, need models to provide relevant information on state variables and state indicators. In this contribution we will limit ourselves to numerical models based on finite difference formulations of the hydrodynamic balance equations. Progress is based upon a number of advances in the following areas: data collection (DGPS, LIDAR, multibeam echo sounding, remote sensing, radar, etc.); data processing and storage (GIS and hydrological databases); and numerical speed and robustness (Stelling & Verwey, 2005). Advances in all these areas lead to more refined numerical models, more accuracy, shorter construction times and faster model execution.

Focusing on the use of hydrodynamic flood simulation models, there is a gradual shift from the use of 1D to 2D depth-averaged models and, further, to the integration of these two types of schematization. Both 1D and 2D models have advantages and disadvantages, as follows:

(a) in terms of model construction time, the construction of 2D models is generally faster when reliable digital elevation models are available and use can be made of land use maps to support roughness parameter estimation;
(b) 1D models, on the other hand, are faster in simulation, which is of particular advantage in flood forecasting;
(c) the accuracy of 1D models can be higher than that of 2D models for flow in the main river, including the flow between river embankments;
(d) 2D models are usually more accurate and cheaper in construction when flow in flood plains has to be modelled;
(e) 1D modelling software is generally available at lower cost than 2D modelling software, as there is more choice in the market.

The third point, in particular, requires further comment. Limiting ourselves to finite difference methods, detailed modelling of the main river bed requires at least ten 2D grid cells over the width of this bed in order to model the flow in the usually meandering channel with sufficient accuracy. For long river stretches, this usually leads to an excessive number of 2D grid cells. Although, at first sight, the 1D schematization of a meandering river is complex, it is relatively easy to compensate for the effects of short cuts over the flood plain in the integration of the flow conveyance parameters along the 1D cross-sections. On the other hand, when large flood plain areas are to be included in the model, a 1D model schematization becomes quite inaccurate. For a number of decades the 1D flood plain cell technique has been used. Although this technique allows for a correct schematization of storage, it is difficult to estimate reliable conveyance parameters as the flow directions may vary significantly during the passage of a flood wave. In this case a 2D schematization is superior (statement d), especially given the possibility to implement depth-dependent roughness descriptions based on vegetation classes.

As both 1D and 2D schematizations have particular advantages and disadvantages, an integration of both types of schematizations will be attractive. There are, indeed, numerous practical examples where flows are best described by an integration of 1D and 2D schematizations. An obvious example is the flooding of deltaic areas, often characterized by a flat topography with complex networks of natural levees, polder dykes, drainage channels, elevated roads and railways, and a large variety of hydraulic structures. Flow over the terrain is best described by the 2D equations, whereas channel flow and the role of hydraulic structures are satisfactorily described in 1D. Flow over higher elevated linear elements, such as roads and embankments can be modelled in 2D reasonably well by raising the bottom of computational cells to embankment level. To increase the accuracy, however, adapted numerical formulations have to be applied, such as the energy conservation principle upstream of overtopped embankments. For the hybrid 1D-2D schematization, basically there are two approaches: one with interfaces defined between 1D and 2D along vertical planes, and the other with schematization interfaces in almost horizontal planes.

Coupling along vertical planes gives a full separation in the horizontal space of the 1D and 2D modelled domains. In the 1D domain the flow is modelled with the Saint Venant equations applied over the full water depth. The direction of flow in the 1D domain is assumed to follow the channel *x*-axis and in the model it carries its momentum in this direction, also above bank level. Without special provisions, there is no momentum transfer accounting applied between the 1D and 2D domains. Momentum and volume entering or leaving the 2D domain at these interfaces, are generated by the compatibility condition applied. As a result, the coupling cannot be expected to be momentum conservative. Depending on the numerical solution applied, the linkage may either be on water level or on discharge compatibility.

In a model coupled along an almost horizontal plane, 2D grid cells are placed above the 1D domain. In this schematization, the Saint Venant equations are applied only up to bank level. Above this level, the flow description in the 2D cell takes over. For relatively small channel widths relative to the 2D cell size, errors in neglecting the effect of momentum transfer at the interface are minor. For wider channels, it is recommended to modify each 2D cell depth used in the momentum equation by adding a layer defined by the local hydraulic radius for that part of the 1D cross-section which underlies the given 2D cell. Further refinements are possible, including terms describing the momentum transfer between the 1D and 2D domains. An advantage of this method of coupling domains is the easy extension of an existing 1D model to a fully integrated 1D-2D schematization.

As an example, WL | Delft Hydraulics has developed its combined 1D-2D package SOBEK for the modelling of integrated freshwater systems. The 1D and 2D parts are built upon robust implicit numerical techniques, avoiding problems with flooding and drying of channels and terrains through time step controllers and a variety of other limiters. The 1D and 2D domains are coupled implicitly via water level compatibility conditions at intersections of 1D and 2D grid cells. The system of equations is solved at each iteration and each time step with a combination of a minimum connection search direct solver and a conjugate gradient technique. With these direct solvers the traditional differences between looped and tree-like channel networks (e.g. Cunge *et al.*, 1980) become totally irrelevant. Furthermore, the efficiency of conjugate gradient solvers has improved significantly over the past years.

CONCLUSIONS

The continuing development of the speed and the data storage capacity of computers has a large impact on the methods used to support studies in the water sector. In the first place, this potential leads to new measuring techniques providing us with large amounts of information (LIDAR, remote sensing, multibeam echo sounding, ADCP, radar technology, etc.). The increased and more accurate sets of data also facilitate the construction and calibration of simulation models. In the second place, the large sets of data can be explored with new data-mining techniques to extract new knowledge from these massive sets of individual numbers or pixels, for example in the form of new empirical equations. This new knowledge, in turn, can either reinforce existing numerical models or provide an alternative to the balance equation based modelling methods, e.g. artificial neural networks. In the third place, there is a trend to use the increased computer power to achieve a better integration of hydroinformatics components, such as models for different physical subsystems, databases, GIS, telemetry, etc. Water resources agencies, in particular, feel the need to arrive at better integration of these various components. In this context, the Open MI standard developed recently through an EU initiative may prove to be very useful, facilitating the development of hydroinformatics platforms such as flood forecasting systems and decision support systems.

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