

# Hydroinformatics and its applications at Delft Hydraulics

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## ABSTRACT

Hydroinformatics concerns applications of advanced information technologies in the fields of hydro-sciences and engineering. The rapid advancement and indeed the very success of hydroinformatics is directly associated with these applications. The aim of this paper is to provide an overview of some recent advances and to illustrate the practical implications of hydroinformatics technologies. A selection of characteristic examples on various topics is presented here, demonstrating the practical use at Delft Hydraulics. Most surely they will be elaborated upon in a more detailed way in forthcoming issues of this *Journal*.

First, a very brief historical background is outlined to characterise the emergence and evolution of hydroinformatics in hydraulic and environmental engineering practice. Recent advances in computational hydraulics are discussed next. Numerical methods are outlined whose main advantages lie in their efficiency and applicability to a very wide range of practical problems. The numerical scheme has to adhere only to the velocity Courant number and is based upon a staggered grid arrangement. Therefore the method is efficient for most free surface flows, including complex networks of rivers and canals, as well as overland flows. Examples are presented for dam break problems and inundation of polders. The latter results are presented within the setting of a Geographical Information System.

In general, computational modelling can be viewed as a class of techniques very much based on, and indeed quite well described by, mathematical equations. These equations often symbolically represent underlying physical phenomena, like conservation of mass, momentum and energy. Diversification to application areas where no clear mathematical formulation may (yet) be present but where adequate data sets are available is illustrated by several practical examples. Again, using computer based technologies, various applications of so-called sub-symbolic techniques like Artificial Neural Networks (ANNs) are discussed and presented. Finally, some reflections on forthcoming developments and likely implications for engineering practice as well as education are outlined.

**Key words** | Delft Hydraulics, computational hydraulics, dam break problems, inundation of polders, artificial neural networks, Kohonen networks

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## INTRODUCTION AND HISTORIC BACKGROUND

Hydroinformatics is all about applications. Backed by substantial theoretical considerations (Abbott 1991, 1993, 1994) the main emphasis has been on practical implementations of advanced information technologies in a wide variety fields on hydrosociences and engineering (Babovic 1996). The rapid advancement and indeed the very success of hydroinformatics is directly associated with such applications. Technological institutes and university research

groups have developed a wide range of hydroinformatics technologies and demonstrated their relevance for practical situations in numerous engineering and consultancy projects. This is clearly reflected by the increasing number of contributions in the proceedings of the biennial Hydroinformatics Conferences in Delft 1994, Zürich 1996 and Copenhagen 1998 (Verwey *et al.* 1994; Müller 1996; Babovic & Larsen 1998).

Yet another implication of the advancing field of hydroinformatics is its role in education. Already in the early 1990s, the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE Delft) initiated a graduate course in hydroinformatics. Well over 100 professionals have been trained at both M.Sc. and Ph.D. level. More recently, other universities worldwide have established hydroinformatics branches or even hydroinformatics departments. Within the European Graduate School of Hydraulics short courses and summer courses on hydroinformatics are being provided as well.

The International Association for Hydraulic Research (IAHR) from the very beginning provided a constructive platform for communication and exchange among university research groups and technological institutes alike. A special Section on Hydroinformatics was created, contributing to the biennial IAHR Conferences as well as initiating the intermittent series of biennial Hydroinformatics Conferences mentioned above. Its origin and emphasis notably lies within the European communities, but interest and involvement from Asia and North America are rapidly increasing. It may be worthwhile to note that the next Hydroinformatics 2000 Conference will be held at the renowned Iowa Institute of Hydraulics, USA.

Contacts with the International Association on Water Quality (IAWQ) increased the awareness and necessity to stimulate the introduction of hydroinformatics technologies in the field of practitioners. This clearly demonstrates the growing interest and rapid development over the past decade. The newly established joint IAHR/IAWQ *Journal of Hydroinformatics* is the result of the mutual interest of both organisations aiming to reach both researchers and practitioners, hence stimulating further advances of hydroinformatics applications in the next millennium.

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## ADVANCES IN COMPUTATIONAL HYDRAULICS MODELLING

The field of hydraulics deals with flow and transport phenomena in both natural water systems (rivers, estuaries) as well as in man-made systems (canals, pipes). Hydraulics has a long tradition of providing a scientific

basis for engineering applications (Rouse 1950; Ippen 1966). At the time, quite often empirical relations obtained from field observations or model scale experiments provided the basis for constructing conceptual models. Mathematics started playing an important role not only to describe these empirical relations, but also to construct analytical solutions to schematised model situations that captured the essential features of particular phenomena. Applying these techniques to help solve practical problems, however, quite often was very much a form of art rather than science.

With the advent of rapidly increasing computer technology, digital processing and numerical techniques became of interest as well. In the early 1970s an IAHR working group was initiated 'to investigate the role of computers in hydraulic engineering'. Some could not imagine that computers would add to or be useful for anything else than fast and automated data collection and data processing from model scale experiments. Others started using computers to solve mathematical equations numerically that could not be handled analytically. This approach is often referred to as computational hydraulics. In fact, nowadays, computational techniques are commonly applied in a wide range of fields in science and engineering, ranging from physics to chemistry and biology.

Of course, the first applications in computational hydraulics concerned programming analytical formulae rather than deriving generic numerical schemes and techniques based on physical principles like conservation laws for mass and momentum. And still, in particular in one-dimensional flow modelling, considerable *a priori* knowledge is required to provide the proper input, even for commercially available packages. Concepts like 'conveyance width' for momentum conservation and 'storage width' for mass conservation are just typical examples. Hence, deciding on the proper choice of values for the various coefficients associated with such systems often requires considerable craftsmanship and experience.

Recent developments, however, extend the field of computational hydraulics to multidimensional modelling of complicated flow phenomena in arbitrarily shaped geometries. More general, in the field of computational fluid dynamics, research and applications are oriented

towards simulating time-varying multidimensional transport processes in high Reynolds number turbulent flow fields, using high performance vector and parallel computers. One such example related to recent advances in the field of computational hydraulics and presented below, is taken from Stelling *et al.* (1998).

### Numerical schemes for shallow-water flow modelling

Shallow-water flow problems are wide ranging, varying from ocean dynamics, through estuaries up to inland waters with rapidly varied flows, or artificial lakes with dams that might break. The numerical techniques for coastal regions and estuaries are often based upon very efficient ADI methods (see, for example, Leendertse 1967), or semi-implicit methods (see, for example, Casulli 1990). The efficiency of these approaches is due to an implicit time integration combined with the application of ‘staggered grids’. Despite their efficiency, these methods are not very effective for flows with large gradients in the water levels because of the presence of hydraulic jumps or the occurrence of bores as a result of dam breaks.

A very different class of numerical techniques is applied for rapid flows with hydraulic jumps and dam break problems. These techniques are often based upon non-staggered grids and the so-called ‘Godunov methods’ as developed for aerodynamics (for extensive overviews see, for example, Hirsch (1990) or Toro (1997)). Applications of these techniques to shallow-water flow problems are described by Chaudry (1993) or Alcrudo & Garcia-Navarro (1993).

Examples of large gradients are tidal bores or the inundation of low lands, such as, in The Netherlands, because of dike breaks. The drying and flooding of tidal flats can also be considered locally as rapid varying flow. Locally, tidal bores could occur and it is questionable whether ‘flooding procedures’ as described by Stelling *et al.* (1986) or Falconer & Chen (1991) give accurate simulations of the local flooding.

To try to bridge the gap between the different approaches, Stelling proposed a numerical technique that in essence is based upon the classical staggered grids and implicit integration schemes such as described

by Leendertse (1967) and Casulli (1990), but that can be applied to problems that include large gradients. This new scheme is based upon the following characteristics:

1. The continuity equation is approximated such that (i) mass is conserved not only globally but also locally and (ii) the total water depth is guaranteed to be always positive which excludes the necessity of ‘flooding and drying’ procedures.
2. The momentum equation is approximated such that a proper momentum balance is fulfilled near large gradients.

The combination of positivity of water depths and mass conservation assures a stable numerical solution. A proper momentum balance provides that this stable solution converges. The numerical principles and numerical examples for flows with large gradients are explained in detail by Stelling *et al.* (1998). The principles can be explained by considering the following one dimensional unsteady flow equations

$$\frac{\partial \zeta}{\partial t} + \frac{\partial(uh)}{\partial x} = 0; \quad (2.1a)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \zeta}{\partial x} + g \frac{u|u|}{C^2 h} = 0, \quad (2.1b)$$

where

- $u$  = velocity,
- $z$  = water level above plane of reference,
- $C$  = Chezy coefficient,
- $d$  = depth below plane of reference,
- $h$  = total water depth,  $h = z + d$ .

If the bottom is assumed not to be time varying, it follows that the continuity equations can be rewritten as:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} = 0, \quad (2.2)$$

which can be considered a transport equation of the scalar quantity  $h$ , allowing application of so-called positive and monotone schemes (see Hirsch 1991). A simple semi-discretization on a C-type staggered computational grid as indicated below, leads to

$$\frac{dh}{dt} + (uh(u))_{0x} = 0, \text{ at } (i) \text{ at } (i) \quad (2.3a)$$

$$\frac{du}{dt} + a(u,u) + g\zeta_{0x} + g\frac{|u|u}{C^2h(u)} = 0, \text{ at } (i + \frac{1}{2}) \quad (2.3b)$$

The relation between the variables in a staggered grid arrangement are indicated by (2.4),

$$\begin{array}{ccccc} & \uparrow & & \uparrow & \\ & \zeta & & \zeta & \\ u & h = \zeta + d & u & h = \zeta + d & u \\ & d & & d & \\ & \downarrow & & \downarrow & \\ i - \frac{1}{2} & i & i + \frac{1}{2} & i + 1 & i + 1\frac{1}{2} \end{array} \quad (2.4)$$

where  $h_i$  refers to the water depth  $h$  at  $i$ ,  $a(u,u)$  denotes some advection approximation, and

$$(u_i)_{0x} = \frac{u_{i+\frac{1}{2}} - u_{i-\frac{1}{2}}}{\Delta x}, (\zeta_{i+\frac{1}{2}})_{0x} = \frac{\zeta_{i+1} - \zeta_i}{\Delta x} \quad (2.5)$$

$$h_{i+\frac{1}{2}}(u) = \begin{cases} h_i, & u > 0 \\ h_{i+1}, & u \leq 0 \end{cases}$$

For discrete time integration there are numerous possibilities (see, for example, Lambert 1991). A well-known integration scheme is based upon the so-called *theta method*, which does not require iterations for the solution of nonlinear equations. Application to the conservation equations leads to

$$\frac{h^{n+1} - h^n}{\Delta t} + (u^{n+\theta}h^n(u^n))_{0x} = 0, \text{ at } (i) \quad (2.6a)$$

$$\begin{aligned} & \frac{u^{n+1} - u^n}{\Delta t} + a(u^n, u^n) + g\zeta_{0x}^{n+\theta} \\ & + g\frac{Zu^n|u^{n+1}}{C^2h^n} = 0, \text{ at } (i + \frac{1}{2}), \end{aligned} \quad (2.6b)$$

where,  $u^{n+\theta} = \theta u^{n+1} + (1-\theta)u^n$ , and  $\zeta^{n+\theta}$  is defined accordingly. Stelling *et al.* (1998) also derived conditions for strict positivity which can be ensured if

$$\frac{\Delta t \cdot u_{i+\frac{1}{2}}^{n+\theta}}{\Delta x} < 1. \quad (2.7)$$

Similar conditions can be derived for other flow directions. Simply fulfilling eq. (6) will prevent wet points from

drying, i.e. no special drying and flooding procedures are required for this approach. It should be noted that the description of the continuity equation in primitive variables rather than integrated quantities, has important advantages: (i) it enables strict positive waterlevels, and (ii) upwinding yields artificial viscosity without influencing strict local mass conservation.

For sufficiently smooth solutions, advection approximations could well be based upon at least second order local truncations errors. In that case numerical viscosity is minimal. However, near local discontinuities in the solution, following from, for example, sharp bottom gradients or hydraulic jumps, the 'order of accuracy' concept is meaningless. Conservation properties are more important aspects in such situations. In accordance with well-known concepts from classical hydraulics, the following quantities are considered: (i) mass, (ii) momentum and (iii) energy head. The numerical approximations introduced above are already mass conservative. For the advection approximation only energy head and momentum are considered. The so-called energy-head conserving formulation of (2.1b) is given by

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(\frac{1}{2}u^2 + g\zeta) + g\frac{u|u|}{C^2h} = 0 \quad (2.8)$$

while the momentum conserving formulation is expressed by

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}(hu^2) + gh\frac{\partial \zeta}{\partial x} + g\frac{u|u|}{C^2h} = 0. \quad (2.9)$$

Both formulations (2.8) and (2.9) are completely equivalent for continuous and sufficiently smooth solutions. At local discontinuities, however, these equations have no unique solution in general. Local discontinuities can either be due to discontinuities in the bathymetry or due to the nonlinearity of the equations such as near bores generated in dam break problems, or near hydraulic jumps. At the discontinuity additional equations are needed to connect the equations at both sides of the discontinuity. In general, conservation of mass and momentum provides the internal boundary conditions, although in case of converging flows and steep bottom gradients conservation of energy head can be applied as well, (see, for example, Chaudry 1993).

For numerical approximation, conservation properties near large local gradients are again important. Near steep bottom gradients mass conservation seems to be imperative. Steep bottom gradients are quite common in estuaries near tidal channels or near tidal flats. ‘Steepness’ is also a notion that depends on the local grid size. As the grid size is smaller the local gradients become larger in the sense that only few grid points are used for its representation. Stelling *et al.* (1998) show two first-order advection approximations, that can be applied for the approximation of the advective terms of (2.8) or (2.9) and that are either energy head or momentum conservative. Under the assumption of a constant density, hydrostatic pressure and no velocity gradient in vertical direction the numerical approximation of the elementary mechanical conservation law applied to a control volume of water leads to

$$\begin{aligned} & \left[ \Delta x \rho \frac{d}{dt} \left( \frac{u}{2} (h_{+i} + h_{-i}) \right) \right] + \left[ \frac{q_{+1} + q}{2} \rho u - \frac{q + q_{-1}}{2} \rho u_{-1} \right] \\ & + \left[ g \rho \frac{h_{+i} + h_{-i}}{2} (\sigma_{+i} - \sigma_{-i}) \right] = 0 \end{aligned} \quad (2.10)$$

where  $\rho$  denotes the constant density. The integrated normal pressure follows from the assumption that in a control volume, the hydrostatic pressure is assumed to be given by:

$$p(x, z) = \rho g (\zeta(x) - z), \quad \zeta(x) = \frac{x_{i+1} - x}{\Delta x} \zeta_i + \frac{x - x_i}{\Delta x} \zeta_{i+1}. \quad (2.11)$$

The integrated result of the normalised pressure now does not depend upon the shape of the bottom profile. The only assumption now is the linear distribution or the free surface. It should be noted that many authors split the pressure term into a gradient of the water depth and of the bottom slope (see, for example, Chaudry 1993), as follows:

$$gh \frac{\partial \zeta}{\partial x} = gh \frac{\partial}{\partial x} (h - d) = \frac{\partial}{\partial x} \left( \frac{1}{2} gh^2 \right) - gh \frac{\partial d}{\partial x}. \quad (2.12)$$

This formulation follows from mathematical manipulation and does not necessarily represent a proper momentum balance in case of discontinuous steps in the bottom

profile  $\partial d / \partial x$  where might tend to infinity. In this way so-called flux splitting methods can be applied, but the shape of the bottom profile now becomes important for a numerical approximation. From a physical point of view this is wrong. Of course both approaches can lead to consistent approximations: i.e. for sufficiently smooth solutions the differences are minor and only near discontinuities differences might play an important role. In the formulation by Stelling *et al.* (1998) all possibilities are included, so that energy head conservation can be chosen for converging flows and momentum conservation for diverging flows.

According to some authors (see Toro 1997), energy head conservation is to be used only if solutions are smooth. For proper shock speeds and shock locations it is imperative to apply a proper momentum balance. However, discontinuities sometimes are not only due to shock formation but also due to the bathymetry. In that case (see Chaudry 1993), sometimes energy head conservation is a better assumption for converging flow. For example, rating curves for sluice gates can be derived from the assumption of energy head conservation in the upstream part, contraction in the sluice gate and momentum conservation in the down stream part of the sluice gate. Of course it is possible at all times, to impose momentum conservation throughout.

Integration in time can be based upon various time integration methods, e.g. the implicit midpoint rule (see Lambert 1991). Strict application for  $\theta = \frac{1}{2}$  will not destroy any of the conservation properties. The equations, however, are then nonlinear. This necessitates the application of iterative solvers. By local linearization, iteration can be avoided. Strict conservation is then difficult to prove. Practical experience has shown, however, that the differences are small. To minimise the amount of computational effort, an implicit approach has been applied. The implicit equations are symmetric and positive definite and can be solved by CG methods (see, for example, Casulli 1990).

The principles explained here can be applied, without any alteration, to more general one-dimensional equations including general cross-sections and they can be extended to two-dimensional flow equations describing the simulation of flow over dry land. Some applications are presented below.

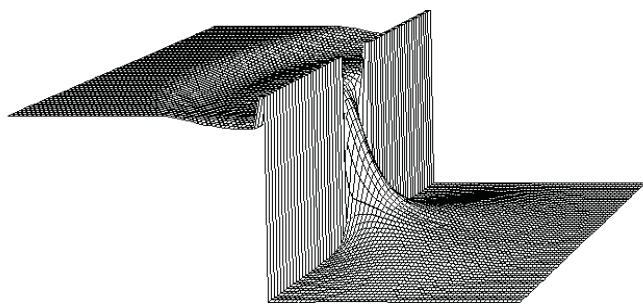


Figure 1 | Two-dimensional dam break, dry bed conditions.

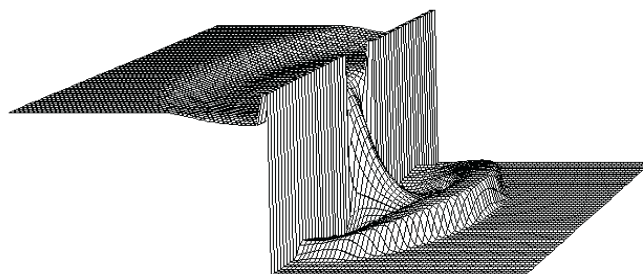


Figure 2 | Two-dimensional dam break, wet bed conditions.

### Application to dam break problems

One such example presented here is related to a two-dimensional dam break problem. As a schematisation the domain is considered to be rectangular and consisting of  $64 \times 114$  grid points, the grid size corresponding to  $\Delta x = 1$  m. The upper reach has an initial water level  $h_0 = 5$  m. The lower reach has an initial water level  $h_1 = 0$  m, i.e. a dry bed. Figure 1 shows the water levels after 5 seconds for downstream dry bed conditions. To demonstrate the effect of the downstream boundary condition, Figure 2 shows the results for a wet bed condition, again after 5 seconds. The shape of the wavefront is seen to be quite different.

In fact, these features correspond to the correct physical behaviour as observed in experiments and can be verified using local analytical solutions. It should be noted, however, that only very few numerical schemes are able to represent the quite different behaviour in both situations. Quite often only wet bed downstream conditions are considered, which indeed is relevant in case of a reservoir dambreak in a river. However, in case of

inundation of polders due to dike break, dry bed conditions should be considered for overland flow. Apart from the specific form of the wavefront, the speed of propagation is quite different in either situation. The numerical scheme developed by Stelling *et al.* (1998) is capable of representing both conditions within the same simulation. Hence it is particularly useful for – and in fact the only way for proper modelling of – solving practical problems related to the inundation of polders.

### Application to inundation of polders

The method introduced above provides the basic computational kernel for the DELFT-FLS system, the numerical flooding simulation package developed by Delft Hydraulics. The DELFT-FLS system is a two-dimensional hydrodynamic simulation package especially suited to simulate the dynamic behaviour of overland flow over initially dry land. It is based on the full two-dimensional shallow water equations. These equations are solved following the finite-difference numerical technique described above on a rectangular staggered grid. The technique always guarantees a positive water depth, and allows flow computations on initially dry land without using any special drying/wetting procedure. It allows a sound simulation of sub- and supercritical flows. It gives accurate and stable results during flow computations on very steep slopes, such as dike walls, structures, etc. It provides realistic and reliable predictions of floods due to dike or dam break, dike overtopping, coast overtopping, heavy rainfalls and other natural hazards.

DELFT-FLS is equipped with an automatic time-step estimator which reduces or enlarges the computational time-step according to the flow characteristics at any moment of the simulation. The package requires good topographical data. It can be given as a GIS-layer (GIS: Geographical Information System) or manually on a suitable rectangular grid. The levels and positions of roads, levees and other infrastructure are also required. A land use map (or a similar representation) is also necessary. The ‘land use’ can easily be converted to hydraulic roughness coefficients, since it is provided with experience based ecotype roughness relationships. Internal boundary conditions are included to simulate dam break/dike break events.

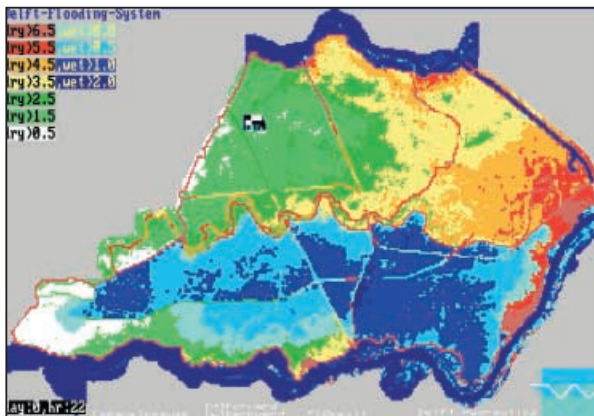


Figure 3 | Inundation map of the polder near Tiel, 22 hours after dike break.

The possible outputs are water levels, water depths, velocities (magnitude and velocity fields), current lines, inundation depth class intervals. These results can be given in GIS format for presentation and further post-processing. The presentation of results using other packages is also possible.

### Simulation of flooding in a GIS-environment

An example is presented here for a typical lowland situation. The polders of Tiel and Culemborg in The Netherlands are limited by the rivers Lek on the North and Waal on the South (both Rhine branches), by the Amsterdam–Rhine channel on the East and by other channels and dikes on the west. The region has been schematised within a rectangular grid with 42,000 active cells (Kernkamp & de Jonge 1997). The size of each cell is 100 m × 100 m. Figure 3 shows the advance of the inundation 22 hours after a dike break in the river Waal, carrying a major flood. The computational results indicate that almost half of the study area is under water. Figure 4 shows the velocity field some hours after a dike break near the city of Tiel (southeast extreme). The DELFT-FLS model clearly gives a better time description and final assessment of a flood and its consequences than the more conventional one-dimensional reservoir modelling approach.

DELFT-FLS has a wide range of applications. It can be used for flood simulation, damage assessment and risk

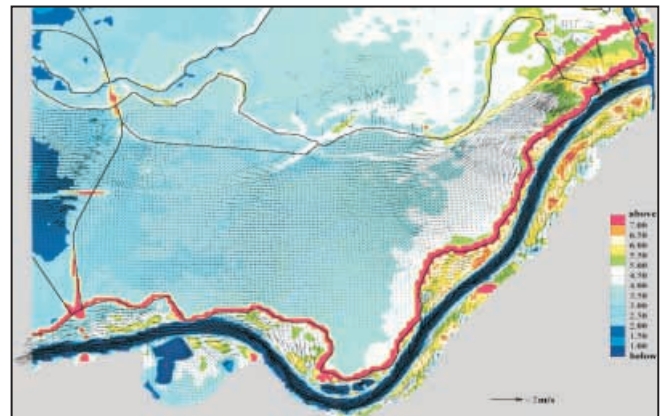


Figure 4 | Velocity field in the polder near Tiel, 14 hours after dike break.

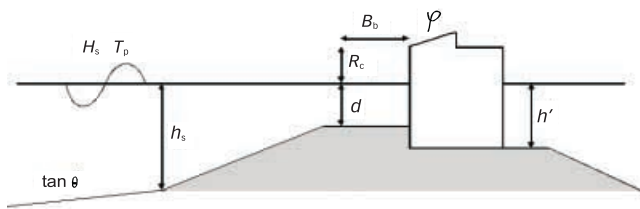
evaluation on coastal areas, river-valleys, mountain and lowland areas. The flow module is used to determine the flooded area at GIS pixel level including the water depth and inundation period.

Damage assessment is possible provided sufficient data of land use and investments are available within the GIS system. Risk maps can be built based on the damage estimation and the combined probability of occurrence of high water and other disasters, such as dam or dike break or any other hazard.

The combined hydraulic model/GIS system can be used during landscape and urban planning phases, showing the influence of the existing or future infrastructure on the flow pattern. It is extremely useful for setting up evacuation plans, since it shows the inundated areas and the available transport ways with time. The results can easily be incorporated in a Decision Support System.

## DEVELOPMENTS IN ARTIFICIAL NEURAL NETWORK MODELLING

The previous examples are typical for computational modelling in that the underlying physics are considered to be adequately described by mathematical equations, symbolising the physical conservation laws of mass and

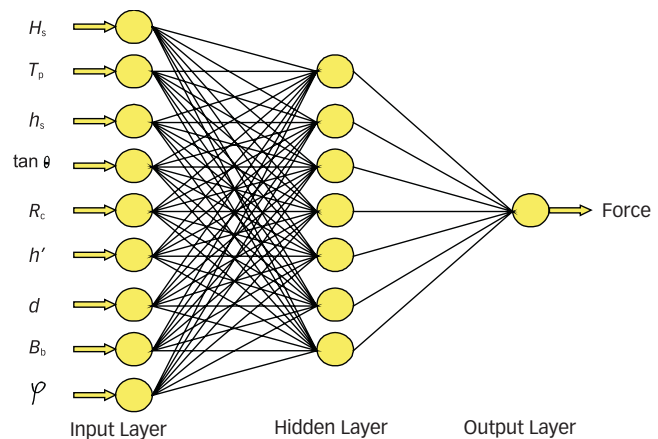


**Figure 5** | Parametrisation for NN-modelling of the horizontal wave force on a vertical breakwater structure.

momentum. In hydroinformatics publications this way of modelling is sometimes referred to as ‘symbolic modelling’. In contrast, a different approach of so-called ‘sub-symbolic’ modelling is emerging rapidly, using techniques that are nowadays becoming amenable for computer-based modelling as well (Minns 1998). In particular in situations where adequate data sets are available from observations, data-driven modelling techniques like Artificial Neural Networks (ANNs) often prove very powerful indeed (Hall & Minns 1993; Scardi 1996; Recknagel *et al.* 1997). If only limited data are available, but at least some qualitative understanding is present on the underlying processes – like in ecology – Fuzzy Logic techniques can be applied, combining data from observations and whatever available knowledge of the underlying processes. Yet again, these techniques have increased in significance because of advancing computer hardware and software technologies—i.e. the increasing role of informatics in the hydro-sciences. In the examples below the emphasis is on various applications of neural network (NN) modelling.

### Artificial Neural Networks for data analysis

When physical processes involve very complex interactions, e.g. wave-structure interaction for the design of vertical breakwaters, computational techniques may not be feasible yet, and physical model experiments are still required. However, the derivation of reliable empirical relations from such tests can be rather difficult. Since large data sets are available from joint research projects, data-driven computational techniques prove very effective



**Figure 6** | Neural Network configuration.

here. The example presented next is based on the work of Sanchez as reported by Gent & Boogaard (1998).

Horizontal forces on the upright seaward section of vertical structures, schematically indicated in Figure 5 often form the most important wave load in the design of vertical breakwaters. Owing to the complexity of the phenomena involved, it is difficult to describe the effects of all relevant parameters in design formulae. For such processes in which the interrelationship of parameters is unclear, although sufficient experimental data are available, NN modelling provides a suitable alternative. Earlier, Mase *et al.* (1995) showed that this technique is valuable for the stability analysis of rubble-mound breakwaters. In the example presented here, a NN is developed for predicting wave forces on vertical structures.

The total horizontal force on a vertical breakwater is the result of the interaction between the wave field, the foreshore and the structure itself. The random wave field is represented by the significant wave field ( $H_s$ ) and the corresponding peak period ( $T_p$ ). The effect of the foreshore is accounted for by the slope ( $\tan \theta$ ) and the water depth in front of the structure ( $h_s$ ). The structure is characterised by the height of the vertical wall below and above the water level ( $h'$  and  $R_c$ ), the water depth above the rubble-mound foundation ( $d$ ), the width of the berm ( $B_b$ ) and the shape of the superstructure ( $\varphi$ ). A definition sketch indicating the nine parameters is given in Figure 5.



A detailed analysis of the parameters involved, as well as a description of available data sets from various hydraulic research institutes in different European countries, is given by Gent & Boogaard (1998).

NN modelling can be seen as a sophisticated data-oriented modelling technique to find relations between input- and output patterns without using detailed process knowledge (it should be noted however, that distinguishing inputs and outputs by itself already requires at least some process knowledge). A more detailed general introduction can be found in a well-written review article on NNs in ACM Communications (1994) and in the book by Beale & Jackson (1990); Haykin (1994) provides further details on technical background, examples and applications.

The NN configuration used here is a so-called multi-layer perceptron type as presented in Figure 6. This type of NN is organised in the form of layers of one or more processing elements called 'neurons'. The first layer is the input layer consisting of several neurons equal to the number of input parameters. The last layer is the output layer corresponding to the number of output parameters. In the vertical breakwater case, the applied input parameters are  $(H_s, T_p, h_s, \tan \theta, R_c, h', d, B_b, \varphi)$ , whereas the output is chosen to be  $(F_{h,99.6\%})$ , namely the threshold value of the horizontal force that is exceeded by only 0.4% of the waves.

The layers between the input and the output layer are so-called 'hidden layers' and can in principle be chosen arbitrarily, but depend very much on the amount of data available for training and testing, as well as the complexity (nonlinearity) of the process that is to be modelled. Each neuron receives inputs from all neurons of the preceding layer via the connectivities. To each connectivity a weight is assigned. The total input of a neuron then consists of a weighted sum of the outputs of the preceding layer. The output of the neuron is generated using a 'nonlinear activation function', often of a sigmoid shape. This procedure applies to each neuron; the output neuron generates the final value.

Before the NN is ready to be used for actual predictions, the weight factors need to be calibrated. To this end part of the data set is used, commonly referred to as 'training the NN'. The calibration of the weight factors is performed by feeding data to the input (*'feed forward*

*procedure'*) and comparing the output with measurement observations. The difference between the predicted and observed values are used to adjust the weights (*'error back propagation rule'*). This iterative procedure is repeated until the agreement can no longer be improved. The procedure usually involves minimisation of some cost function (also denoted as error function) using gradient based methods.

An important step in NN modelling is to find the optimal number of neurons in the hidden layer. This often involves considerable trial and error procedures, increasing the number of nodes and monitoring the performance of the NN. If the NN starts exhibiting noisy fluctuations, it is being overtrained. To detect and prevent such overtraining, often not all available data is used for training; part is reserved for verification. Although NNs are sometimes referred to as a 'black box approach', it can easily be argued that the choice of the number of layers and the number of neurons per layer implies some form of 'modelling' of the underlying physical processes. Also, specific expertise is often required to assess the NN model performance in a proper way. In mathematical terms, NNs can be regarded as universal function approximators, the number of weights corresponding to the number of degrees of freedom of the system. In engineering terms, knowledge of the relations between various input parameters can lead to further improvement of the NN model performance. Interesting engineering applications involving Froude scaling applied to the specific example of the vertical breakwater case are presented by Gent & Boogaard (1998). They also explored the reliability of the NN predictions by establishing the 95% confidence intervals. The results are presented in Figure 7.

On the left, the predictions of the NN tool are presented, whereas the right graph shows the upper and lower limits of the 95% confidence intervals for these predictions. The results show that NN modelling can well be used for the prediction of horizontal wave forces on vertical breakwater structures. The accuracy (reliability) of the NN predictions is largely determined by the quality of the data set. For the data set used by Gent & Boogaard (1998) the predictions by the NN model show a better comparison with measured data than the

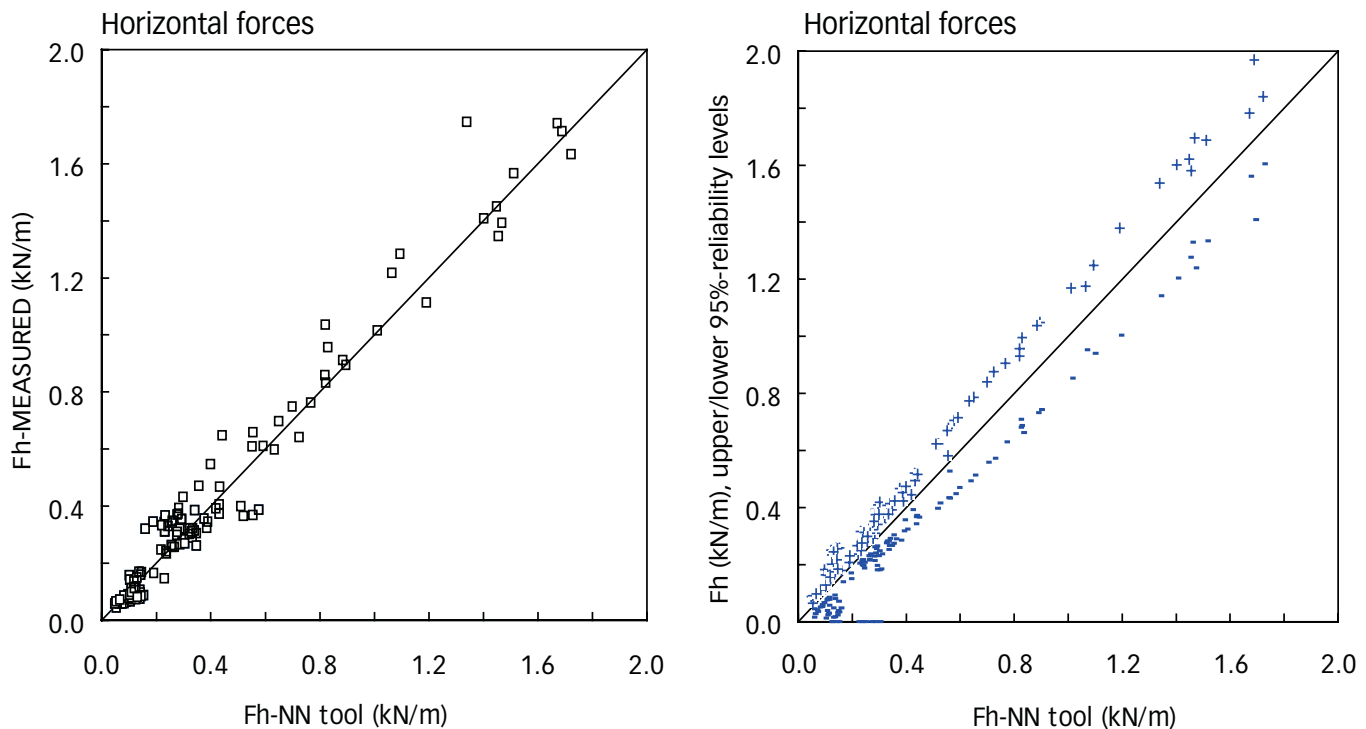


Figure 7 | Comparison of NN-results versus measurements (left) and indication of upper/lower 95% reliability levels (right).

classical Goda-method, often used in engineering practice.

### Auto-regressive neural networks for time series analysis

In the previous example the physical process (wave loading on the breakwater structure) was considered to be stationary, implying that the statistical properties of the process do not vary with time. As a result, the output (horizontal wave force) depends entirely on one specific combination of input conditions represented by the various parameters. In fact, there is no explicit mutual interaction between the various input-output patterns. However, in other processes – like flood forecasting or the prediction of algal blooms – time dependency and time evolution plays a crucial role. Hence, standard NNs as described above cannot be applied directly, but need to be extended to account for nonlinear dynamics that govern

the time evolution and as such the correlation of successive samples. This has been achieved here in a way that is closely related to traditionally applied time series analysis techniques based on linear models of type ARMAX (Auto Regressive Moving Average with exterior input (see, for example, Ljung & Söderström 1983)). In a sense, ARNNs and ARMAX models can both be viewed as black box models, ARNNs being a nonlinear generalisation of linear ARMAX models. An illustration of an auto-regressive NN architecture is presented below, where  $X_t$  represents the autoregressive output, and  $U_t$  the external forcing of the process.

To demonstrate the similarity between linear black box ARMAX models and nonlinear NN models, some common features and background of the formulations are briefly described hereafter. Common among both types of model is their dynamic form, namely an ARNN can be viewed as a general nonlinear modelling approach for dynamic processes. On the one hand, within an ARNN a standard NN is used to model a transfer function, and as

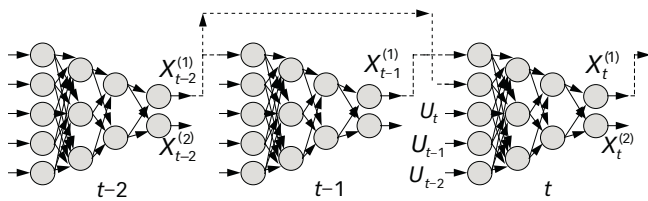


Figure 8 | Example of an Auto-Regressive NN of MLP architecture.

such an ARNN is largely a data-driven modelling technique. On the other hand, however, conceptual (physical) knowledge is explicitly contained in the state space form of the ARNN, and hence can be seen as a step towards introducing physically based modelling within NN simulations.

Traditionally, linear black box models of type ARMAX are frequently used in time series analysis. In discrete time stepping procedures these models have a form where the model's response at time  $t$  depends linearly on the external forcings at time  $t$  as well as at preceding time steps ( $t-1$ ,  $t-2$ ,  $t-3$ , ...). The forcing may consist of deterministic components as well as random components. Apart from this linear *regressive part* with respect to the forcings also a linear *auto-regressive part* is often included by feedback of a linearly weighted sum of the outputs computed in one or more preceding time steps. Randomness in the model's definition can be included to account for uncertainties in the forcings and/or model uncertainties in more general sense (system noise). Mathematically all this can be expressed as

$$X_t = \sum_{k=1}^K \alpha_k X_{t-k} + \sum_{l=0}^L \beta_l U_{t-l} + \sum_{m=0}^M \gamma_m Z_{t-m}, \quad (3.1)$$

where  $X_t$  represents the output process,  $U_t$  the deterministic forcing (input process), and  $Z_t$  a random forcing which is assumed to be white (i.e.  $Z_{t_1}$  and  $Z_{t_2}$  are statistically independent for  $t_1 \neq t_2$ ) and stationary. The parameters  $\alpha_k$ ,  $\beta_l$ ,  $\gamma_m$  are assumed to be constants. Clearly this type of dynamic model is in complete parametrised form, the weights in the regressive formulation being the unknown parameters. For a proper initialisation of the model, these parameters must be identified on the basis of observed input-output combinations. See, for example,

Priestley (1992) and Gourbesville & Lecluse (1994) for applications within hydrology.

In hydraulics, hydrology, ecology, etc. most conceptual dynamic models describing the time evolution of the (spatially dependent) state variables have the form of one or more coupled partial differential equations. They are often written in a form with the first-order time derivatives at the left-hand side and all the other terms at the right-hand side. The terms at the right-hand side involve e.g. convection and/or advection, friction, dispersion, reaction, as well as terms that represent the contribution of sinks and/or sources, or other model forcings such as boundary conditions. Owing to nonlinearities and/or non-constant or non-uniform coefficients these equations cannot be solved analytically but must be discretized with respect to time and the spatial coordinates. This leads to a discrete time model in state space form:

$$\mathbf{X}_t = \Phi(\mathbf{X}_{t-1}, \mathbf{U}_t | \mathbf{a}) + \mathbf{V}_t. \quad (3.2)$$

Vector  $\mathbf{X}_t$  represents the system's state at discrete time  $t$  and at one or more spatial positions (or even in distributed form, e.g. the water levels and discharges at every grid-point of a one-dimensional flow model of a branched river system). Vector  $\mathbf{U}_t$  represents the non-autonomous part i.e. the system's inputs or forcings (e.g. wind, lateral discharges or boundary conditions). The (nonlinear) function  $\Phi(\cdot)$  represents a transfer function that governs the dynamics of the system's time evolution. In fact, it incorporates all the system knowledge that forms the basis of the underlying conceptual model (and involves physical principles such as conservation laws for mass, momentum, energy, heat, etc.). The vector  $\mathbf{a}$  represents unknown parameters in the conceptual model that must be determined by calibration.  $\mathbf{V}_t$  is a random system noise, similar to the ARMAX approach, that is included to account for uncertainties in the forcings and/or model uncertainties in general. In stochastic numerical models the inclusion of system noise, together with uncertainties in observations of the state variables, forms the basis for sequential data-assimilation techniques (see, for example, Long 1989).

Clearly the dynamic models implied by Eqs(3.1) and (3.2) have the same generic form in the sense that the new state is determined from the preceding state(s) and

quantities that govern the system's forcing. However, the following differences should be mentioned:

1. The linear ARMAX-model is in fully parametrised form, and the model as a whole must be identified on the basis of a large set of observations. Hence ARMAX is a black box model and a data-oriented modelling technique. On the other hand, the numerical state space model of Eq.(3.2) is usually nonlinear and almost completely based on system knowledge. It will contain only a (relatively) few unknown parameters that originate from uncertainties in one or more model coefficients and/or (sub)processes. These parameters must also be determined by means of calibration but because of the knowledge-based form of modelling, a sparse rather than a densely distributed measurement set will often be sufficient.
2. In addition to (1) it can be also be mentioned that ARMAX (as well as NN) models will be most suitable for modelling the time evolution of a limited number of state variables (e.g. time-dependent water levels at one or a few spatial positions). They will not be appropriate for the modelling of spatially distributed processes (e.g. water levels and/or currents on a large and dense two-dimensional computational grid as described in the previous section on computational modelling of flooding systems), because this would require very large data sets to provide all relevant spatial and temporal correlations. In practice such distributed data sets are not easy to obtain although remote sensing techniques may provide important opportunities for the near future.
3. The auto-regressive terms on the right-hand side of the ARMAX-model of Eq.(3.1) may involve state variables and forcings of more than one preceding time steps. In the conceptual model of Eq.(3.2) this 'horizon' is at most one time step which is the result of only first-order temporal derivatives in the underlying partial differential equations defining the conceptual model. It must be noted, however, that conceptual models involving second- or higher-order temporal derivatives (e.g. wave equations) can easily

be rewritten into a form with two or more coupled equations of first order (in combination with an appropriate extension of the state variables). Sometimes this is also done within the ARMAX approach to achieve that the model is auto-regressive of order 1, and in this way enable recursive (filtering) techniques for the identification of its parameters (Ljung & Söderström 1983). Apart from this, we must recall that ARMAX techniques are often applied to model a system's state at one or a few spatial positions. Therefore the model cannot, or only marginally, deal with, or 'learn' from *spatial* correlations and to compensate this absence, all information must be obtained from *temporal* correlations suggesting (auto)regressive parts of higher order.

In essence, the state space form is a common feature of the dynamic models underlying both Eq.(3.1) and Eq.(3.2). At the same time, however, these models are in some sense opposite 'extremes' with respect to the origin of the transfer function  $\Phi(\cdot)$ : it is a fully parametrised and linear function for the ARMAX models of Eq.(3.1), and a nonlinear function (almost) fully based on system knowledge, in Eq.(3.2). Hence, recalling the property that NNs are universal function approximators (Cybenko 1989), a powerful generic form of a dynamic system can be obtained by modelling the transfer function with a nonlinear NN. For the general case of a  $K$ -dimensional multivariate time series  $\mathbf{X}_t$  as output, with the  $k$ th component auto-regressive of order  $M_k$  ( $M_k \geq 0$ ), and an  $L$ -dimensional external forcing  $\mathbf{U}_t$  with the  $l$ th component regressive of order  $N_l$ , and for the moment dealing with deterministic models only, this leads to the following nonlinear auto-regressive model:

$$\begin{pmatrix} X_t^{(1)} \\ X_t^{(2)} \\ \vdots \\ X_t^{(k)} \\ \vdots \\ X_t^{(K)} \end{pmatrix} = NN \begin{pmatrix} X_{t-1}^{(1)}, X_{t-2}^{(1)}, \dots, X_{t-M_1}^{(1)}, \\ X_{t-1}^{(2)}, X_{t-2}^{(2)}, \dots, X_{t-M_2}^{(2)}, \\ \vdots \\ X_{t-1}^{(K)}, X_{t-2}^{(K)}, \dots, X_{t-M_K}^{(K)}, \\ U_1^{(1)}, U_{t-1}^{(1)}, \dots, U_{t-N_1}^{(1)}, \\ U_t^{(2)}, U_{t-1}^{(2)}, \dots, U_{t-N_2}^{(2)}, \\ \vdots \\ U_t^{(L)}, U_{t-1}^{(L)}, \dots, U_{t-N_L}^{(L)} \end{pmatrix}. \quad (3.3)$$

The NN is a neural network (here assumed of type MLP) with  $\sum_{k=1}^K M_k + \sum_{l=0}^L N_l$  neurons in the input layer and  $K$  neurons in the output layer. The example shown in Figure 8 is an illustration of such a model where  $K=2$ ,  $M_1=2$ ,  $M_2=0$ ,  $L=1$ , and  $N_1=2$ .

The dynamic model of Eq.(3.3) will be referred to as an *Auto-Regressive NN (ARNN)*. It is in state space form and in this way a main property of conceptual numerical models is explicitly incorporated in the description of the time evolution of the involved processes. As a result the system of Eq.(3.3) much more represents a *model* in the strict sense, than the NNs used in standard form where no time evolution or any other prior system knowledge is taken into account.

The training of an ARNN will be a difficult problem because the ensemble of input–output combinations is mutually dependent, i.e. inputs determine the outputs and vice versa, and the standard approach based on the error-back-propagation-rule cannot be used anymore, and must be generalised. It turns out that for this generalisation the adjoint formalism known from data assimilation in large-scale deterministic numerical models is most appropriate.

### Application to water balance in Lake IJsselmeer

An illustrative example of an ARNN application concerns the modelling and prediction of the water balance of Lake IJsselmeer in The Netherlands. In a more detailed form this application is described by Gautam (1998). The most important factors that affect the management of the water balance are the inflow by the discharge of the river IJssel, and the inner (lake side) and outer (sea side, i.e. the Dutch Wadden Sea) water levels at the sluices of Den Oever and Kornwerderzand. A plan view of the area is shown in Figure 9. The difference of the inner and outer (tidal) water levels determine when (e.g. at low tide) and how long water can be drained from the lake into the Wadden Sea, or vice versa. However, it must be taken into account that the water levels can be significantly affected by wind.

On this basis an ARNN was prepared with five forcings as exterior inputs: the discharge of the river IJssel; the North–South and East–West components of the wind;



Figure 9 | Plan view Lake IJsselmeer.

and the tidal water levels at the sluices of Kornwerderzand and Den Oever. The (auto-regressive) output consists of the water level of the IJsselmeer. The time step in the model is  $\Delta t = 1$  day, adopted from the sampling rate for which observations of the discharges of the river IJssel and the lake's water levels were available. For synchronisation also the wind speeds and the outer tidal water levels were represented by daily samples. Here this was done by taking the daily maximum for the wind speed and the daily minimum of the tidal water levels.

For the IJsselmeer area different target water levels are maintained during summer and winter. Within the present study only winter régimes were considered, which are particularly interesting owing to their pronounced dynamic behaviour. In this way the data ensemble consists of daily samples within the periods 1 October until 31 March, for all 15 winter seasons from 1978–79 until 1992–93. From this ensemble nine seasons were chosen for training and the other six seasons for verification. This was done in such a way that the training and test ensemble were statistically representative for the whole data set. On the basis of repeated training sessions, systematically varying the orders in the model's regressive part with respect to the five forcings, and also varying the order in the

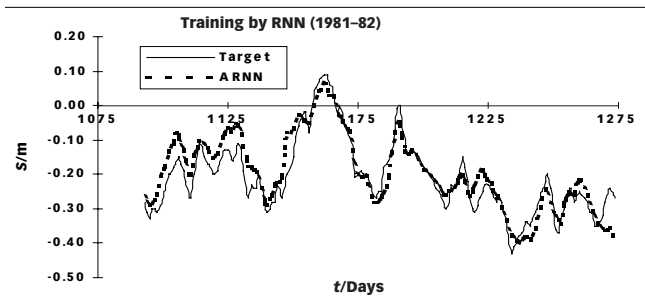


Figure 10 | Observed (target) and predicted (ARNN) water levels within the training ensemble.

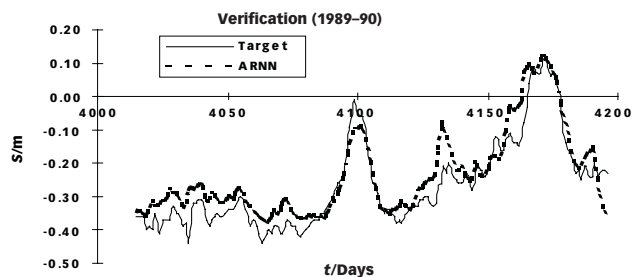


Figure 11 | Observed (target) and predicted (ARNN) water levels within the verification ensemble.

auto-regressive part, followed by a comparison of the model's performance on the training set and the verification set, the 'optimal' ARNN architecture was determined. This turned out to be auto-regressive of order 1, second-order regressive with respect to the discharges of the river IJssel, and 0th order (i.e. non-regressive) with respect to the other forcings.

For two seasons, the water levels computed with the trained ARNN are compared with the observed water levels in Figures 10 and 11. The first period is from the training ensemble, and the second period from the verification set. From these plots, as well as from those of the other years, a reasonable performance of the ARNN is observed, although at certain time intervals considerable mismatches of the observations and NN predictions were found. For the training and verification sets these mismatches are of the same qualitative form and quantitative size. Therefore these mismatches are almost certainly caused by the (*a priori* already known) uncertainties in the river IJssel's discharges and uncertainties in the wind

directions and wind speeds, and not the result of an inappropriately prepared ARNN. In fact, the predictions with the ARNN were even found to be slightly better than the results obtained from a numerical model study carried out before by Fokkink & Ellen (1997). Their approach was also hampered by the uncertainties mentioned above.

### Self-organising feature maps (Kohonen Networks) for pattern classification

The main difference between Self Organising Feature Maps (SOFMs, or Kohonen networks, introduced by Kohonen (1982)) and NNs based on Multi Layer Perceptrons or Radial Basis Functions, is that SOFMs are not of input-output type but process input patterns only. These input patterns, all of the same but arbitrary dimension, are transformed into a one- or two-dimensional discrete map, i.e. in a topologically ordered fashion. In this section the main steps of this transformation are briefly described. For more detailed and easily accessible introductions to SOFM, Haykin (1994), Melssen *et al.* (1994) and Beale & Jackson (1990) are recommended.

The input ensemble is assumed to consist of  $K$  vectors  $\mathbf{X}_k$  in an  $N$ -dimensional space, where  $x_{kn}$  ( $1 \leq k \leq K$ ,  $1 \leq n \leq N$ ) denotes the  $n$ th component of  $\mathbf{X}_k$ . This ensemble of inputs is used to train the SOFM. Owing to the self-organising property of the SOFM no targets have to be specified for the input vectors. A SOFM consists of a one- or two-dimensional discrete lattice of neurons usually arranged in a rectangular form. To each of the neurons a weight vector is assigned and this weight vector is of the same dimension  $N$  as the input vectors. If the number of neurons is  $M$  (e.g. in a one-dimensional arrangement or  $M = M_1 \times M_2$  in a two-dimensional architecture) then the network consists of  $M$  such weight vectors  $\mathbf{w}_m$ . It must be noted that the weight vectors do not refer to connectivities between the neurons in the lattice, rather that the weights are involved in the processing of the input vectors  $\mathbf{X}_k$  during training. In fact, the neurons in the lattice are *not mutually connected* and the ordering of the neurons within the lattice is only used for a proper definition of neighbourhoods for each neuron. During training these neighbourhoods are used to induce the topology of

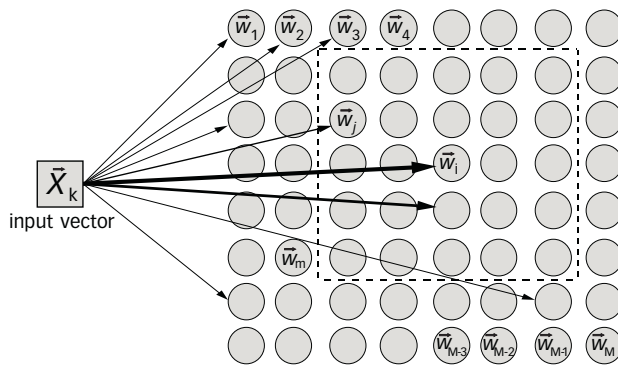


Figure 12 | Example of a two-dimensional  $8 \times 8$  Kohonen Network.

the input ensemble into the set of weight vectors. An illustration of a two-dimensional SOFM-architecture (Kohonen Network) is given in Figure 12.

### Training of the SOFM

Each neuron  $m$  in the network is fed by the input vector  $\mathbf{X}_k$  and is equipped with a single weight vector  $\mathbf{w}_m$  which is of the same dimension as the input vectors. The arrows represent the evaluation of the similarity between the input vector and the weight vectors. The larger the similarity, the more bold an arrow is plotted. Neuron  $i$  is then the 'winning' unit. The dashed box denotes a neighbourhood where during training the weights  $\mathbf{w}_j$  of the enclosed units  $j$  are slightly adapted towards the input vector  $\mathbf{X}_k$ .

Before training of the SOFM can be started, a function  $D(\dots)$  must be specified that  $D_{mk} = D(\mathbf{w}_m, \mathbf{X}_k)$  measures the similarity of a weight vector  $\mathbf{w}_m$  and an input vector  $\mathbf{X}_k$ . With this similarity measure the degree of agreement ('similarity') between two vectors is defined, varying from 'equivalent' to 'totally different'. The similarity measure will have a large effect on the classification process because similar input vectors will after training refer to the same, or neighbouring neurons in the feature map, whereas very different inputs will activate neurons that are far apart. With the similarity measure, however, the user can bring in system knowledge and/or strategies to control the classification process.

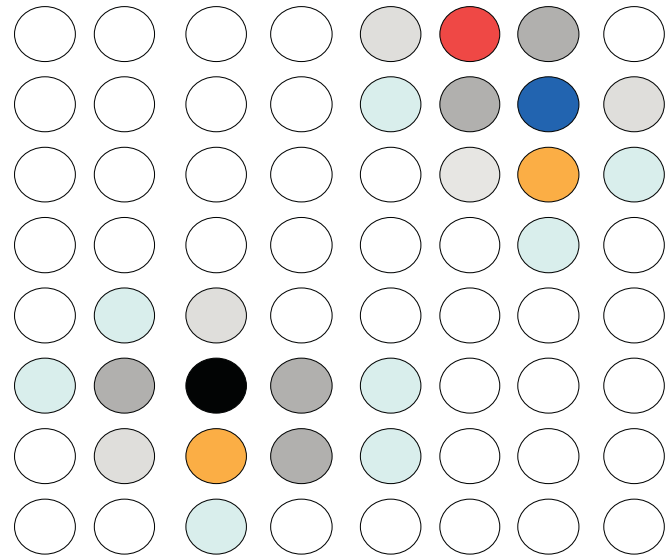


Figure 13 | Example of a count map of a trained SOFM.

For the similarity measure several alternatives are possible. Most common are distance measures, such as the Euclidean distance, or non-Euclidean distance definitions like the Minkowski distance. Also, distances may be taken that involve scaling of one or more of the coordinates (or even involve the inverse covariance matrix of the training set) to obtain that in all directions the range of variation is the same. Sometimes, also, similarity measures are used based on the dot or inner product of the vectors, and apart from possible normalisations of the input vectors, two vectors are then similar if they are in the same direction.

Training of the SOFM, as for all types of NNs, implies that the weights in the network are identified on the basis of the input data set. In the SOFM the weight vectors are often randomly initialised at the beginning of the training process, but sometimes in some way use is made of (an approximation of) the distribution of the input vectors, if possible.

Then the following iteration is performed which will be repeated many times (therefore the iteration is labelled with a discrete time index  $t$ ). An iteration starts with a random selection of an input pattern  $\mathbf{X}_k$  and for all the neurons  $m$  ( $1 < m < M$ ) in the lattice the similarity measure  $D_{mk}$  is evaluated. Then the neuron  $i$  is selected for which the similarity is maximal (the so called 'winner',

see Figure 13). Next the weights  $w_j$  of all neurons  $j$  in a neighbourhood of the winning unit are modified according to

$$w_j(t + 1) = w_j(t) + \eta(t) \cdot \lambda(t,r) \cdot (X_k - w_j(t)). \quad (3.4)$$

The weights of the neurons that are not within the neighbourhood of the winning unit are not changed. After this is done for the first input vector, these steps are repeated until all patterns have been selected once, but in a random order. This process is repeated many times until no noticeable changes are observed in the feature map. In each iteration the  $K$  input patterns must be selected in a random order.

The symbol  $\eta(\cdot)$  in Eq.(3.4) is a learning rate parameter and the function  $\lambda(\dots)$  is the neighbourhood function in which  $r$  denotes the distance in the Kohonen map between neuron  $j$  and the winning neuron  $i$ . Often the neighbourhood function is of a 'top hat' form meaning that it is constant on a square region around the winning neuron. A distance  $r = 1$  then includes the winning neuron plus its 8 nearest neighbours, whereas a 'radius'  $r = 2$  will include the next 16 neurons as well. Apart from 'top hat', the neighbourhood function  $\lambda(\cdot)$  may take other forms, of course, such as a Gaussian dependency on the distance  $r$  between the neurons, or even Mexican hat forms, in very much the same way as in Fourier Transform theory.

The learning parameter and neighbourhood function depend on the iteration number and there is no strict theoretical basis how these parameters must be taken. From experiments it is found that the learning rate should initially be chosen in the range between 0.1–0.5 and gradually decrease towards values around 0.001–0.0005. The neighbourhood function should initially include all neurons in the network and gradually shrink to contain the nearest neighbours of the winning neuron only, eventually activating the winning unit only.

Note that the updating rule of Eq.(3.4) for the weight vectors shows that the weights are slightly modified towards the input vector  $X_k$ . This is done for all the weights in the vicinity of the winning unit so that (after many iterations) neurons that are adjacent in the lattice will tend to have similar weight vectors. In this

way the topology of the input space is preserved best as possible.

### Interpretation of the trained SOFM

After training the  $K$  input patterns have been transformed into  $M$  weight vectors. Then for each neuron in the map the number of inputs can be counted for which this neuron is the winner. From this count map regions can be identified with high counts (i.e. high densities in the input space in the vicinity of the corresponding weight vectors) or low, and/or absence of counts (low densities in the input space). If within the lattice two or more regions with high counts are found, separated by units not assigned as winner, these regions will represent clusters. See Figure 13 for an illustration of a count map with two clusters. For further details on the interpretation of the SOFM, see, for example, Melssen *et al.* (1994).

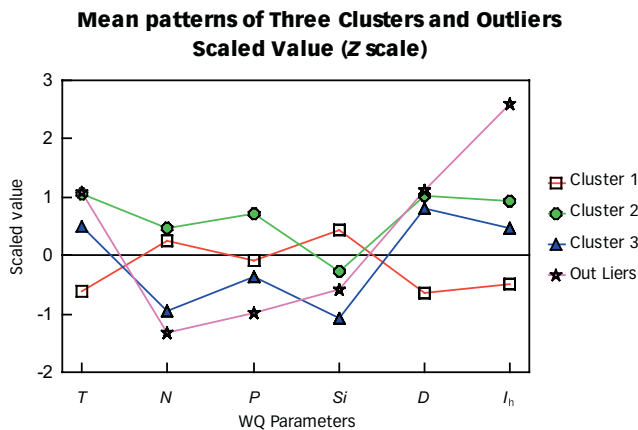
The counts are represented by a grey code, and the darker the neuron is plotted, the larger the number of input vectors that are mapped onto that unit. In this example two main clusters can be identified within the input ensemble, towards the upper right and lower left corner respectively.

### Application of SOFM analysis to ecological data sets

To illustrate the type of applications that are suitable for SOFM analysis, an ecological data set is considered here. The objective is the classification of the data. Only the main aspects are described here and for the details reference is made to Ali (1997).

The application deals with the analysis of a data set containing ecological and water quality parameters that were measured in nine shallow lakes in The Netherlands. These measurements were in the form of daily averaged values of biotic and abiotic parameters recorded at (bi-)weekly intervals from 1975 to 1985. For some lakes data were absent during sub-periods, however. The measurements involved temperature ( $T$ ), duration of daylight ( $D$ ), light radiation intensity at the surface ( $I$ ), background extinction ( $E$ ), the water depth ( $d$ ), as well as concentrations of nitrogen (N), phosphorus (P), silicon (Si) and chlorophyll-a (Chl-a).





**Figure 14** | Features obtained from a SOFM-analysis of 1001 biotic and abiotic parameters measured in nine shallow lakes in The Netherlands.

From the radiation intensity, depth and background extinction the accumulated intensity parameter  $I_h = I/(d \times E)$  was determined. The chlorophyll concentration is a measure of the algal mass present in the system and is actually ‘determined’ by the other parameters. In the past, either conceptual models or MLP type NNs were applied to predict the chlorophyll level from the accumulated intensity parameter  $I_h$ , and the remaining five forcings  $T$ ,  $N$ ,  $P$ ,  $Si$ , and  $D$ . Within the (preliminary) MLP-type applications, not so much attention was paid at first to a proper validation analysis of this six-dimensional input ensemble. To overcome this ‘omission’, the feasibility of SOFM for such an analysis was investigated (Ali 1997). The main results are summarised below.

In total 1001 patterns of various ( $T$ ,  $N$ ,  $P$ ,  $Si$ ,  $D$ ,  $I_h$ )-combinations were available and used to train a two-dimensional  $8 \times 8$  and a one-dimensional  $20 \times 1$  SOFM. The input ensemble was renormalized first by determining the residuals with respect to the ensemble mean, then scaling the residuals with the mean spreading value. The two and one-dimensional approaches both produced consistent classifications of the input ensemble leading to four main features, which are graphically summarised in Figure 14.

The results of the SOFM analysis allow the following interpretations:

1. In all features a pronounced positive correlation of the abiotic parameters ( $T$ ,  $D$  and  $I_h$ ) is observed:

when one of these parameters is positive (i.e. above the mean) then this is also the case for the other two. In the same way, if one of the three parameters is negative also the other ones are negative. This correlation can easily be explained from the physical fact that temperature depends on the light intensity which in turn is correlated with day length (i.e. common input correlation owing to seasonal effects: low values in winter and high values in summer).

2. For Cluster 1 the temperature, duration of daylight, and accumulated sunlight intensity are all low, so that in fact this feature represents winter patterns. The opposite is found for Cluster 2, corresponding to summer patterns. In Cluster 3 the temperature, daylight and intensity are between those of Feature 2 and 1, and Feature 3 represents spring and autumn patterns. Cluster 4 contains outliers, possibly due to errors in the estimation of deficient values of the background extinction during pre-processing of the data.
3. A clear negative correlation is observed for ( $T$ ,  $D$ ,  $I_h$ ) samples on the one hand (see  $i$ ), and  $Si$  on the other. From an ecological viewpoint this can be explained as follows. In early spring, diatoms (an algae subset) start to grow and consume biotic compounds, mainly silicon. The silicon concentration will thus decrease during the summer and become less than during winter (see Features 1 and 2). After exhausting silicon, the diatoms will deposit as sediments on the bed. The silicon concentration will remain low till late autumn when the algae will consume the nutrients. From late autumn the silicon concentration will rise again since the algae population is reduced and the nutrient demand decreases.

In addition to interpretations of SOFM analysis with regard to temporal aspects, spatial effects were also investigated. This was done by partitioning the input ensemble according to the corresponding lakes, followed by an inspection and comparison of these regions within the overall feature map (i.e. the lattice of neurons) that are most frequently activated by the individual lakes. This

allowed a rough classification of the lakes that could be related to the measured chlorophyll concentrations in these lakes. Moreover, for a few lakes, the inputs were partitioned in time as well by no longer activating some regions in the map over some period of time, thus simulating management strategies to reduce eutrophication in the lakes. In this way a sudden trend as a result of the management strategy could be clearly identified. Although the obtained trend was not really a surprise (since the management strategy was known to have taken place), the results nevertheless clearly confirmed its implications, thus demonstrating the SOFM's potential for general data analysis and interpretation.

## CONCLUSIONS AND REFLECTIONS ON FORTHCOMING DEVELOPMENTS

In this paper various applications of computer-based modelling are presented. For problems that are well described by mathematical equations, numerical simulation techniques can be used. Examples are given for dam break problems and for inundation of polders. When no explicit mathematical formulation can be given, but when adequate data are available, computer-based techniques can be employed yet again. Data-driven modelling techniques like NNs, developed in artificial intelligence, are particularly useful for data analysis and pattern recognition when no *a priori* knowledge of the underlying processes is available. Several applications are shown here, including horizontal wave forces on breakwaters, water level predictions in lakes, and feature analysis of ecological data sets. All examples are taken from recent work at Delft Hydraulics, although only a limited selection could be presented here. More elaborate contributions as well as other topics can be expected in forthcoming issues of this *Journal*.

Advances in the field of computational modelling clearly demonstrate the feasibility of using numerical simulation techniques for solving realistic problems (like the inundation of polders). When the physical aspects are well described by mathematical equations and the numerical scheme has been validated against experimental inves-

tigations and field observations (the IAHR working group on dam break problems is one such validation forum), computer simulations can provide valuable insight. In particular, when the computational results are embedded in a geographical information system environment and the time evolution of the computed results is displayed dynamically, the inundation process can easily be interpreted. In the near future a combined one-dimensional network/two-dimensional horizontal flow simulation system embedded in a GIS environment will become available, which can be applied to rural and urban area flooding problems simultaneously. When incorporated within a decision support system, alternatives for evacuation plans and risk assessment can be explored directly. Government authorities and insurance companies have already expressed great interest in such systems. Several directly relevant practical applications are likely to be expected in the very near future. Moreover, the distributed use of such advanced modelling systems via the Internet will make them more accessible to practitioners and at the same time better to maintain and update by developers (see, for example, Mynett *et al.* 1998).

Diversification of computer-based modelling technologies to application areas where no clear mathematical formulation may (yet) be present but where adequate data sets are available, has been illustrated by several realistic examples from engineering practice. Various applications of one particular class of so-called subsymbolic techniques, namely Artificial Neural Networks (ANNs), clearly demonstrate the power of such approaches (Boogaard *et al.* 1998*a,b*). Although often presented as 'black box modelling', it should be stressed, however, that adequate knowledge and experience is often also required here, if reliable and practicable answers are to be obtained. For example, input-output relations have to be imposed, which implies at least some *a priori* knowledge on cause-effect relations. This is not always trivial in dynamic ecosystems, however. Also, choosing the proper number of layers in an MLP-type network is very much related to the amount of data available for training and verification, if under- or overtraining is to be avoided. However, dependencies may be present within the data set. Hence, pre-processing and classification of data, introduced here as an application of self-organising

feature maps (Kohonen Networks), can be a very valuable first step in NN modelling. Combinations of various techniques are being explored as well. In general, alternative computational modelling techniques like 'neuro-fuzzy computing' are developing rapidly and practical examples of such approaches may be expected in the near future. The same applies to optimization techniques for decision support when evaluating complex dynamic systems: whether based on a 'constraint logic' approach or on 'evolutionary computing', new developments are under way to become relevant methodologies in engineering practice.

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