2 Review of hydraulic modelling methods in wetlands and floodplains

2.1 Why develop a model?

A model is a simplified representation of some part of the real world (Jewitt *et al*, 1998) and predicts effects from causes. This can be by means of mathematical equations used to describe the behaviour of some physical characteristic or by non-mathematical, qualitative 'rule-based' means where a system is described through 'if-then-else' rules. Simple models can be derived and calculated on paper, but larger and more complex ones require the use of computers, so it was really with the advent of the computer in the mid-twentieth century that mathematical models first came to the fore. Most models, once set up, are used to see how a system will react to changes in its environment or inputs. For instance ecological models can be set up to investigate the effects that global climate change will have on plant species, or a city transportation model can be used to see how the development of a new suburb will affect the traffic on roads in the area.

Other than their predictive power, models help us to understand the functioning of systems better. Models structure knowledge, and the process of model building imposes orderliness on understanding and enforces consistency between different aspects of a problem (Pattern, 1994). Jewitt *et al* (1998) comment that models are known to identify shortfalls in understanding and data availability and thus stimulate further research and monitoring, and that "models which provide a quantifiable response to a given catchment development scenario are sought within many disciplines in order to aid objectivity in planning exercises". Palmer *et al* (1999) comment: "Models provide estimates of impacts based on assumptions, including assumptions about the future that may be uncertain. They cannot identify which assumptions are best. Thus models can shift the political debate from one that questions what will likely happen given some set of assumptions to what are the most likely or most plausible set of assumptions.

Models can provide estimates of economic, environmental and ecological impacts throughout the [river] basin associated with individual project design and operating policies. These estimates can then serve to identify which designs and policies, if any, best serve the interests in the basin as a whole." Jewitt *et al* (1998) argued that a "fundamentally important reason for model development lies in their use as tools to assist in developing and nurturing communication between scientists of different disciplines".

Bates *et al* (1992) argue with specific reference to flood events: "The transient and unpredictable occurrence of flood events often means that the technical capability to undertake frequent measurements over an extensive network of measuring sites may not exist. Furthermore, magnitude and frequency considerations demand that any measurements should be undertaken over a wide range of event magnitudes. In the light of this there is a need to develop models capable of simulating the behaviour of flood flows with a high degree of spatial and temporal resolution, in order to reduce reliance on external measurement."

With the increase in computing power in recent years, there has been a corresponding increase in the complexity of models and today it is possible to model systems on a personal computer that only a few years ago would have been impossible to model at all. There are many commercial modelling packages available, some of which are sold by software companies and can be very expensive to purchase, while others that are free to copy and use have been developed by government sponsored organisations, non-governmental organisations, individuals and universities. Examples of these organisations are the United States Army Corps of Engineers, Hydrological Engineering Centre (HEC) and the Water Research Commission (WRC) in South Africa. Many models are continuously being improved as errors are discovered and fixed and so models are not only becoming more complex and powerful, but many of them are also becoming more stable and reliable. Many modern modelling programs are relatively easy to use, using a graphical windows-based interface as opposed to the older text-based systems. Choosing which modelling program to use is not an easy task and depends on the specific system that needs to be modelled.

2.2 The choice of a modelling method for the Nylsvlei floodplain

In the mid 1990s, DWAF had the desire to set up a model of the Nylsvlei floodplain to determine the impacts of catchment developments on inundation, due to the failure of previous models to do so. These previous models are reviewed briefly later in this chapter. The choice of modelling method and program to use for the Nylsvlei floodplain was a crucial one as it could impact on model accuracy and ease of use. The outputs required from a hydraulic model of the Nylsvlei floodplain were time series of inundation areas and inundation depths (Chapter 1), including representations of these in a graphical format.

There were various modelling methods available to model the Nylsvlei floodplain such as mass (water) balance hydrological methods, numerical models in one-dimension, numerical models in two-dimensions (such as finite-element, finite volume, finite-difference, diffusion equation methods) and numerical models in three dimensions. All of these rely on the solution of equations and each has its own advantages and disadvantages.

Morgan (1996) used a mass-balance method to model the Nylsvlei floodplain, which is reviewed later in this chapter. Mass-balance methods often rely on a series of cells inside of which the water balance is calculated separately, and can be interconnected so that outflows from one cell become inflows to another cell. The boundaries of cells are often defined as physical barriers to flow such as dam walls, road causeways and levees. These methods have the advantage of simplicity, but cannot give flow velocities in the floodplain and generally operate on a time scale of at least months, although it may have been possible for Morgan's (1996) model to operate on a daily time step. Most of the models using this method cannot map inundated areas or depths. Many hydrological models use these methods.

A one-dimensional model called HEC-RAS (available from the United States Army Corps of Engineers, Hydrological Engineering Centre) was used to model the Nylsvlei floodplain in this project (Chapter 6). One-dimensional models model flow in one-dimension only, in a downstream direction parallel to the channel or floodplain and have the advantage of being simpler than two or three-dimensional models, but cannot describe the two or three-dimensional nature of flows on floodplains. When a one-dimensional model is used with a digital terrain model (DTM), flooding areas and depths can be mapped and they can generally be run at any time-step desired. There is a wide range of one-dimensional modelling packages available and making the choice of which one to use is not an easy one. According to Crowder *et al* (2003), many one-dimensional modelling programs use the one-dimensional energy equation for steady-state gradually varied flows (with energy losses being accounted for by friction), the momentum equation or governing hydraulic equations for a given structure for rapidly varied steady-state flows, and a simplified one-dimensional form of the St Venant equations for unsteady flows. However the approach to discretization, calculation of conveyance and inclusion of losses may be different, leading to different solutions to the same problem. A bench marking study was conducted by the United Kingdom Environmental Agency (Crowder *et al*, 2003) into three commercial one-dimensional models in widespread use: HEC-RAS (US Army Corps of Engineers, USA), ISIS (Halcrow/Wallingford Software, UK) and MIKE11 (Danish Hydraulic Institute, Denmark). All three of these programs can model steady and unsteady flow states, and the benchmarking exercise compared numerical accuracy (against the analytical solution for various physical situations or configurations), capability, reproducibility, adaptability, and form and function of each program. The study highlighted the strengths and weaknesses of each program through tests involving various conditions, which included subcritical and supercritical flows, a triangular channel, various weirs, culverts, bridges and the monoclinal rising wave as described by Chow (1959) as a special case of unsteady flow. There were many conclusions: a few examples were that all three packages are capable of modelling steady-state subcritical, supercritical and transitional flows to an acceptable order of accuracy; that the modeller must take care in using default calculation settings and calculation options as these may not be the most appropriate for the situation; and that the choice of a representative Manning's roughness is important if either an underestimation or overestimation of water levels and velocity is to be avoided (a result from the Monoclinal Wave test).

Two-dimensional models are more accurate than one-dimensional models due to their use of a grid or cell system to describe the terrain of the floodplain. Water flow is modelled in the longitudinal and lateral directions to the channel in these models. The accuracy is determined by the size of the cells or grid, although the greater the number of cells, the longer computation times become. Birkhead *et al* (2004) attempted to model the Nylsvlei floodplain for this project, using a commercial two-dimensional model called SMS (available from Boss International), but numerical stability problems were experienced in the wetting and drying of cells and the method was abandoned.

Three-dimensional models are available but are complicated and at present questionable for use in a floodplain, where water depths are generally shallow and flow generally proceeds in two-dimensions.

Rule-based modelling methods have been used to model geomorphological change in rivers in South Africa (Nicolson, 1999), and could be used as an alternative method to model floodplains if only a low-resolution model was required. This modelling method has the advantage of not using any numerical methods and therefore having none of the stability problems inherent with the other (mathematical) methods.

2.3 Review of previous attempts to model the hydraulics of the Nylsvlei floodplain

Three previous studies were attempted to model the hydraulics of the Nylsvlei floodplain. The first two (both hydrological models) were developed by DWAF and Steffen, Robertson and Kirsten Consulting Engineers (SRK) respectively, and are reviewed in detail by Morgan (1996). The third model, developed by Morgan (1996), relied on a digital terrain model and water (mass) balance using cells.

2.3.1 DWAF model of the Nyl River basin

This model was developed by DWAF (Nel *et al*, 1989) to determine the impact that the then-proposed Olifantspruit Dam would have on flows in the Nylsvlei floodplain. What is given here is a summarised version of Morgan's (1996) review.

The DWAF model was a hydrological rainfall-runoff model and was used to quantify the absorption effect the Olifantspruit dam would have on flow at the dam site (DWAF gauge A6H012), the entrance to the floodplain at A6H002 (Deelkraal) and at the floodplain exit at A6H001 (Moorddrif) (Figure 1.3). Missing rainfall data were patched and missing flow data were augmented with modelled flows from the Pitman and multiple regression models. Being a hydrological model, this model could not output areas or depths of inundation on the floodplain.

Flow duration analyses were conducted, one with the Donkerpoort Dam in the model and another with the Donkerpoort and then-proposed Olifantspruit Dams. The absorption potential of the Olifantspruit Dam was estimated as a percentage of annual flow to be 4.2% at the floodplain entrance and 2.3% at the floodplain exit. This absorption potential was however, found to vary between 20% at low flows and 1% at high flows at A6H002 and between 10% at low flows and 0.3% at high flows at A6H001. No relationship was established for monthly flows, but absorption was estimated to be between 0% and 50% at A6H002 depending on the size of the flow in a particular month and volume of water in the reservoir at the time.

Morgan (1996) was highly critical of this model as it had many inaccuracies and was based upon what Morgan thought were poor assumptions. Losses to groundwater were not adequately incorporated due to lack of understanding of how these losses take place. Morgan was critical of the model determining the contribution of the Olifantspruit as a percentage of the entire basin area. Tarboton's (1989) records showed that certain catchments contributed disproportionately more surface water than others compared to their areas. The Olifantspruit, Tarboton (1989) reasoned, was one of the larger contributors and so the importance of this catchment was severely underestimated in the DWAF model. The analysis of catchment scenarios in Chapter 8 shows that the Olifantspruit is a very important catchment, being one of the larger contributors in relatively dry years. Morgan (1996) also found that the mean annual runoff (MAR) predicted for A6H001 at the floodplain exit was greatly exaggerated, a figure of 117Mm^3, despite the zero stage recorded in most years at this gauge plate.

2.3.2 SRK model of the Mogalakwena River basin

SRK (Steffen, Robertson and Kirsten Consulting Engineers) released the results of a comprehensive study of the Mogalakwena drainage basin in 1992 (Schultz, 1992), of which the Nylsvlei floodplain and catchments make up a part. This model was also reviewed in detail by Morgan (1996) and his review is summarised here.

This study made use of a hydrological model called WRSM90 version 2.1, based on the Pitman Model and developed by Pitman and Kaakebeeke (1991). WRSM90 simulates water movement in a river basin through an interlinked system of catchments, river reaches, reservoirs and irrigation areas and works on a monthly time step. Monthly rainfall, evaporation, streamflow, irrigation and reservoir data were used in the model and runoff from ungauged catchments was modelled. Morgan (1996) was critical of this model as it accounted for losses to evaporation and infiltration in an artificial manner; these losses were estimated and included in the model as a series of dummy dams to model the floodplain. The sizes of these dummy dams were then adjusted by trial and error until the required inflow-outflow relationship from the floodplain was generated.

It was estimated that present day mean annual runoff in 1992 was 20% lower than the volumes expected from an undeveloped catchment. The simulations also suggested that above-average years were relatively unaffected by water resource developments while below-average years showed a marked reduction (Higgins *et al*, 1996). These results led Higgins *et al* (1996) to conclude that the water resources of the Nyl River floodplain were already stressed and that the construction of a dam would reduce the frequency, spatial extent and duration of flooding.

Morgan found that the model was very useful as it could model outflows from the Nylsvlei catchments, giving an estimate of losses to evapotranspiration and infiltration in each of these catchments. Unfortunately, this model worked on a monthly time-step, which was too coarse to adequately describe flooding of the floodplain. The model also could not describe flooding in terms of inundated areas, depths and durations.

2.3.3 A mass-balance model of the Nylsvlei floodplain

Morgan (1996) attempted to model the hydraulics of the Nylsvlei floodplain using the mass-balance approach. The mass-balance equation included inflows from tributaries and the Nyl River, outflow from the floodplain in the Nyl River, change in storage, losses through evaporation and losses through seepage to groundwater. Losses to transpiration and surface water abstraction were ignored, as these were considered small.

It was impossible to calculate the volume of water held in storage on the floodplain using conventional stage-discharge techniques due to a general lack of stage and flow data on the floodplain (Morgan, 1996). Losses to infiltration were also not known. As Morgan intended to use his model to determine these losses, the storage volume term in the mass-balance equation had to be known. Morgan calculated this storage volume using a digital terrain model (DTM), created from contours and spot heights digitised off orthophotos and topographical maps.

He divided the floodplain into four cells separated by dykes, dams or road crossings on the floodplain, specifically chosen as barriers to flow. This was intended to simplify the mass-balance calculations as the outflow component of the water balance in each cell could be ignored for a time until the water reached a height where it could pass over or through the barrier. The first cell extended from the upstream end of the floodplain at Modimolle to the Deelkraal dam, the second cell from the Deelkraal dam to a dyke at Vogelfontein, the third cell from the dyke at Vogelfontein to the Crecy/Roedtan road crossing and the fourth cell from the Crecy/Roedtan road crossing to the outflow point of the Nylsvlei at Moorddrift.

Morgan derived a stage-storage relationship for cell one (which had the dam at Deelkraal as its downstream boundary (Figure 1.3)) at DWAF gauge plate A6H002. Flow data were available from flow gauges upstream of the floodplain and the cumulative inflow for chosen three to four week periods corresponding to the first flood in certain seasons were calculated and defined as the storage, as there was no outflow due to the Deelkraal Dam. The storage in the cell calculated at a chosen time could be plotted against the average weekly stage at the gauge in the cell at that time, and a stage storage relationship was derived. This relationship was used to calibrate his model.

The program that Morgan used could only draw horizontal contours on the DTM, which presented a problem as the water surface of the inundated floodplain is not horizontal and follows more or less the gradient of the floodplain. These contours were needed to calculate depths and volumes. This problem was solved by assuming that the maximum floodline in the recent geological history of the Nylsvlei floodplain coincided with the boundary of the alluvial sediments in the floodplain. A further assumption that lateral and longitudinal flooding occur at approximately the same time and that the channel does not have the capacity to route the high discharge volumes rapidly downstream allowed him to calculate a water surface that ran along this flood line and was horizontal in the lateral flow direction. Morgan then calculated a surface derived from the algebraic difference between the maximum water surface in the floodplain corresponding to the alluvium boundary and flat in the transverse direction and the topography of the floodplain below. This yielded a surface only describing the water volume on the floodplain. Flood lines (or concentric contours on the DTM) were then calculated in this new surface at regular intervals below and parallel to the highest possible flood line until the situation of zero flow was reached where there was no water in the cell. Each of these floodlines could then be used to calculate a corresponding volume and surface area of water inundating the floodplain. The stage-storage curve for the gauge plate in the cell derived from cumulative inflows was compared to the stage-storage curve derived from the DTM and hence the model was calibrated.

Evaporation losses could then be calculated using an evaporation rate and the inundation area from the model, enabling the infiltration losses to be calculated as the only unknown left in the water balance equation. A daily series of inundated areas could be mapped using daily stage data at the calibration gauge (A6H002) and Morgan's DTM method.

The DTM approach used by Morgan would allow the determination of inundation depth at any point in the floodplain and the mapping of inundation areas. However, the inundation areas and depths given by this modelling method represent a steady-state situation, due to the stage-storage curve being derived for only one gauge plate in cell one, and the assumption that the floodline is parallel to the boundary of the alluvial sediments. This is not the case particularly on the rising limb of a flood hydrograph. This technique also relies on various assumptions that need to be proven such as the assumption that the maximum flood edge would coincide with the alluvium boundary. An advantage to Morgan's modelling method is that vegetation resistance to flow does not have to be taken into account in the model, as this can be difficult to measure. It is also relatively simple. Unfortunately, Morgan only managed to calibrate the first (upstream-most) cell of his model. He was hampered by an inaccurate DTM due to a lack of topographical data and a lack of flow and stage data to complete the water balance equation and calibrate the model. If this method were used again it would be desirable to develop the model from scratch using the LiDAR data now available (Chapter 3).

2.4 Review of a few similar projects in other wetlands and floodplains

2.4.1 Hydraulic models of three floodplains in South Africa (Weiss, 1976)

Weiss (1976) developed a set of models that could be used for modelling floodplain topography, hydraulic modelling of flow of water through floodplains and the modelling of economic damage from floods. These models were developed for the Msunduze floodplain through Pietermaritzburg in KwaZulu-Natal, the Umflozi/Mzunduze floodplain in Zululand and part of the Vaal River floodplain through Vereeniging. He developed different hydraulic models using a steady-state backwater method, a cell-type flood routing method, a continuum-type flood routing method and a rigorous-type flood routing method.

The steady-state backwater model represented the geometry of the floodplain as a series of cross-sections normal to the direction of flow and calculated the water surface profile for a given steady-state discharge through a step-wise solution of the energy equation. The calculation was interrupted and set approximately equal to that for critical flow at places where critical or supercritical flow took place. Peak values of stage and velocity in the channel and on the floodplain could then be output.

The cell-type mathematical model was developed for routing of floods through complex river systems where account has to be taken of storage attenuation effects, cross-channel flow and flow reversal between channel and side-valley storage. Cell-type models generally represent the system as a series of storage cells with level water surfaces interconnected by either short channels or overspill weirs. Due to the level pool assumption, difficulties can arise with long river reaches especially with steep gradients and if detailed hydraulic modelling is required. Weiss derived cells with inclined water surfaces in the general direction of flow, and all these river cells were both storage and flow cells allowing the water surfaces to be continuous. The shape of cells is determined by the floodplain topography and cells can be created in a lateral direction to represent parts of a floodplain and ponded areas. Information required for dynamic routing of water through cells (such as the stage/flow area, stage/surface area, stage/conveyance relationships) is obtained from cross-sections. Boundary conditions include inflow hydrographs entering each reach, stage-discharge or tide-stage (for ocean outflow) relationships at the outflow from each reach. The model makes use of the (modified) equations of motion and of continuity for unsteady flow in rivers without lateral inflows expressed in finite difference form, solved using matrices. Advantages of this type of model include relative simplicity and a smaller demand on computing power. Weiss found that in steep floodplains and rivers the cell-type model gave answers that differed only slightly from the rigorous-type model despite the lower accuracy of the cell-type model. Output from the model may take the form of stage and discharge hydrographs at selected points on the cross-sections and of stage hydrographs at the middle points of all cells. This includes extent, depth and duration of inundation as well as average velocities of flow normal to the cross-sections, both in the channels and on the floodplains. The model was set up and calibrated for the Mfolozi/Msunduze floodplain and gave satisfactory results.

A (calibrated) continuum-type model was used to model a small part of the Mfolozi floodplain and gave good results. This sort of model can model flow and sediment transport in two-dimensions, using two-dimensional equations of motion and continuity. Weiss used the boundary conditions and inputs from the cell model.

A rigorous-type flood routing model was developed by Weiss to simulate unsteady flow in multiple channels that spill onto adjacent floodplains. Flows within the individual channel branches of the floodplain were handled with the equations of continuity and momentum, the links between branches and flows into or out of off-channel storage were represented by weir-flow, orifice-flow and or energy balance relationships. Stage and average velocity graphs versus time were output at all cross-sections.

2.4.2 One-dimensional model of the Porter Ranch wetland, Michigan, USA (Hammer & Kadlec, 1986)

Hammer and Kadlec (1986) developed a hydrological model of the Porter Ranch wetland in Michigan, USA in one dimension. A one-dimensional model was chosen, as it is simpler to implement than a two-dimensional model. Water flow in a wetland is essentially one-dimensional anyway; if the wetland simulation axis is chosen to correspond to the direction of maximum ground surface gradient, great simplification is possible (Hammer and Kadlec, 1986). Hammer and Kadlec (1986) were also worried about the ability to validate a two-dimensional model due to a lack of data. This wetland had a similar status to the Nylsvlei floodplain in that it is also perched - it seemed that the wetland was not in communication with the aquifers underneath it, being sealed off by a clay layer.

The model relied on a mass-balance equation and rate laws describing velocity as a function of water depth, hydraulic radius, Manning's roughness and a change in water surface elevation with a change in distance along the axis of the wetland. A spatial grid was constructed with each grid point corresponding to a point along the axis of maximum ground slope, downstream. At each grid point (since this was a one-dimensional model) data on wetland width, ground elevation, initial water depths and values of soil conductivity and porosity were specified. Water additions or withdrawals within the wetland were specified as flow rates and assigned to the nearest grid point. Boundary conditions were specified using one of five relationships: a shore boundary, a weir-controlled boundary, controlled inflow/outflow, controlled elevation at boundary and pool-and-weir boundary. The water velocity, depth and elevation as well as the wetland water budget were computed.

2.4.3 A water balance model of the Hadejia-Nguru wetlands, Nigeria (Thompson & Hollis, 1995)

The Hadejia - Nguru Wetlands are located in northern Nigeria and were modelled by Thompson and Hollis (1995) using a water balance model. These wetlands, like the Nylsvlei floodplain, were threatened by dam developments in the catchment areas that had affected the flow of water into the wetland. A mass-balance equation was used which took into account flow into the wetland, rainfall and runoff from the uplands, flow out of the wetland, losses due to evapotranspiration and evaporation, recharge of soil moisture with the advancing flood, infiltration into the groundwater table and water pumped out of the wetland for irrigation. The mass-balance found the volume of water in the wetland on a monthly time-step that was converted to an inundated area using an area-volume relationship. The model also determined ground water storage within the wetlands on a monthly time-step. The model was calibrated using observed flood extents and was operated from 1964 to 1987 to predict the area inundated on a monthly time-step with different dam and dam-release scenarios in the catchments. A conclusion was that it would be better not to dam the rivers upstream as the economic value of the wetland outweighed that of irrigated lands - the lost productivity of the wetland due to smaller inundated areas outweighed the increased productivity of the newly irrigated land. It was also suggested to implement an operating model for the dams upstream to release artificial floods and to enable distribution of water between users in the catchments and the wetlands downstream, to assure flooding of certain areas and recharge the groundwater.

2.4.4 WETFLOW (Feng & Molz, 1997)

WETFLOW (Feng and Molz, 1997) was used to model the steady state hydraulics of the small (roughly 330 x 320 metres in area) Taladega wetland in Alabama, USA. WETFLOW makes use of a two-dimensional diffusion equation based on the continuity equation and the momentum equation. The convective and local acceleration terms are ignored due to the low gradient nature of the wetland, greatly simplifying the equations without great loss in accuracy (Feng and Molz, 1997) and only those terms describing the effects of gravity and friction remain. Ignoring the acceleration terms means that the water surface slope and the friction slope become the same, acceptable for a low gradient environment like a wetland (Feng & Molz, 1997). The two-dimensional diffusion equation is solved using a finite-difference approximation method. The solution to these equations is found within a rectangular domain chosen by the user. The boundary conditions that are input into the model all lie on the edge of the rectangular domain. The boundaries defined in the WETFLOW model are: the inlet to the wetland, the outlet from the wetland (these boundaries are fixed by the user although their width may vary with time) and the line of interception of the land surface and the water surface (which is found in the solution). This line of interception of the water surface defines internal boundaries (islands), and an external boundary - the limit to flooding of the area. Known head at the entrance and exit from the wetland at the rectangular boundary is a boundary condition that can be expressed as a function of time, and x and y coordinates. For the rest of the rectangular boundary that would lie in the uplands above the wetland, a condition of no flow or zero head is maintained at all times. The water surface elevation is output as a grid of points with x, y and z coordinates. Within the rectangular domain, the boundary that occurs at the edge of the inundated area is determined in the iteration process and since this boundary is changing position all the time, the iteration process gives a position of this boundary with respect to time. Evapotranspiration, precipitation and infiltration are represented as sink and source terms in the WETFLOW model. The WETFLOW model requires land surface elevation and flow resistance. Both these physical properties must be measured and/or generated in detail if one is to simulate accurately the hydrodynamics of the wetland.

2.4.5 RBFVMD-2D (Zhao *et al*, 1994)

A model called RBFVM-2D developed by Zhao *et al* (1994) was used to model a section of the Kissimmee River in Florida, USA. RBFVM-2D is a two-dimensional unsteady flow model, based on the finite volume method with a combination of unstructured triangular and quadrilateral grids in a river basin system. Wetting and drying of areas in a floodplain and subcritical and supercritical flows can be handled by the program as it calculates the mass and momentum flux across each side of an element as a Riemann problem, which is solved using an Osher scheme. It can also include inflows from tributaries, and the presence of weirs, culverts and bridges on the floodplain. RBFVM-2D gave results that agreed well with field data on the Kissimmee River and data obtained from a physical model of the system.

2.4.6 Modelling the River Culm, UK, using RMA-2 (Bates *et al*, 1992; Anderson & Bates, 1994)

A two-dimensional finite-element model for depth-averaged free surface flows, RMA-2 (http://chl.wes.army.mil/software/tabs/rma2.htp) (originally developed by King and Norton (1978)), was used to model an 11km (later extended to 14km) reach of the River Culm in the United Kingdom. RMA-2 solves the depth-integrated Reynolds Equation for two-dimensional free surface flows in the horizontal plane using the finite-element technique and can be applied to steady or unsteady flows. The Bousinesq approximation is used to represent turbulence effects through an equivalent eddy viscosity coefficient. The floodplain was divided into a large number of elements, the choice of which had to be done carefully as large volumes of water passing through small elements could make the model unstable. The mean nodal spacing in the mesh was approximately 30 to 40 metres. Stability also depended on the slope of the floodplain and channel angular deviation from the downstream direction in a single element as extremes of these could also cause instability in the model. The model had to be refined by adjusting the size and position of the elements until a stable solution could be found. Element size also determined the resolution of the model and the computing time required - a trade-off was required here as smaller elements improve resolution but increase computing time. Too great a topographical representation showing microscale features also caused instability. A friction value and elemental volume coefficient (which determines possible wetting and drying processes occurring over an element) was needed for each finite-element. Manning's roughness was estimated using the photographic definition of roughness type and assigned individually to each element. A discharge hydrograph at the upstream boundary and a stage-discharge relationship at the downstream boundary of the mesh were required for boundary conditions. Measurements of depths and velocities at intermediate points and an observed discharge hydrograph at the downstream boundary were used to validate the model’s internal operation. The inundation areas and depths on the study reach were broadly in line with field observations.

RMA-2 is available commercially as part of a package called SMS, available from Boss International (www.bossintl.com) (see Chapter 6). Birkhead *et al* (2004) attempted to model the Nylsvlei floodplain using SMS but stability problems were experienced with the wetting and drying of cells and the method was abandoned.

2.4.7 Modelling the River Culm, UK, using a two-dimensional finite-difference model (Nicholas & Walling, 1998)

Nicholas and Walling (1998) designed a model that could predict floodwater extents, flow depths, velocities and patterns of suspended sediment dispersion and deposition using a simplified hydraulic scheme to enable a detailed and accurate representation of the complicated floodplain topography within the study reach – important for prediction of sediment transport and deposition. This was a reaction to the problems experienced by Bates *et al* (1992) with the RMA-2 model described previously, who found it might not always be possible to solve the Navier-Stokes equations in environments that are characterised by complex topography. The degree of difficulty involved in obtaining a stable solution to a given set of equations is dependent on the complexity of both the process equations and the topographic boundary conditions employed (Nicholas and Walling, 1998). Elements that were too small affected the stability of the solution in the finite-element modelling technique employed by Bates *et al* (1992). A lot of smoothing of the landscape (represented by the finite-element mesh) had to be implemented due to the minimum size of the elements required to maintain stability, affecting the resolution of the output.

Nicholas and Walling (1998) employed a two-dimensional finite-difference square grid with a nodal spacing of 5m, based on a set of continuity-of-mass and continuity-of-momentum equations (equivalent to the diffusion wave form of the Saint-Venant momentum equation). A 600m reach of the River Culm in the United Kingdom was modelled. Although a finite-element approach would offer greater control over the mesh geometry, the fine nodal spacing of the finite-difference grid utilized in the model provided a detailed and accurate representation of the complex floodplain surface within the reach (Nicholas and Walling, 1998). Temporal derivatives and convective acceleration terms were ignored so that friction slopes were approximated by water surface slopes. Various other simplifications were employed in the treatment of the inflow and outflow hydrographs and convective acceleration effects and momentum transfer owing to turbulence were neglected. Nicholas and Walling (1998) argued that these simplifications allowed the finite-difference grid to better describe the complex features of the floodplain at a higher resolution than would otherwise have been possible.

Nicholas and Walling (1998) divided the floodplain into two Manning's roughness classes for the channel and the floodplain. They suggested that the realistic representation of microtopographical elements must form the basis of any modelling attempt of a floodplain-type environment as these features have a large effect on the inundation sequences and velocity vectors on the floodplain.

Flow surfaces termed a 'water surface function' were derived for a set of upstream water levels by solving the continuity-of-mass and momentum equations, to describe the water surface elevation at each node in terms of the upstream and downstream water levels. A relationship had previously been found between the upstream and downstream water surface elevations. These differential equations were approximated using finite-difference methods and solved to yield the water depth at each node. A ponding algorithm was then used to adjust the flow depth in certain areas where either backwater ponding had occurred or where recession ponding (where water is retained in depressions after the water has receded) had occurred.

The model was calibrated using qualitative data obtained from ground photographs detailing inundation sequences. The model predictions compared well with field observations of the inundation mechanisms.

2.4.8 Modelling the Waihao River floodplain, New Zealand, using Hydro2de, a two-dimensional finite volume approach and MIKE11, a one-dimensional model (Beffa & Connell, 2001; Connell *et al*, 2001)

Hydro2de (http://www.fluvial.ch) is a commercial program using a two-dimensional finite volume method to model water flow over floodplains described by a uniform grid. Hydro2de is based on the depth averaged shallow water equations in conservation form, in which depth and specific flow are related to spatial coordinates (x,y) using conservation of mass and momentum (Connell *et al*, 2001). The program requires at least two grids of information: the bed topography and the resistance coefficients. The flow passes from one cell to the next cell based on the difference in water levels, flow velocity and direction of flow - the fluxes in water flow into and out of cells are balanced using explicit time integration with a finite volume method. The calculation starts with an initially dry floodplain with water being inputted at the boundaries so that the correct water flow directions are found from the terrain shape and the inflow point and discharge. The advantage of this modelling method is that it can handle sub-critical, critical and super-critical flows. This means that the assumption that the water surface slope and friction slope are parallel is not made here. Hydro2de can also handle the wetting and drying of cells. A hydrograph is required at the upstream boundary and a flow depth, water level, or the energy slope is required at the downstream boundary. Output from Hydro2de is in graphical form showing spatial distributions of water velocity, x and y water velocity components, water depth, water level, Froude Number and energy slope. The input spatial distributions of ground level in the DTM and surface roughness coefficients can also be viewed.

MIKE11 (www.dhi.dk) is a commercial finite-difference model based on the shallow water equations, and models flow in one-dimension.

Hydro2de and MIKE11 were applied to the Waihao River floodplain on the South Island of New Zealand. A digital terrain model (DTM) of the area was derived from an aerial photogrammetry survey, with over 90 000 points and more than 6 000 breaklines (definitive ridges and valleys) with a claimed accuracy of ±0.3m in all three dimensions. A 20 x 20 metre grid with a rectangular calculation domain was used. Additional floodplain detail such as embankments were added manually to ensure they were represented. A geographic information system (GIS) was used to manipulate terrain information for modelling and presentation. The authors used aerial photos to estimate Manning's roughness for the grid areas. The inflow hydrograph was routed from a gauging station 10km upstream of the study area using MIKE11. Overtopping and breach analyses of various levees on the floodplain were also carried out. One run of Hydro2de for a flood event would take about 24hrs, with the number of cells being of the order of 50 000 for the floodplain. Hydro2de was applied to uncalibrated and calibrated runs of the input hydrographs.

The floodplain was broken up into a network of channels and cross-channels and the channels were determined by the modellers when MIKE11 was applied to model the floodplain. MIKE11 was only used for uncalibrated runs of the hydrograph through the floodplain. Mean flood level differences between modelled and observed given by the uncalibrated MIKE11 model were approximately 50% greater in magnitude than those differences given by the uncalibrated Hydro2de model.

A series of aerial photographs of flooding, video photographic records, real-time flood observations and detailed interviews of floodplain residents gave flood data for validating the model. The degree of error for the calibrated Hydro2de model was about the same for the predicted flood levels and extents as the known DTM errors.

2.4.9 The Okavango Delta, Botswana (Dincer *et al*, 1987)

Dincer *et al* (1987) developed a hydrological model of the Okavango Delta, the aim of which was to predict over time: water depths, inundation areas (in terms of position and area) and flow out of the delta through the rivers that drain it. This would enable prediction of the response of the system to natural and man-made changes in the catchment of the Okavango River and within the delta itself. The delta was divided into a small number of large cells (about ten cells), defined along the various distributary systems in the delta and divided downstream according to the input period (precipitation, inflow and evapotranspiration). For a monthly period, the model required four or five cells along the flow line to simulate the travel of the flow wave through the delta (Dincer *et al*, 1987). Each cell in the study represented a reservoir with sloping surface, which could be divided into a surface and subsurface reservoir. Inundated areas of each cell were calculated from cell volumes using an area-volume relationship. A water balance for each cell was calculated taking into account inflow to the cell from upstream or neighbouring cells, surface water and groundwater outflows, precipitation additions and evapotranspiration losses. Outflows from each cell were estimated by assuming a linear relation between the volume of the surface reservoir and the discharge corrected by the Muskingum flood routing parameter. Evapotranspiration (estimated using the Penman method (Penman, 1948)) and precipitation were calculated using the inundated areas of the cells. Recharge to groundwater was estimated from the water balance of an experimental area in the delta (as it was the only unknown in the water balance equation), and found to be approximately proportional to the area inundated. A flow distribution parameter was used to divide outflows from cells to the cells downstream, when required. The flow distribution parameter was estimated from satellite photographs and an assumption that flow at a cross-section is proportional to the area downstream of that cross-section. Calibration was achieved by comparing modelled with observed outflows on the Thamalakane River, water levels at certain stage plates in the delta and inundated areas and total evaporative areas (including areas not inundated but wet). Groundwater was found not to be a significant contributor to surface flooding in most years.

A statistical approach was also used to estimate the outflow from the delta using the annual outflow as a dependent variable and inflow, precipitation and the previous year's outflow as independent variables. The last variable was used as a measure of the antecedent conditions in the swamp. This approach gave reasonable results.

2.4.10 Rule-based modelling methods

The rule-based modelling technique is completely different to any of the numerical techniques reviewed in this chapter. Nicolson (1999) describes this technique in detail and applied it to model sediment transport in the Sabie River. Rule-based methods use rules that are constructed from our knowledge of a system. These are generally if-then-else rules, are at a low resolution and thus appropriate to modelling large scales in both space and time. Rule-based methods are ideally suited to disturbance driven systems where changes take place quickly and where numerical modelling would be difficult due to instability. Rule-based systems require less data to be input than numerical models making them easier to apply, they also output far less data making it easier to deal with and interpret all the data. They are more flexible and easier to update than simulation systems based on complicated equations (Starfield *et al,* 1989). Rule-based models are generally quite easy to understand and do not make use of complicated mathematics, which tends to alienate people from other disciplines such as biologists who would otherwise be able to contribute to the debate about the model (Nicolson, 1999). Qualitative rule-based models are becoming more popular in areas where the intricate and complex nature of a process may defy manageable mathematical description (Jewitt *et al*, 1998).

Rule-based or qualitative models allow us to build up an understanding of how systems respond (Nicolson, 1999). Nicolson (1999) stated that our understanding of natural systems is often piecemeal and so instead of starting with the outcome of the task (as in most numerical methods), and trying to develop the expert's rules for reaching that outcome, we begin with the rules and see how different combinations and sequences can lead to various outcomes. He also stated that these models can be used to test hypotheses, if the real world is assumed to behave in some specified way (as spelt out in the model), then the model reveals the logical consequences of those assumptions. Often the individual rules are easy to understand in isolation, but their interactions can lead to non-intuitive results (Nicolson, 1999). According to Nicolson, the model not only allows us to trace the logical consequences of the rules, but where there may be disagreement over the rules (i.e. the assumptions) it allows us to build several different versions of the model to see the effect of the alternative assumptions.

However, some systems may require to be modelled at a greater resolution and in these cases, mathematical models become relevant.

2.5 HEC-RAS

A one-dimensional model using the United States Army Corps of Engineers program HEC-RAS (Hydrologic Engineering Center's River Analysis System) version 3.1 was chosen by Birkhead (Birkhead *et al*, 2004) for the hydraulic modelling in this project. HEC-RAS, a freeware program available on the Internet for download (www.hec.usace.army.mil), was one of a suite of three programs used for the project (Chapter 6).

HEC-RAS version 3.1 is able to perform steady flow water surface profile computations and unsteady flow simulation (Brunner, 2002). The workings and capabilities of HEC-RAS are very briefly outlined here, for a detailed explanation, see the HEC-RAS Hydraulic Reference Manual (Brunner, 2002).

HEC-RAS has a steady flow module that can calculate water surface profiles for steady, gradually-varied flow in natural and constructed channels. The energy equation is solved using an iterative procedure called the standard step method, to calculate water surface profiles from one cross-section to the next (Brunner, 2002). The energy equation is only applicable to gradually-varied flow situations. Whenever the water surface passes through critical depth and the flow becomes rapidly varied, the momentum equation or an empirical equation is used. HEC-RAS uses the momentum equation whenever a hydraulic jump occurs, in low flow hydraulics at bridges and at stream junctions. The steady flow module of HEC-RAS relies on various assumptions: that flow is steady, flow is gradually-varied except in the cases mentioned earlier, flow is one-dimensional and that the river channel has a small slope (say less than 1:10) (Brunner, 2002).

HEC-RAS can simulate unsteady flow through a network of channels. The unsteady flow equation solver was developed from Dr. Robert L. Barkau's UNET (Unsteady Network) model (Barkau, 1992). The unsteady flow component of HEC-RAS was developed primarily for subcritical flow regime calculations (Brunner, 2002). As the Nylsvlei floodplain has a smooth gradient of approximately 1:1000 to 2:1000, flow is generally subcritical making this program suitable. Structures such as bridges, culverts, weirs, spillways, and storage areas can be modelled with HEC-RAS unsteady. HEC-RAS unsteady is based on the continuity equation (principle of conservation of mass) and the momentum equation (principle of conservation of momentum). Both these equations are expressed as partial differential equations. HEC-RAS unsteady uses an implicit finite-difference scheme to solve the momentum and continuity equations. The scheme is relatively stable; convergence is not a problem where the wavelengths of floods compared to spatial distance are long (Brunner, 2002). Brunner (2002) comments that in practice this is not always the case however: dramatic changes in channel cross-sectional properties, abrupt changes in channel slope, characteristics of the flood wave itself, complex structures such as weirs, levees, culverts, bridges and spillways can lead to stability problems in a model. Brunner (2002) therefore recommends that any model application should be accompanied by a sensitivity study, where the accuracy and stability of the solution are tested with various time and distance intervals. Stability problems were experienced in the development of the Nylsvlei hydraulic model and are detailed in Chapter 6.

A force term to account for the additional forces exerted on flow from structures such as bridges and navigation dams and a momentum term to account for the momentum of lateral inflows such as tributaries are inserted in the finite-difference form of the momentum equation. The momentum and continuity equations are non-linear, with the result that they can be slow to solve and convergence problems can result when using a non-linear solution. These equations are therefore linearised in HEC-RAS. Flow distribution between channel and floodplain is given by the ratio of conveyance in HEC-RAS, based on the assumption that the friction slope is the same for the channel and the floodplain.

For subcritical flow, only the downstream boundary conditions are required; for supercritical flow only the upstream boundary conditions are required but if a mixed flow regime analysis is going to be performed then both upstream and downstream boundary conditions are required. The upstream boundary condition of a study area is applied as a discharge hydrograph. A stage hydrograph, discharge hydrograph, single-valued rating curve or normal depth from Manning's equation can be specified as a downstream boundary condition, depending on the nature of the data available and the area of the boundary condition. Interior boundary equations are required to specify connections between reaches. The set of linear equations consisting of the boundary equations and momentum and continuity equations in their respective forms are solved as a matrix using a storage algorithm called the skyline solver to speed up solving of the matrix.

HEC-RAS was found to be reasonably easy to use and outputs a large amount of data for each cross-section, some of which proved very useful. The fact that HEC-RAS is free, also made sense financially. Stability problems were experienced requiring a large effort to calibrate the model to a stable state.

2.6 Summary

There are many different methods and commercial models available to model floodplains including numerical models such as one-dimensional, two-dimensional, three-dimensional and mass-balance methods and rule-based methods.

DWAF (Nel *et al*, 1989) and later SRK (Schulz, 1992), modelled the Nylsvlei floodplain using hydrological methods, but unfortunately these studies were unsatisfactory due to a lack of data available, the monthly time steps used and the fact that hydrological models cannot convert flows into inundation depths and areas. Morgan (1996) used a mass-balance approach with cells and a DTM to model the Nylsvlei floodplain. His model could convert flows into inundation depths and areas, but was best suited to steady-state modelling and was hampered by a lack of flow, stage and topographical data. An advantage of his modelling method was that resistance to flow, which is difficult to measure, did not have to be measured.

Other modelling techniques that were considered included cell-type methods, used by Weiss (1976) to model various floodplains in South Africa and Dincer *et al* (1987) to model the Okavango Delta. These methods can model unsteady flow and produce inundation areas and depths, are relatively simple and make smaller demands on computing power than various other numerical modelling methods.

The freeware program HEC-RAS, a one-dimensional program based on the continuity and momentum equations, was finally used for this project. HEC-RAS was chosen for this project as it is widely used in South Africa for hydraulic modelling, is free, no development of the hydraulic modelling method was required, it can model steady and unsteady flows, it can output all the relevant data required to determine inundation depths, durations, frequencies and extents and is relatively simple to use. However, a drawback to using numerical modelling methods such as HEC-RAS is numerical instability when unsteady flows are modelled, which can take a long time to solve.

The next chapter is about the collection of data that was required to create a model of the Nylsvlei floodplain.