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77

Simulating the Hydrology of Small Coastal Ecosystems in Conditions of Limited Data

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Contents

Summary

Water resources and irrigation developments have direct impacts on aquatic ecosystems. These impacts need to be quantified and predicted to understand the environmental costs of water projects. The assessment of such impacts in most developing countries is often hampered by the lack of reliable observations on physiographic variables used as inputs to simulation models. Complex and information-consuming models may not always be appropriate in such conditions, whereas simpler, pragmatic simulation approaches may perform well whilst their data requirements can be more easily satisfied. This report illustrates the use of such methods to simulate the hydrology of several small coastal water bodies. Such water bodies are normally not taken into account when development projects are being planned and implemented. However, these water bodies often represent a source of livelihoods for local communities, may have a high recreational value and/or serve as a habitat for rare species. Three examples are illustrated in this report. The first deals with the assessment of the impacts of a future irrigation scheme on a coastal lagoon in Southern Sri Lanka. The catchment upstream of the lagoon and the lagoon itself are simulated by water balance models, which operate with a weekly time step. The details of the upstream tank and paddy systems are ignored and large parts of the catchment are represented by dummy reservoirs to be commensurate with the level of input information available. Several realistic scenarios describing irrigation development and lagoon management are then defined and simulated. They include different levels of inflows from the proposed scheme into the lagoon, envisaged upstream catchment changes associated with the scheme and some aspects of lagoon water level management. The second example deals with coastal lagoons in Sri Lanka which are already receiving additional drainage flows from irrigation schemes. The goal in this case is to establish and simulate the reference hydrological condition, which existed prior to irrigation development. This reference condition is necessary to assess the present-day impacts on lagoon hydrology and to design a set of management measures to alleviate adverse impacts. The example illustrates how the combination of local knowledge and simple spatial interpolation methods may be used to simulate a daily time series of reference water levels in the lagoon. The third example focuses on temporarily closed/open ungauged estuarine ecosystems along the east coast of South Africa. The duration of the closed and open phases of an estuarine mouth are determined by the interaction of river inflow and the sea in the mouth region whilst the dynamics of the mouth affects the structure and functioning of the estuarine biotic community. The report describes methods for simulating the daily upstream inflow time series to such estuaries and for linking simulated hydrological data to the estuarine mouth state. It is concluded that parsimonious methods can serve as a sound basis for the quantification of impacts and generation of required hydrological data of different types. Such methods may also identify immediate research priorities, specify the requirements for monitoring networks and serve as the basis for sound management decisions.

Simulating the Hydrology of Small Coastal Ecosystems in Conditions of Limited Data

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Introduction

Informed management decisions on water resources allocation and irrigation development, and the assessment of the impacts of these developments can only be made if the processes and dynamics of aquatic ecosystems are properly understood and quantified. Such quantification is hampered in most developing countries due to the acute lack of long-term, accurate and reliable observations of hydrological processes and variables such as rainfall, evaporation, river flow and water levels. Common problems associated with the available hydrological data include gaps in the time series, short observation periods and inaccurate observations.

One conventional way of generating representative hydrological time series (e.g., for ungauged sites) is through the use of deterministic rainfall-runoff models. The application of such complex methods with their large data requirements is not always appropriate in the data-poor regions (i.e., in most of the developing world). Instead, the use of pragmatic techniques of data generation may be more justified and/or equally successful. In order to be competitive with more complex simulation methods, such “pragmatic” approaches need to provide results which are suitably accurate, be simple and parsimonious, quick and easy to set up and run, and capable of generating hydrological time series for ungauged catchments or water bodies for different scenarios of catchment and/or water resources development.

This report highlights three case studies where hydrological data generated using these pragmatic techniques were required. All three studies deal with small coastal ecosystems. The first study is an evaluation of the ecological impact of an irrigation scheme extension at a coastal lagoon (Karagan Lewaya) in southern Sri Lanka. The lagoon is likely to receive high quantities of drainage flows from the future scheme. This could change the natural water balance, deteriorate its water quality and thereby the suitability of the lagoon as a habitat for migratory birds. It could also lead to flooding of adjacent settlements. The study attempts to quantify the impacts on the lagoon’s water levels resulting from future development scenarios.

The second study focuses on three coastal lagoons (Bundala, Embilikala and Malala) in southern Sri Lanka. Some of these lagoons are already receiving drainage flows from upstream irrigation schemes. There is concern that continuous input of agricultural drainage into these lagoons will change their ecology and render them unsuitable for the existing aquatic species. Quantification of the impacts of drainage flows may only be possible if the condition of the lagoons prior to scheme implementation is known. The focus of the study is therefore the simulation of these reference hydrological conditions.

The third study deals with the hydrology and dynamics of the mouths of small estuaries. It uses data from the east coast of South Africa as an example. The state of an estuary mouth is generally one of the most important factors governing the structure and functioning of the resident biotic community. It influences invertebrates and fish, which have a marine phase in their life cycle, many plant species, which are dependent on particular inundation regimes of the estuary, and certain water bird species, which favor tidal exposure of estuarine sediments. No systematic observations are currently being conducted on the hydrology or mouth openings and closures of South African estuaries. At the same time, these small coastal systems often have high conservation and/or recreational value. The duration of the closed and open phases of an estuary mouth depends on the interaction of river runoff, evaporation, seepage, floods and wave over-wash events in the mouth region. As the inflow to an estuary reduces due to upstream catchment developments (such as irrigation withdrawals), the mouth may close more frequently. This could lead to a significant change in the status of an estuarine ecosystem. The study explores the ways of quantifying these processes, which are important for making informed decisions on catchment water allocations.

All three studies were conducted with very limited hydrological data and are intended to provide quantitative methods, which can work in such conditions. All three studies also attempted to bring more attention to the issue of conservation and management of sensitive small coastal water bodies on which local communities often depend for their livelihoods.

Evaluating Irrigation Impacts on the Hydrology of Karagan Lagoon

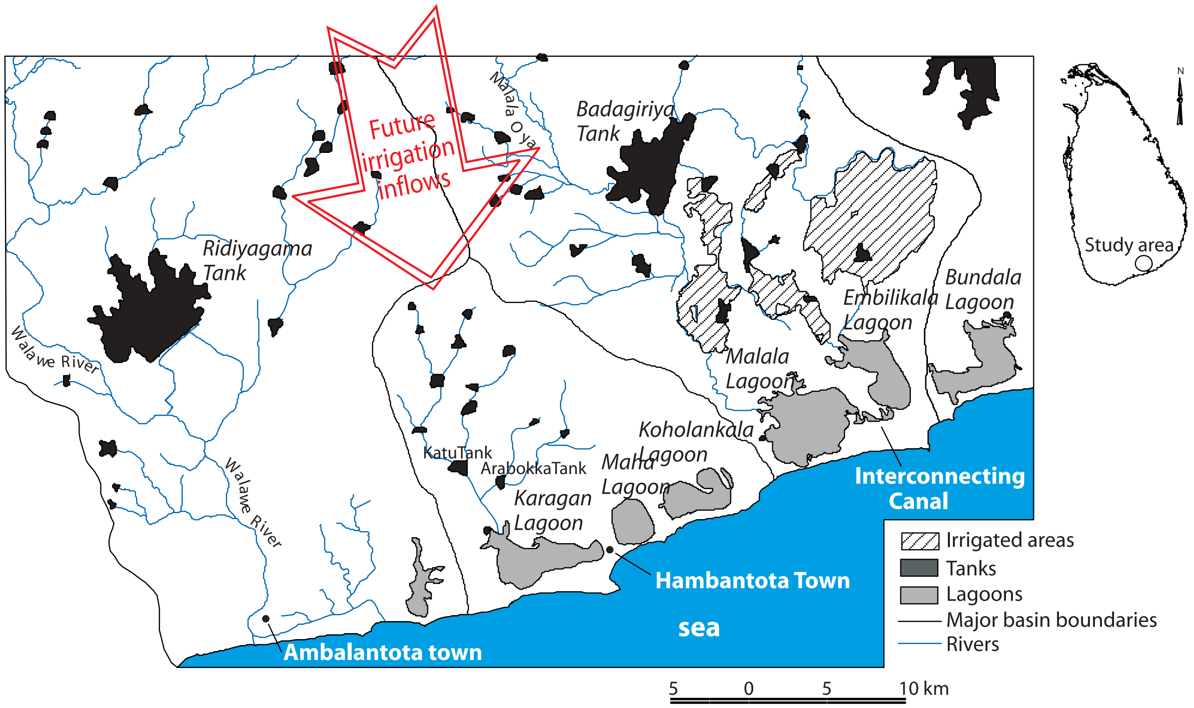
The Study Area and Problem

Karagan Lagoon is one of several coastal wetlands located in southern Sri Lanka (figure 1). These lagoons are transitional wetlands between fresh and salt water bodies and provide habitat for many animals and plants that are characteristic of the region. Karagan, for example, supports rare, vulnerable or endangered species or subspecies of plants and animals, and hosts a variety of waterfowl (WCP 1994). However, unlike many of its neighboring coastal wetlands, the lagoon has been permanently separated from the sea as a result of development activities in the region.

The maximum water surface area and depth of the lagoon are 3.2 km^2 and 1.5 m, respectively. Both are subject to high seasonal and annual variations. The lagoon is separated from the sea by the main coastal road and sand dunes in its western part and by Hambantota town in the east. The upstream catchment area is 54 km^2. The topography of the area is undulating in the north, with a gentle seaward slope to the flat southern parts of the catchment. Elevations range from 60 m in the northeast to 1.5 m below sea level at the bottom of the Karagan Lagoon.

The upstream catchment area includes over 10 small old tanks (farm dams) with a capacity less than 100,000 m^3. Surface inflow to the lagoon comes from two sources. First, water released from the two most downstream tanks of the upstream tank cascade systems (TCSs) is used to irrigate the downstream paddy fields and after that the return flows run through one major drainage channel into the lagoon. These TCSs are known by the names of their terminal (most downstream) tanks—Katu and Arabokka (figure 1). Runoff from the sub-catchments adjacent to the lagoon partially drains into this channel as well and partially into the lagoon directly.

FIGURE 1.
The study area showing the location of coastal lagoons and irrigation schemes in southern Sri Lanka.



The inflows from the sea into the lagoon at present are limited. Since 1970, the lagoon has had no connection to the sea, except for temporarily channels built through the sandbar for the drainage of excess water during floods. An emergency outlet channel through Hambantota constructed in 1998 has never been used.

Agricultural activities in the upstream area of the Karagan Lagoon are confined to the major (*Maha*) cultivation season due to the scarcity of water. To expand agricultural activities in this area, it was proposed to further develop the existing Udawalawe irrigation scheme (figure 1). The development will include the extension of the left bank main canal some 19 km further south. This would ensure the irrigation of an additional 5,100 ha and facilitate the settlement of almost 4,000 families.

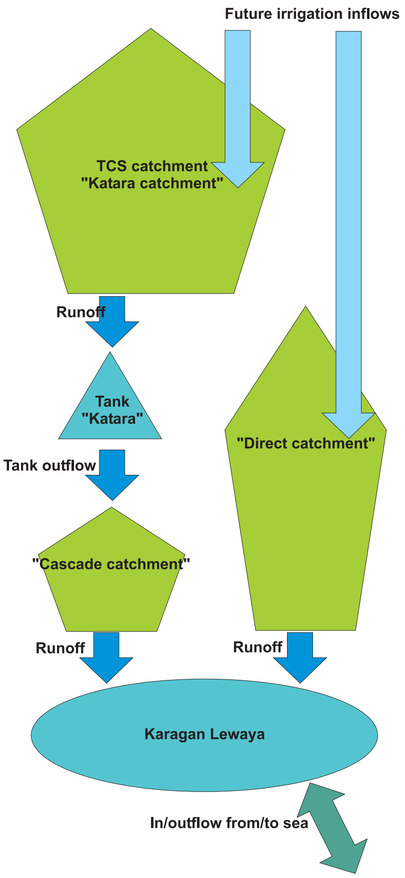
At present there is no connection between the Karagan catchment and Karagan Lagoon to the Walawe river basin and Udawalawe irrigation scheme. After the implementation of the irrigation extension project, a substantial amount of drainage water from irrigated areas will flow into the Karagan Lagoon. The hydrology of both the upstream catchment area and the lagoon itself will change. Possible adverse effects on the Karagan Lagoon due to the implementation of the irrigation project are changes in water and salinity levels associated with agricultural return flows. Consequently, the flora and fauna of the lagoon could be severely affected. An assessment of hydrological changes (e.g., in water levels) is of paramount importance for understanding and quantifying other associated environmental impacts.

A Summary of the Simulation Approach

The catchment upstream of the Karagan Lagoon is effectively a combination of different units, which include sub-catchments, tanks and paddy fields (or other crop fields). Tanks are located at the downstream ends of sub-catchments. Paddy fields are located downstream of tanks and upstream of the next catchment. There are a number of units of each type, which makes catchment representation very complex. An attempt was initially made to represent the water flow between different units in full. The model developed included a detailed description of all the individual components of the Karagan catchment (all the major tanks, sub-catchments and paddy fields). Individual physical and artificial processes such as rainfall, evaporation, runoff, water releases for irrigation and spills were accounted for. This was largely a conceptual exercise, carried out in order to understand the input information requirements, which were necessary for the comprehensive simulation of this system. Stanzel et al (2002) have shown, amongst others, that practical application of such a model would not be feasible in the near future due to the limitations imposed by lack of input data.

A simplified catchment model, illustrated schematically in figure 2, was then developed in an attempt to reduce the input information requirements. The entire catchment of the two tank cascade systems with a total area of 36 km^2 is simulated as one dummy catchment ("Katara catchment", which combines the names of Katu

FIGURE 2.
A schematic representation of the components of the Karagan catchment in the hydrological model.



and Arabokka TCSs). Paddy fields and smaller tanks upstream are treated as parts of the catchment area. Runoff from the “Katara” catchment is routed into one lumped reservoir, called “Katara tank”. This dummy reservoir pools the capacities of the two terminal tanks. Outflow from the reservoir is routed into a smaller “cascade catchment” which includes the cultivated and non-cultivated areas eventually draining into the Karagan Lagoon. The areas draining into the lagoon through minor streams and ditches, both east and west of the “cascade catchment” area, are combined into one catchment, referred to as “direct catchment”. Runoff from both these catchments is an input to the Karagan Lagoon water balance model.

The details of the model algorithms are discussed in Stanzel et al. (2002), but a summary of the model is given below. The water balance equation for the catchments, shown in Figure 2 is:

$$dV = P + S + X + IR + N - ET - R - D \qquad (1)$$

Where dV is the change in catchment storage, V, over one time step t. P is precipitation, S is seepage from an upstream tank, X is spill from an upstream tank, IR is water released (issued) from an upstream tank for irrigation, N is additional (new) inflow from the future irrigation scheme (applicable to “Katara” catchment and “direct” catchment), ET is evapotranspiration, R is runoff and D is deep percolation. The tank water balance equation is similar to that for catchments but includes seepage, spill and water issues as outflow components (negative sign), and runoff inflow from an upstream catchment (positive sign). All components are in cubic meters.

Precipitation volumes are calculated by multiplying the gauged rainfall by the catchment area. Seepage from the tank is calculated with a formula based on Darcy’s law, as a product of tank water depth, water surface area and a ratio of hydraulic conductivity to distance of seepage (Stanzel et al. 2002). Evapotranspiration (ET) is calculated using the formula:

$$ET = (ET_o * K_C * A)/1000 \qquad (2)$$

Where ET_o is reference evapotranspiration (mm), A is catchment area (m²) and K_C is a non-dimensional catchment crop factor. Reference evapotranspiration (ET_o) is calculated by the Hargreaves formula, using minimum and maximum temperature and radiation (Allen et al. 1998).

Irrigation releases (IR), runoff (R) and percolation (D) terms are computed using equations of the following generic form:

$$W = f{*}Vr\ V \qquad (3)$$

Where W is either IR, R or D, f are non-dimensional factors (model parameters which differ for different processes), Vr is a relative catchment water storage (a ratio of the current water storage V to the catchment storage capacity Vc).

Calculations of these three processes also include three threshold parameters. Runoff from a catchment is assumed to occur only if the current catchment storage exceeds a threshold minimum storage parameter (Vmin). Calculation of percolation includes a threshold volume parameter (VD). The use of this threshold accounts for the fact that rainfall on dry soil leads to an increase in soil moisture, until the soil is saturated and water starts to percolate to lower layers. This percolating water does not contribute to the inflow into Karagan Lagoon, but is used in the basin by capillary rise, uptake by roots or is pumped by tube-wells. Percolation does therefore not occur until catchment storage exceeds VD.

Irrigation releases (IR) are computed in a similar way to runoff and percolation. They are assumed to be proportional to “Katara” tank water depth and volume. Irrigation is assumed to start as soon as a water level threshold is exceeded. Irrigation will then continue for a maximum of 18 weeks (which is the usual paddy irrigation period in the area) or until the dead storage depth is reached. Land preparation requirements, crop requirements and rainfall are not taken into consideration in this form of simulation, because it is not possible without explicit representation of paddy fields.

The water balance of the lagoon itself is described by the following equation:

$$dV = R + P - E - D - O \qquad (4)$$

Where dV is the water volume change in the lagoon over one time step, R is the total runoff from both upstream catchment areas ("cascade" and "direct"), P is precipitation onto the maximum surface area of the lagoon, E is evaporation from the current lagoon water surface, calculated similar to equation 2. D is deep percolation and O is outflow, which occurs only if the lagoon volume exceeds its capacity and is calculated as the difference between the two. All components are in m^3.

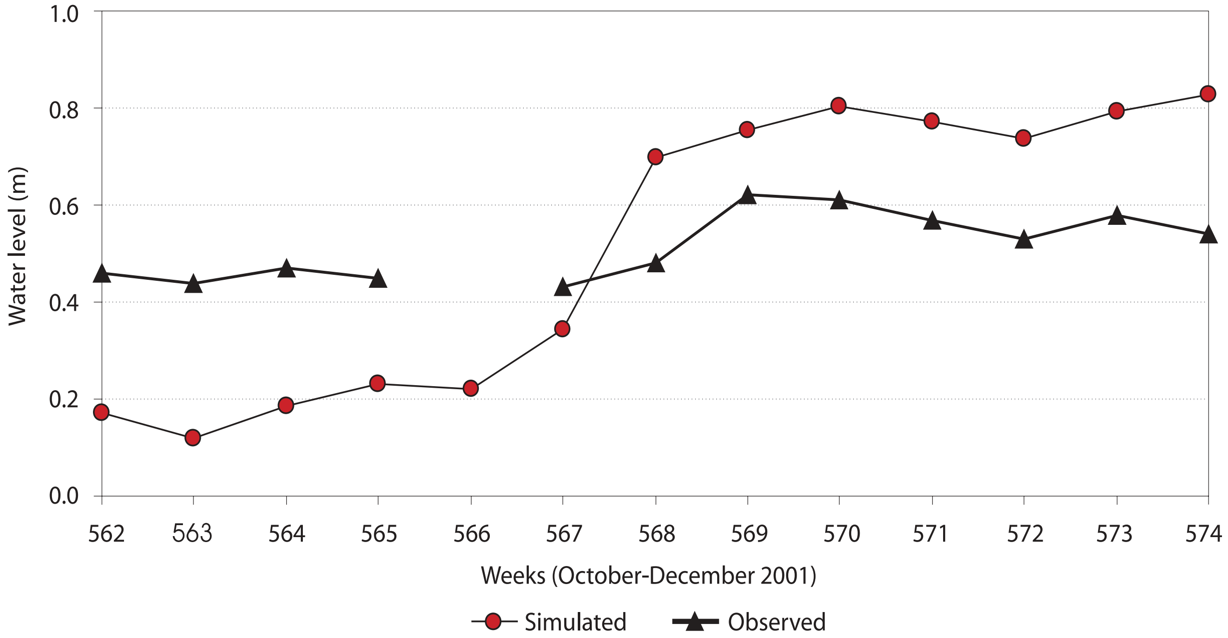
Simulating Present Conditions

The models described above are relatively simple and parsimonious. However, the scarcity of available input data and observed information impose severe constraints on model calibration and validation. Both models (described in equations 1 and 4) were set to operate with a weekly time step. Weekly precipitation data were used as input to the models. Daily rainfall data for eleven years (1991-2001) from the nearest meteorological station (Hambantota) were used to derive weekly rainfall.

Other input information, such as water levels at the two terminal tanks and in the Karagan Lagoon, as well as quantitative data on spillage, cropping and irrigation water releases were collected during the monitoring program which formed part of the study (Stanzel et al. 2002). The monitoring period was however very short (September to December 2001) and was during an unusually dry year. It therefore allowed only some basic data inputs for the model to be collected. Some model parameters (f factors, catchment storage, etc.) were evaluated through a process of "soft calibration" (Stanzel et al. 2002). An attempt was made to achieve in some years the water levels in a combined tank, which were high enough for irrigation water issues, or could lead to the cases of spilling from real tanks (which were reported by local farmers). Some model parameters were assigned values based on literature sources. For example, for calculation of evapotranspiration, values of crop factors and K_C, were based on Allen et al. (1998). The natural vegetation in the study area consists primarily of dry scrub, which can be expected to have a low K_C, and trees, which have a higher K_C. Proportions of the area covered by scrub and trees could only be roughly estimated, and as a first approximation, the Kc value of 1 was therefore used on average. Evaporation from the lagoon water surface was calculated using an increased Kc value of 1.15 to account for high wind speeds in the area (Allen et al. 1998; Stanzel et al. 2002). The simulated lagoon water volumes were converted into water levels and water surface areas, using depth-area and depth-volume relationships. These relationships were established using available contour maps of the lagoon (Stanzel et al. 2002).

Because of the limitations in observed data, commonly used criteria of model performance could not be used and only a visual comparison of observed and simulated water levels was possible. Figure 3 illustrates the observed and simulated water levels in the lagoon during the period of water-level monitoring. While the timing and pattern of the water-level fluctuations in the lagoon are reproduced correctly, the model seems to simulate more variable water levels. However, longer observations on lagoon water levels (covering the entire water-level range) would be able to bring more clarity on the latter issue and, most likely, improve the simulation results. Apart from the inherent uncertainty associated with "soft calibration," part of the differences may be caused by the use of Hambantota rainfall for the entire

FIGURE 3.
Observed and simulated water levels in Karagan Lagoon during the period of the monitoring program.



Karagan catchment, which ignores significant spatial variability of precipitation in the coastal zone (Stanzel et al. 2002).

A form of model validation could be made if the lagoon water levels are translated into water-spread areas and compared with the estimates of water-surface areas from available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images. These images have a resolution of 15 X 15 m. This comparison is illustrated by figure 4, which shows that the pattern of water-surface area fluctuations was generally well reproduced by the model, regardless of the number of assumptions and simplifications of the real processes that have been made.

Figure 5 shows the simulated lagoon water levels during the entire, 11-year long simulation period. The pattern of very low water levels in some summers and higher water levels in wet maha seasons is reproduced in the simulated time series. The gradual fall of water levels from the flood water level of 1998 to zero in autumn 2001 (confirmed through the discussions with local farmers, fishermen and cattle owners) was reproduced well by the model. A complete drying-up of the lagoon in autumn 2001 (actually recorded) is also reflected in the simulated time series. This may be the only such case that actually occurred over the period considered, as no quantitative confirmation of earlier dry cycles is available. The near-dry stages in lagoon regime in the earlier parts of this period may therefore also be correctly simulated.

Scenario Formulation

The main sources of information for developing future scenarios of irrigation were engineering reports of Nippon Koei (1999) and SAPI (2000). The design discharge for the left bank main canal at the head end of the extension area is 9.12 m^3s^{-1}. If the canal is assumed to operate as planned (full flow during the nine month cultivation period and 50 percent of full flow for 5 percent of the time in the three off-season months), the amount of water delivered to the head end would be 216 million m^3 (MCM). If more conservative

FIGURE 4.
Simulated lagoon water-surface areas compared with water-surface areas estimated from available remote sensing images.

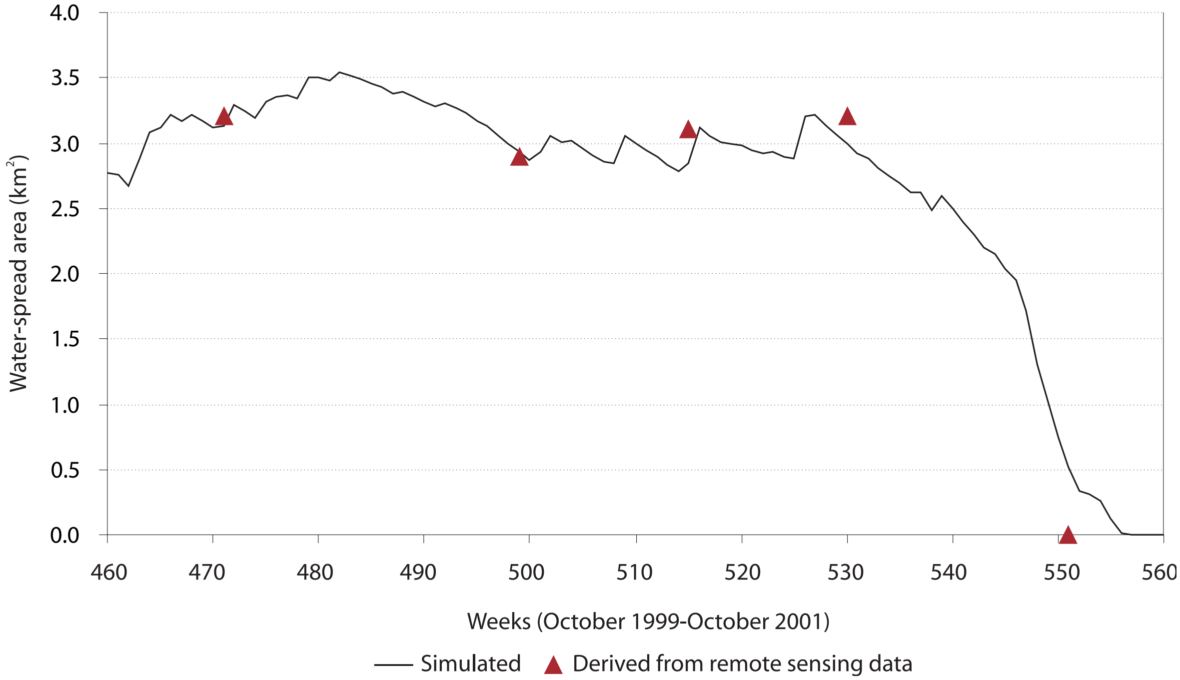
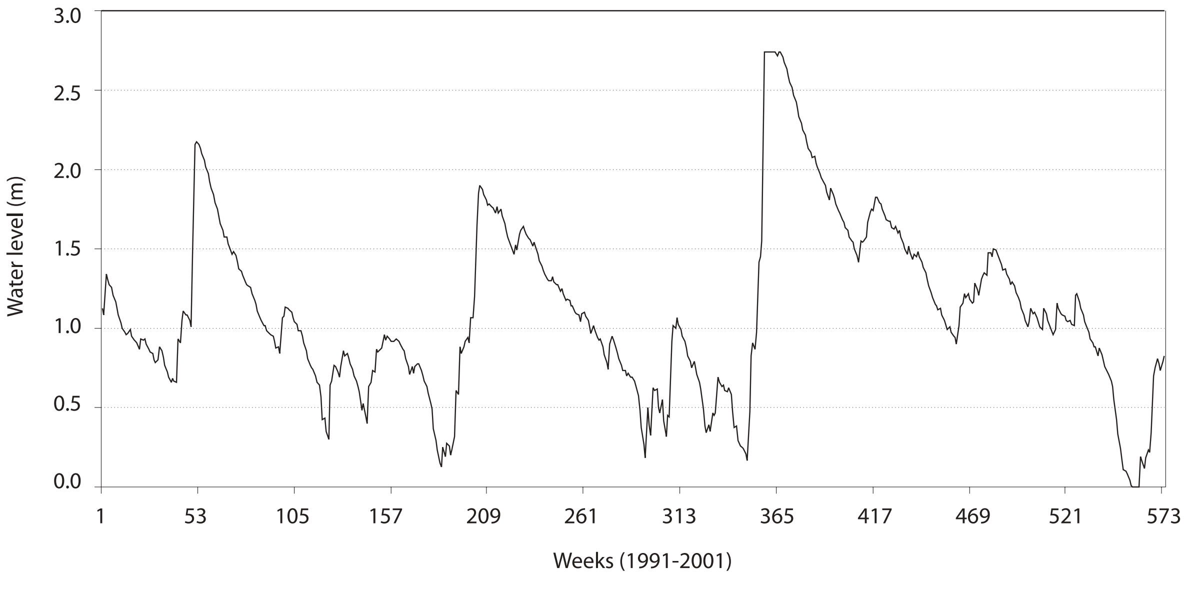


FIGURE 5.
Karagan Lagoon water levels simulated over a 11-year long period.



assumptions on irrigation efficiencies are used, the water demand for the left bank extension area would be 166 MCM (SAPI 2000). Furthermore, the amount of water that could be released to the extension area without causing water shortages in the whole Udawalawe irrigation scheme equals 120 MCM (SAPI 2000). To deliver 166 MCM of water, approximately 75 percent of the design discharge will be sufficient, while for 120 MCM, only about 55 percent of the design discharge is required. Based on these assumptions, three different scenarios of irrigation scheme operation have been considered. They correspond to 100, 75 and 50 percent of the design inflow (scenarios 1, 2 and 3 in table 1).

All three scenarios consider the increase in catchment storage due to the construction of new tanks and the augmentation of the capacity of some existing ones. This increase was set to 20 mm (Stanzel et al. 2002). The increase in paddy cultivation area is expected to lead to higher storage capacity in the basin. Similarly, areas covered with other crops may store more water than in what are currently "natural" areas. This higher storage capacity was taken into account by further increasing the catchment storage parameters by 30 mm. Finally, the crop factor K_C was also increased, to represent the higher evapotranspiration capacity of the newly cultivated areas.

In all three cases, it is anticipated that the regime of water levels in the lagoon will change and that water levels will generally increase due to increased inflows associated with irrigation return flows. One possible option for reducing the impact of increased flows to Karagan Lagoon is a drainage channel diverting drainage flows directly to the sea before they reach the lagoon. The effect of such a diversion channel was investigated in two additional sub-scenarios. Both used the inflow calculated using the scenario of 75 percent of design inflow—this is one of the two most probable scenarios of future scheme operation: the 75 and the 50 percent of design inflow (Meijer 2000). In these two sub-scenarios, 75 and 100 percent of the total runoff from the catchment was diverted to the sea (scenarios 4 and 5 in table 1, respectively). Lagoon water levels can also be managed by opening or closing its outlet channel to the sea. It is very unlikely, that this channel will remain closed when additional drainage flows start reaching Karagan Lagoon, as this may result in frequent flooding of parts of Hambantota town. It was therefore generally assumed that the channel will be open in the future scenarios outlined above (scenarios 1–5). To illustrate the effects of not opening the channel, the scenario of 75 percent of design inflow was also simulated but with the outlet to the sea closed (scenario 6 in table 1).

TABLE 1.
Future scenarios of irrigation inflows to Karagan Lagoon and the management of the lagoon.

Scenario	Scenario Description
1	Inflow is 100% of the design capacity of the main canal
2	Inflow is 75% of the design capacity of the main canal
3	Inflow is 50% of the design capacity of the main canal
4	Inflow is 75% of the design capacity of the main canal. 75% of inflow is diverted to the sea before reaching the lagoon
5	Inflow is 75% of the design capacity of the main canal. 100% of inflow is diverted to the sea before reaching the lagoon
6	Inflow is 75% of the design capacity of the main canal. The outlet to the sea from the lagoon is closed

Simulating the Impacts of Scenarios

Simulations show that all scenarios of future irrigation inflow from the extended Udawalawe scheme will have a significant impact on the hydrology of the Karagan Lagoon. The amount of irrigation inflow is the most influential factor of the future scenarios, while changes in the runoff model parameters do not have a significant effect (Stanzel et al. 2002). The simulated water levels of the three main scenarios (1, 2 and 3 in table 1) can be seen in figure 6. To aid interpretation only the period from 1997 to 2001 is shown. This period contains the wettest maha season of 1997 and the very dry summer of 2001.

In the 100 percent scenario (scenario 1), water levels never drop below 1.60 m and outflow to the sea occurs during long periods. The periods of outflow are slightly shorter in the 75 percent scenario (scenario 2). The water level drops below 1.40 m in dry periods. The 50 percent scenario (scenario 3 in table 1) results in significantly lower water levels of less than 1 m in dry periods.

Figure 7 compares the current condition with two scenarios of water diversion to the sea (scenarios 4 and 5 in table 1). The partial diversion of 75 percent of the lagoon inflow to the sea leads to no significant drop in simulated water levels. A complete diversion of all lagoon inflow through the main drainage channel leads to simulated water levels being considerably lower than the water levels in current conditions. A complete drying up during longer periods, however, does not occur.

The scenario with a closed outlet (scenario 6) shows that this is a practically impossible option (figure 8). The simulated water levels are almost constantly above a level at which the houses closest to the lagoon would be flooded.

Apart from the time series of water levels in Karagan Lagoon, a useful means of summarizing the simulation results is a duration curve of water levels. A duration curve is a cumulative distribution of values in a time series. It shows the percentage of time that a

FIGURE 6.
Lagoon water levels simulated using different future scenarios of irrigation development.

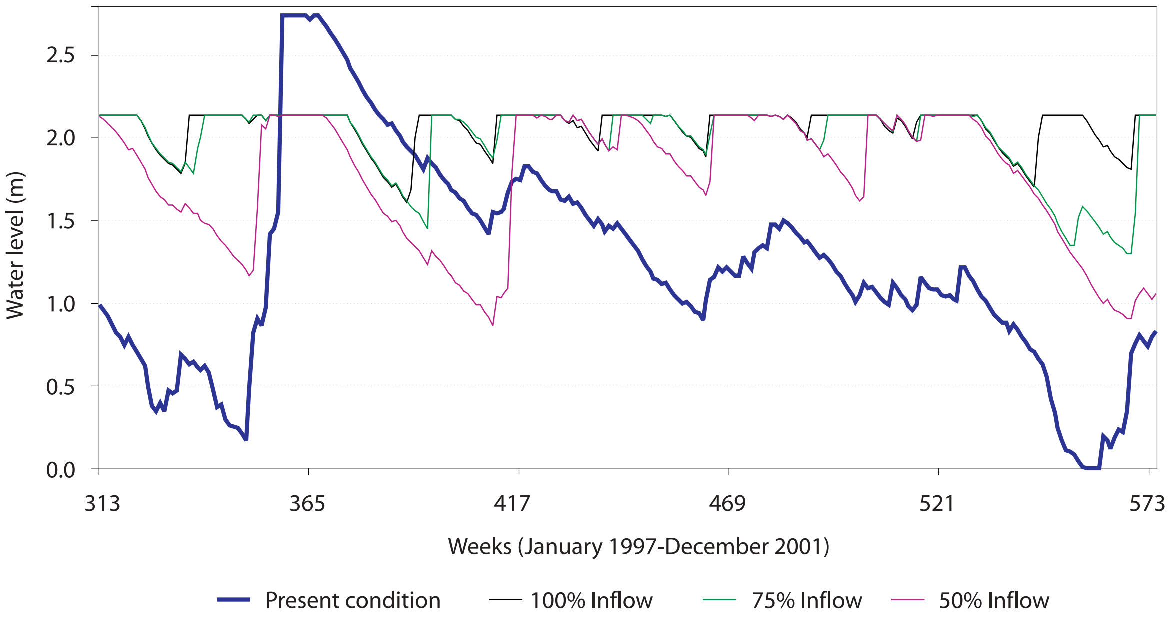


FIGURE 7.
Lagoon water levels simulated in different scenarios of diverting irrigation drainage water to the sea.

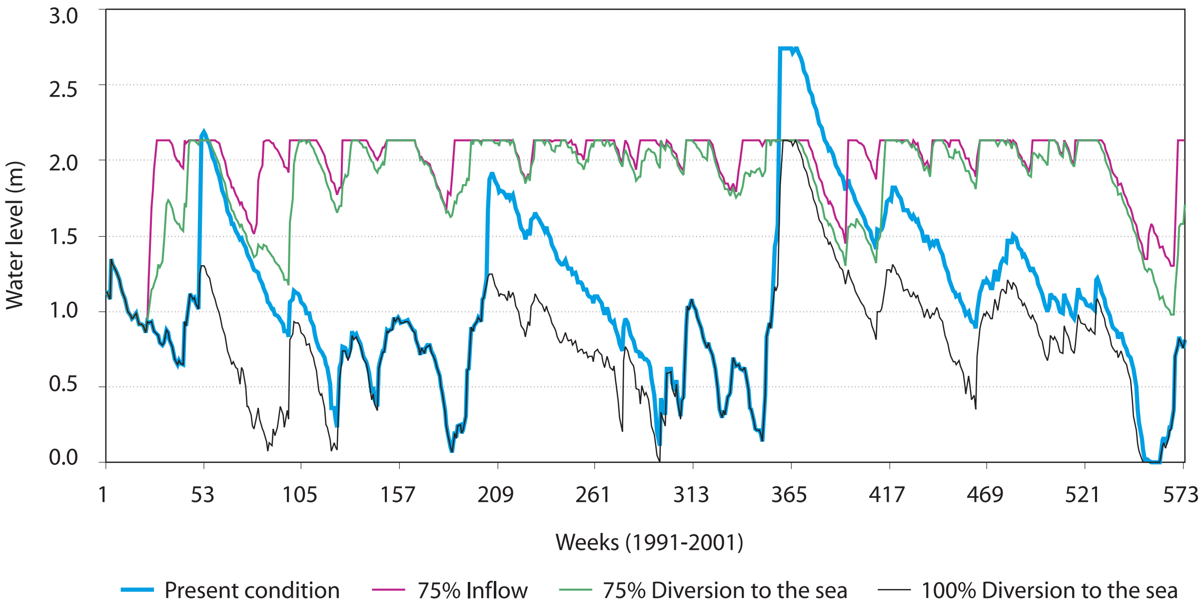
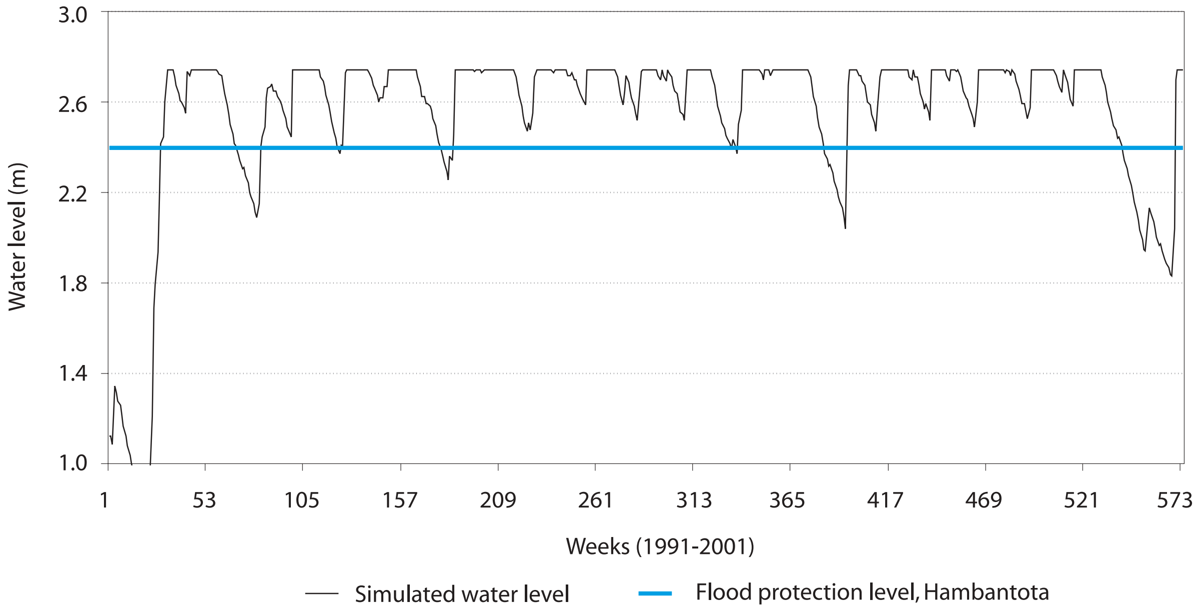
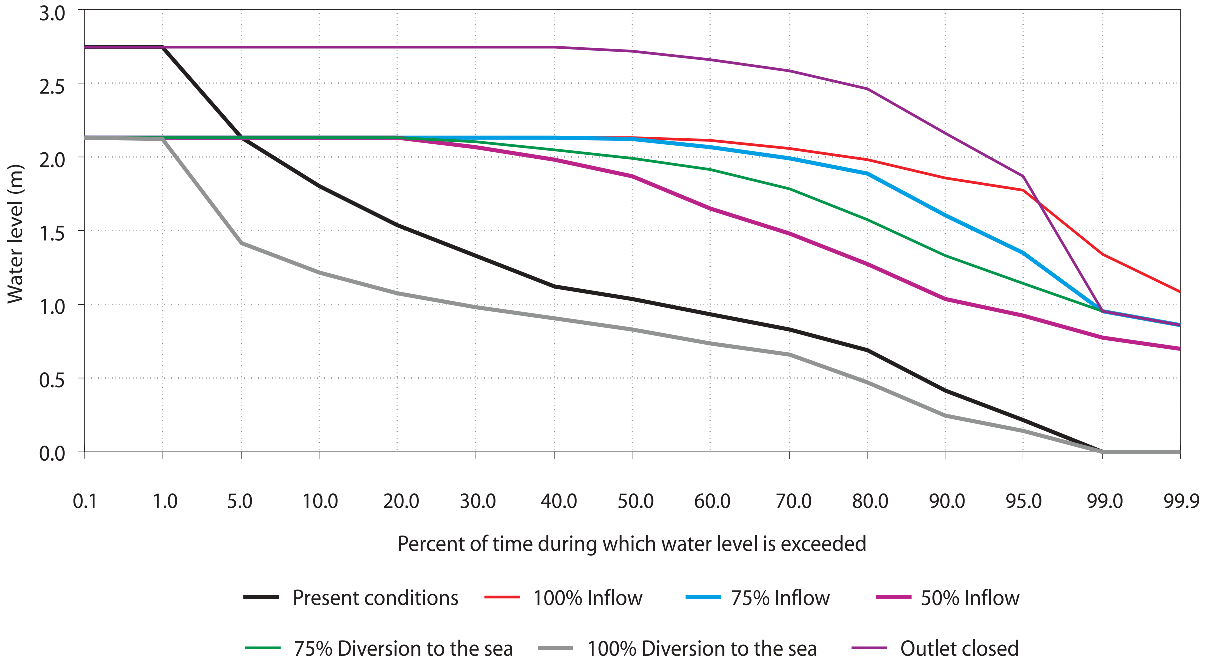


FIGURE 8.
Simulated lagoon water levels in the scenario of a closed outlet to the sea.



certain value (lagoon water level in this case) is equaled or exceeded. In other words, it provides a measure of assurance and risk of exceeding certain water levels and gives an indication of how frequently a certain water level occurs in a simulated (or observed) time series. This analysis may point to various thresholds, which may need to be avoided (or maintained) from ecological, management or development perspectives. The duration curves of water levels simulated by the different scenarios are presented in Figure 9. They all are compared with the duration curve representing the simulated lagoon water levels under present conditions. The curves illustrate, for example, that if 75 percent capacity inflow to the lagoon is expected, the lagoon water levels will remain above 2 m for about 75 percent of the time throughout the simulation period. If 50 percent capacity inflow occurs, water levels of 2 m will be exceeded for 50 percent of the time. At present, this water level is reached or exceeded for approximately about 7 percent of the time (figure 9). Therefore, the most probable scenarios of irrigation development will effectively convert the Karagan Lagoon into a perennial water body with relatively minor water level fluctuations. Diverting some of the inflows from the irrigation scheme directly to the sea could provide a means of mitigating these changes and recreating the natural pattern of water level fluctuations.

FIGURE 9.
Duration curves illustrating the variability of simulated Karagan Lagoon water levels under different scenarios of future irrigation development.



Simulating Hydrological Reference Condition of Bundala Lagoons

The Study Site and Problem

Bundala, Embilikala and Malala are the coastal lagoons of the Bundala National Park. This park is a Ramsar wetland site and is located east of the Karagan Lagoon (figure 1). The Bundala Lagoon has an estimated maximum water surface area of 5.2 km^2 (CEA 1993). It lies within a catchment of approximately 20 km^2, although the boundaries of the catchment are not well defined. The two other lagoons, Embilikala and Malala, are interconnected (figure 1) and have a total maximum surface area of 10.8 km^2 (CEA 1993). Being interconnected, the two lagoons effectively operate as one single hydrological entity. All three lagoons are important feeding and resting sites for migratory and resident water birds and also serve as nurseries for shrimp, finfish, and a variety of other marine organisms (Matsuno et al. 1998; Amerasinghe et al. 2002).

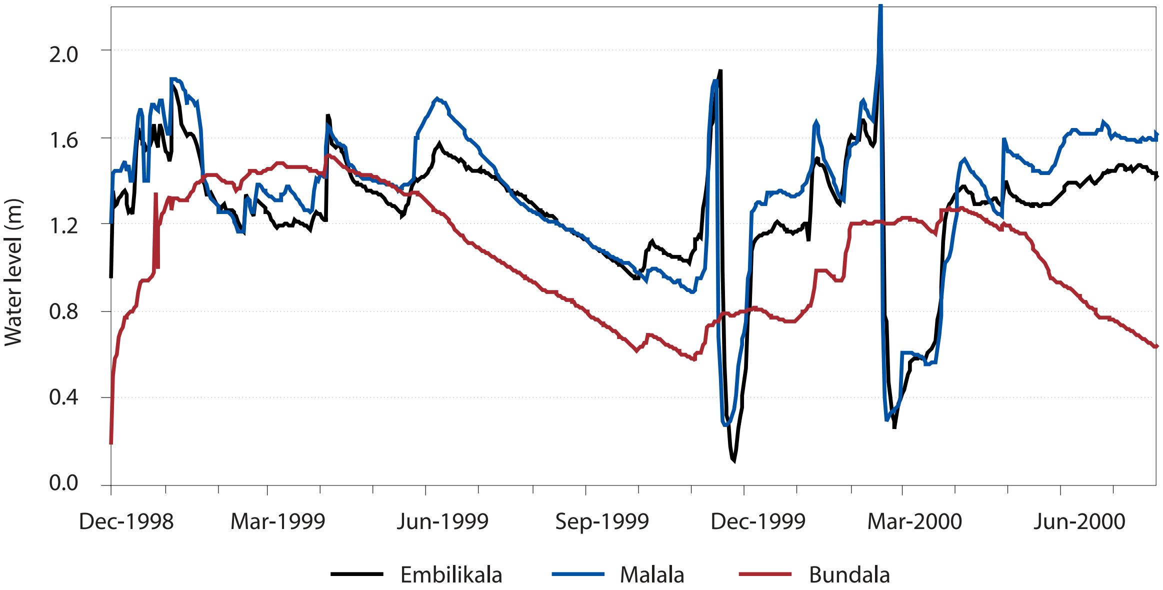
The Park currently experiences adverse impacts on its environment, of which the most important are those associated with irrigated agriculture (Kirindi Oya–Badagiriya irrigation system) immediately upstream of the park boundary and the lagoons. Since 1989 drainage water from the upstream irrigated area (figure 1) of about 26 km^2 has flowed into the Embilikala and Malala lagoons. The drainage flow component is mixed with the runoff generated from rainfall within the same area. As a result of extra drainage inflow, water levels in the Embilikala-Malala system often fluctuate over a wider range than in pre-development conditions. In order to prevent occasional flooding of irrigated land upstream, the Embilikala-Malala lagoon system is breached regularly (at least once a year) by local residents. This breaching causes the lagoon system to empty almost completely in approximately 6-7 days while the breached outlet (mouth) stays open. After mouth closure, the lagoons quickly fill up again due to the continuous upstream inflow dominated by irrigation drainage water.

The Bundala lagoon has not been impacted to date by irrigation drainage flows and its hydrology is still driven by natural physical processes. As a result, the fluctuation of water levels in Embilikala and Malala lagoons is currently very different from that of observed Bundala water levels. Figure 10 illustrates the observed variability of water levels in the three lagoons during a period of 19 months in 1998-2000 (Piyankarage 2002). The water level fluctuations in Embilikala and Malala lagoons are similar to each other, and show larger fluctuations due to mouth opening and closure than within Bundala lagoon.

There is concern that further increases in freshwater input to the lagoons would render them unsuitable to existing aquatic species (Matsuno et al. 1998). One of the major impacts of irrigation water could be the raising of water levels in the lagoons that could make feeding sites unavailable for many water birds. Also, the increased freshwater inputs to the lagoons may effectively convert these rare brackish coastal ecosystems into freshwater ones and have a profound impact on the associated biota.

The analysis of the hydrological regimes of the lagoons is important for quantifying the lagoons' past and present hydrological conditions and for improving the understanding of the linkages between hydrological characteristics of the lagoons and their aquatic life. Prior to the establishment of the upstream irrigation scheme, the three lagoons were likely to have had a very similar temporal pattern of water-level fluctuations. They have similar ranges of depths and are all close to each other. Therefore it is reasonable to expect that they are subject to similar patterns of rainfall and evaporation. This, in turn, implies that Bundala lagoon (which has not been affected by irrigation inflows), may be considered as a

FIGURE 10.
Observed water levels in Embilikala, Malala and Bundala lagoons.



'reference wetland'. If its water level regime is quantified, it could be 'transferred' to the other two lagoons.

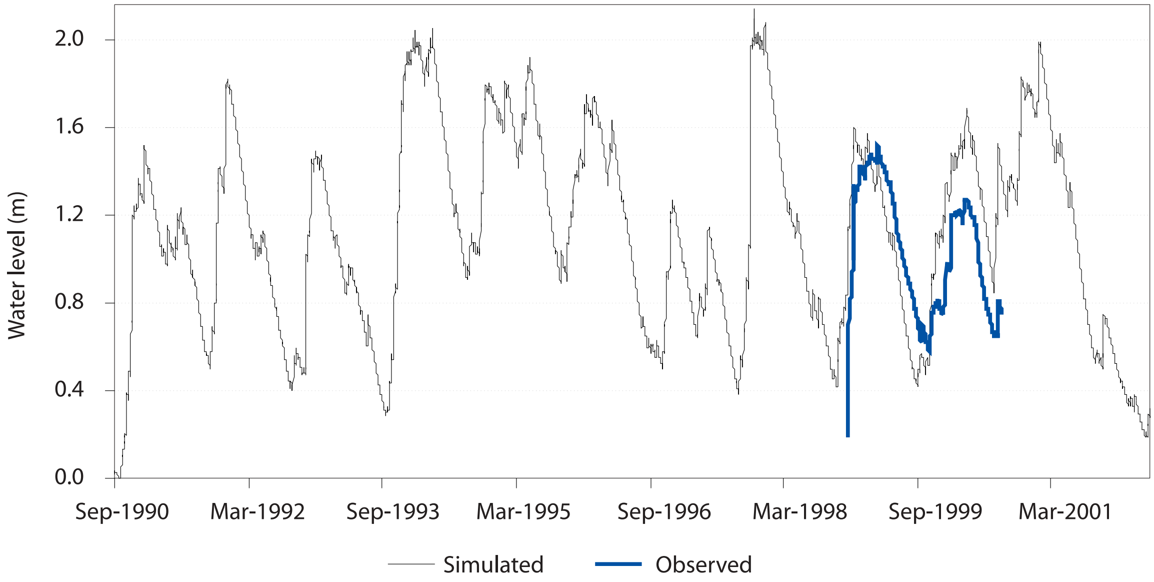
Simulation Approach

The focus has been on simulating the hydrological conditions which could have existed in the Embilikala and Malala lagoons prior to the implementation of the upstream irrigation systems. Such reference conditions will reflect the pre-development status of the lagoons and allow the quantification of hydrological changes in the lagoons to be made.

Smakhtin and Piyankarage (2003) simulated the water levels in Bundala lagoon using a simple lagoon water balance model, similar to that developed for Karagan Lagoon described in the previous section, but operating on a daily time step. The model was however simplified even more compared to the Karagan case. The area that was likely to contribute to the lagoon water balance ('active catchment area') was approximated by the maximum water surface area of the lagoon. This assumption effectively implies that lateral inflow to the lagoon was very limited and its major part occurred predominantly from the area surrounding the lagoon itself. The assumption was based on the fact that the topography of the Bundala catchment is flat and no clear drainage network exists. This assumption allowed two components of the water balance (rainfall on the lagoon surface and lateral runoff) to be simulated as one lumped inflow. No separate simulations were therefore carried out for runoff inflows from the upstream catchment.

The simulation period was again determined by the length of the input rainfall data at the nearest rain gauge (11 years of observations in Hambantota town). The model reproduced the general pattern of observed water-level fluctuations correctly (figure 11). However, the duration and occurrence of the dry phases in the lagoon hydrological cycle (which are present according to local residents) were not satisfactorily reproduced due to multiple problems with input data (Smakhtin and Piyankarage 2003). It was therefore important to revisit the simulations in an attempt to simulate the dry periods in the lagoon hydrological cycle.

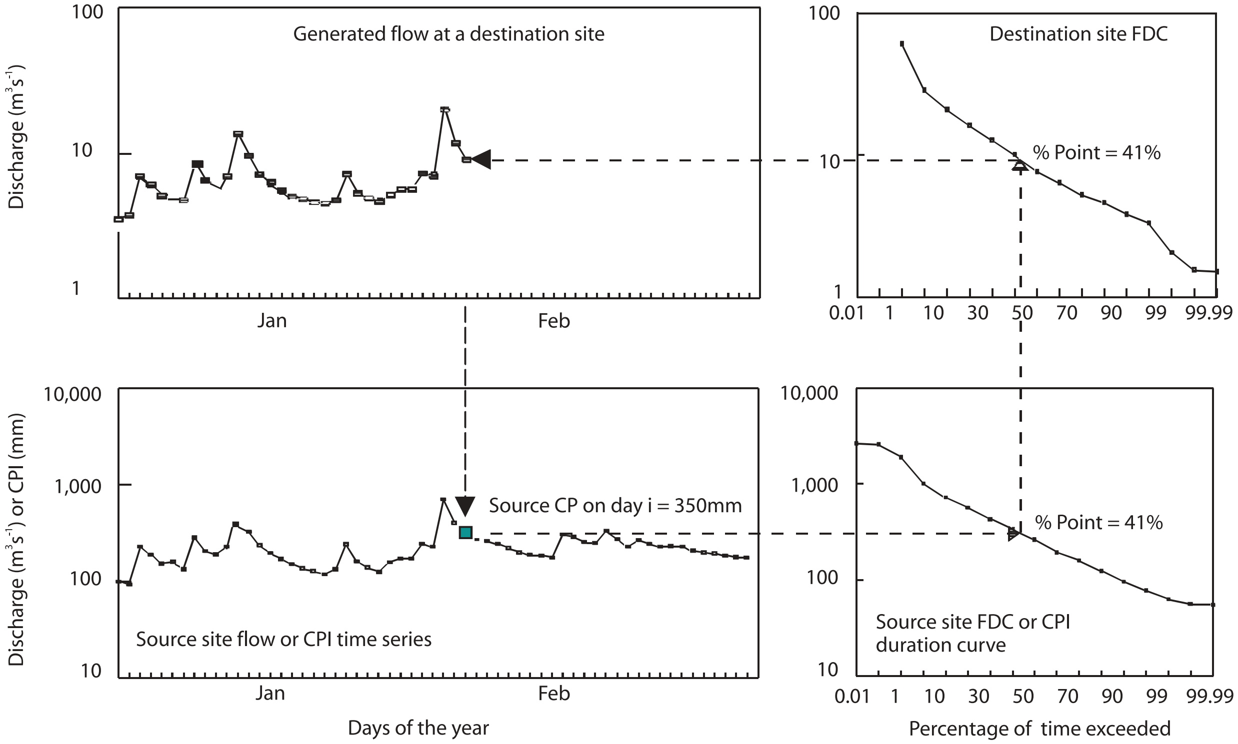
FIGURE 11.
Water levels in Bundala Lagoon: observed and simulated using a daily water balance model.



Adjustments were made to carry out the simulation through a spatial interpolation approach developed by Hughes and Smakhtin (1996), Smakhtin (1999) and Smakhtin and Masse (2000). The technique transfers a hydrological time series from a source site (a site with data) to a destination site (normally an ungauged site, where the simulation of a hydrological variable, such as discharge, is intended). A key component of this technique is a flow duration curve (FDC)—a graphical summary of stream flow variability at a site, illustrating the relationship between flow magnitude and its frequency of occurrence. The main assumption of the spatial interpolation technique, in its original form, is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs. The source and the destination site FDCs are represented by tables of discharge values corresponding to 17 fixed percentage points (0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99%). These tables are generated monthly for the whole year. Following the main assumption of the algorithm, the core of the computational procedure includes the estimation of the percentage point for each day's flow at the source site and the identification of flow for the same percentage point from the destination site's FDC (figure 12). The discharge tables are used to "locate" the flows on corresponding curves and log-interpolation is used between 17 fixed percentage points.

Similarly, the approach may be used for simulation of other hydrological variables (e.g., water levels). In the context of the present study, the main assumption will be that reference daily water levels in Bundala Lagoon and the daily water levels for the Embilikala-Malala lagoon system in natural, pre-development conditions, correspond to similar probabilities on their respective duration curves of water levels. A duration curve of water levels for Bundala lagoon may be calculated from water levels simulated by Smakhtin and Piyankarage (2003). In the context of the spatial-interpolation approach, Bundala Lagoon becomes the source site, from where the information will be transferred. Embilikala-Malala lagoon system becomes the destination site to which the information will be transferred as it is

FIGURE 12.
Illustration of spatial interpolation algorithm.



effectively ungauged (no observations of water levels representative of pre-development conditions are available).

The spatial interpolation approach naturally requires the establishment of a duration curve for the ungauged destination sites prior to the simulation of the actual time series. To establish a duration curve at the destination site, a brief survey of the local residents was carried out. These interviews suggested that before the implementation of the upstream Kirindi Oya–Badagiriya irrigation scheme in 1989, Embilikala and Malala lagoons used to dry up every year. No suggestions were made about the length of the dry phase. Residents said that Bundala Lagoon dries up about once in two years for at least one month. On this basis, it can be assumed that at least for one month a year (or approximately 10% of the time on average in one year) the Embilikala and Malala lagoons may have been dry. Some sources suggest that Embilikala and Malala lagoons now fluctuate frequently in the range of 1.0 to 2.2 m (Jayawardena 1993) whilst observations indicate that manual breaching is done at water levels of 1.9-2.2 m (figure 10).

Based on the above information, three water levels with corresponding probabilities of occurrence may be specified: 2.2 m—almost never exceeded (0.01% of the time), 1 m as a likely median (exceeded 50% of the time) and 0 m (dry lagoon) which occurs 10% of the time (exceeded 90% of the time). The median value of 1 m has been approximated from the observed water levels in Bundala Lagoon (figure 10) as this is the only source of quantitative information available. Water levels at other intermediate percentage points (e.g., 5, 10, 20%, etc.) may be found by means of interpolation between the three established points thereby completing the duration curve for the destination site.

Analyzing the Impact

Figure 13 illustrates the simulated water-level time series, which may be interpreted as either a water-level time series for Bundala Lagoon in current conditions, or as a water-level time series for the Embilikala-Malala system, which could have existed prior to the implementation of the irrigation scheme. The observed water levels in Embilikala-Malala lagoon system for a 19-month period during 1998-2000 are also shown in order to illustrate the substantial departure of present and probable past water-level variations.

Figure 14 shows duration curves of water levels in the Embilikala-Malala lagoon system. The curve based on daily observations during the 19-month monitoring period, reflects the variation of impacted water levels. The other curve is based on daily water-level time series simulated using the spatial interpolation approach discussed above (reference water-level time series). Comparison of the curves allows the changes brought to the system by additional drainage flows to be quantified. For instance, it can be seen that although the simulated water levels are generally lower than those observed throughout the whole range of probabilities, the major differences occur at probabilities of over 50 percent. This indicates that low water levels in the lagoons are currently higher than they used to be before the implementation of the upstream irrigation scheme. The proportion of time when the lagoon is dry was also greater in the pre-irrigation conditions than at present. For example, a water level that is equaled or exceeded for 70 percent of the time in the observed times series is approximately 2.3 times higher than the corresponding water level in the reference time series. A water level of 1 m is currently occurring as often as 80 percent of the time compared to 50 percent of the time in the simulated time series. This type of analysis may similarly allow for the quantification of changes in other (e.g., ecologically meaningful) water levels in these lagoons.

FIGURE 13.
Simulated reference water levels for Bundala Park lagoons and observed water levels in the Embilikala-Malala lagoon system.

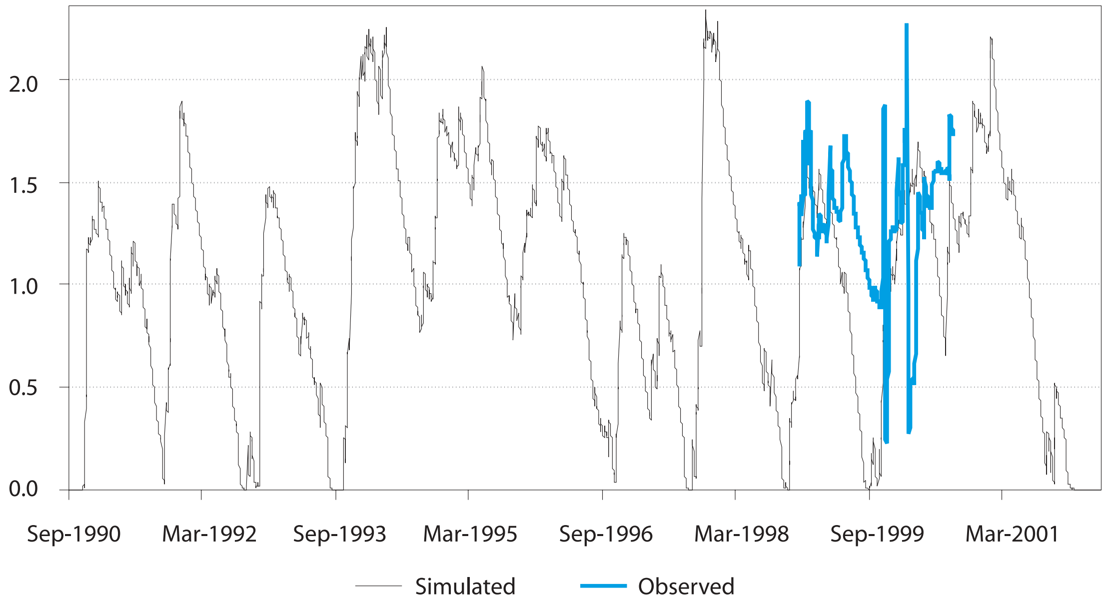
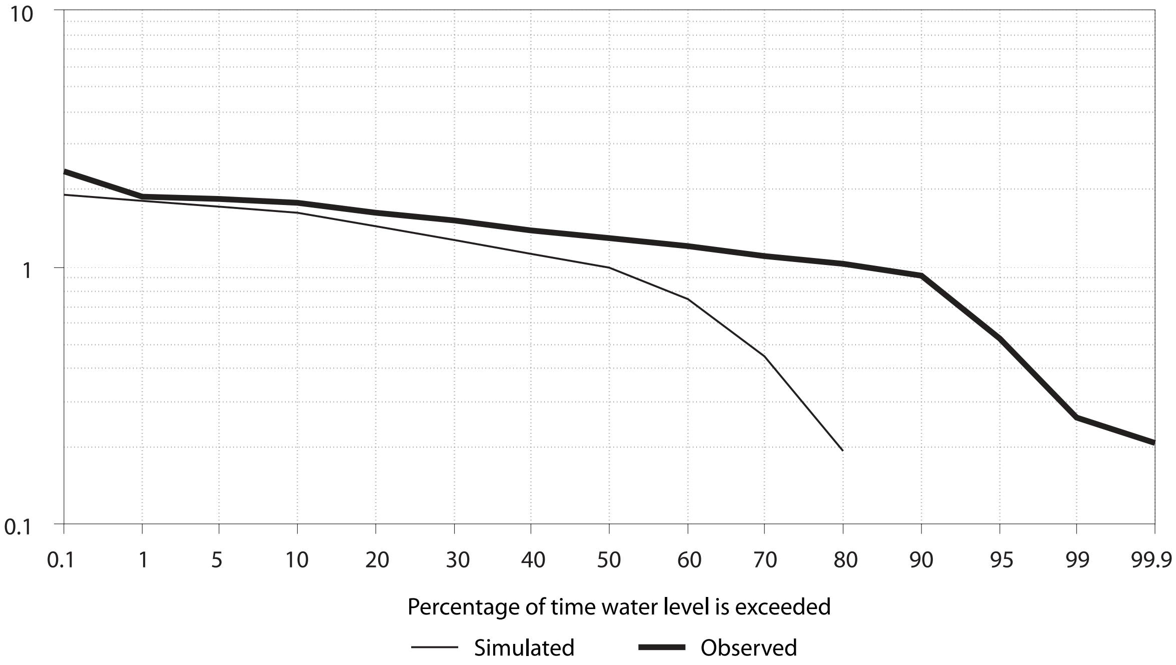


FIGURE 14.
Duration curves of water levels in Embilikala-Malala lagoon system based on observed and simulated data.



Simulating Inflow to and Mouth Conditions for Small Estuaries

The Study Problem

This example focuses on small estuarine systems, which are widespread in different parts of the world. For illustrative purposes, however, specific cases from the South African coast line are considered. Many estuaries along South African's coast may be classified as temporarily closed systems. Such systems are also known as "temporarily open", "blind" or "lagoonal" estuaries (e.g., Day 1981a; Whitfield 1992). The state of an estuary mouth is probably the single-most important factor determining the estuarine salinity regime and governing the structure and functioning of the resident biotic community. This applies particularly to many invertebrates and fish which have a marine phase in their life cycle, but for which estuaries often serve as nursery areas. It also influences many plant species, which are dependent on particular inundation regimes prevailing within the estuary. Similarly, certain water bird species favor tidal exposure of estuarine sediments whereas others benefit from prolonged closure of an estuary mouth.

Temporarily closed or open estuaries and lagoons are blocked off from the sea for varying lengths of time by a sand bar, which forms at the estuarine mouth (figure 15). The duration of the closed and open phases are determined by the interaction of river runoff, evaporation, seepage and wave over-wash events in the mouth region. Unlike the coastal lagoons in Sri Lanka featured in the earlier sections of this report, which represent an example of more static water bodies with limited interaction with the sea, the dynamics of many small estuaries is driven by river inflow.

The closed phase normally occurs during periods of low inflow, whereas floods breach the mouth and scour an estuary.

Small estuaries in South Africa usually have small river catchments (10–500 km^2) and stream flow that is seldom measured, either in the catchment or at the mouth. Observations on estuary mouth conditions are very scarce, inconsistent and fragmented between different historical periods, institutions or individuals. For most South African estuaries, no documented observations on changing mouth conditions are available. The lack of continuous observations on freshwater inflow and mouth condition precludes the development of tools for quantification of estuarine dynamics.

The approach described below highlights the combined use of simple modeling tools, which have been described in the previous sections. However, due to the nature of the problem and dominating processes in this case, the focus is made on integrating both the spatial interpolation method and a simple reservoir water-balance model. The first is used to simulate inflow to estuaries whilst the second indicates the openings and closures of the estuarine mouth.

Simulating Inflow to Estuaries

The most appropriate time resolution for the description of physical processes in small estuarine systems is 1 day. The spatial

FIGURE 15.
Aerial view of the temporarily closed Umgababa estuary in KwaZulu–Natal Province, South Africa.

interpolation approach, which operates with a daily time step, has been described in the previous section of this report (in the study of Bundala lagoons). More details of this method are available from Hughes and Smakhtin (1996), Smakhtin et al. (1997) and Smakhtin and Masse (2000). This approach can also be used to transfer the available daily rainfall time series at some source site(s) into stream flow time series at the destination site of interest (the destination site in the context of this study is represented by an estuarine mouth). Since all or most of the estuaries along the South African coast (and similar systems elsewhere in the world) are unlikely to be gauged, no suitable source flow gauge(s), with observed records, can be identified. The use of more readily available rainfall records provides a potential solution. These records will first need to be converted into some continuous function of rainfall, to allow spatial interpolation. This is necessary because daily rainfall itself is a very discrete process and rainfall duration curves are normally very steep as it rains for only for a small percentage of the time on average during a year. Smakhtin and Masse (2000) suggested the use of a current precipitation index (CPI) for this purpose. The CPI reflects the catchment wetness and accounts for current daily precipitation input and the exponential depletion of catchment moisture content during a period of no rainfall.

$$CPI_t = CPI_{t-1} K + R_t \qquad (5)$$

Where CPI_t is the CPI (mm) for day t, R_t is the precipitation (mm) for day t and K is the recession coefficient. On any day with no rain ($R_t = 0$) the CPI is equal to the CPI of the previous day multiplied by K. If it rains on any day, the daily rainfall depth is added to the CPI on that day. The recession coefficient, K, normally varies from 0.85 to 0.98 (Smakhtin and Masse 2000) and a standard value of 0.9 was found to be suitable for most applications.

Once a continuous daily CPI time series is generated for a source rainfall site, the required CPI duration curve may also be established. It may then be used in the spatial interpolation algorithm as a substitute for the source flows, and represents a source time series, which allows a destination site duration curve to be converted into actual destination site discharges. In the context of this study, these discharges are inflows to an estuary. The major assumption of the algorithm in this case becomes that both the CPIs occurring at rainfall site(s) in reasonably close proximity to an estuary and estuarine inflows, themselves correspond to similar percentage points on their respective duration curves. The layout of the computational procedure outlined initially by Hughes and Smakhtin (1996) remains the same and similar to that presented in figure 12.

As the estuary mouth is also ungauged, it is necessary to calculate its FDC *prior* to the generation of the actual daily stream flow time series. In a South African context, daily FDCs may be derived from FDCs based on coarser, monthly time step stream flow data. The latter have been simulated (Midgley et al. 1994) for a large number of small and normally ungauged incremental drainage subdivisions known as quaternary catchments. These data are currently widely used in South Africa for a variety of engineering and environmental applications (Smakhtin et al. 1997; Hughes and Hannart 2003). The average catchment area of a quaternary catchment is around 650 km^2 and the total number of catchments is close to 2,000. Coastal quaternary catchments may include several streams and, consequently, estuaries. For such streams of sub-quaternary size, the simulated monthly-flow time series may simply be apportioned based on the ratio of a sub-quaternary catchment to the total quaternary catchment area.

The method of establishing daily FDCs from monthly data is based on the premise that for any stream, the variability of daily flows is higher than that of monthly flows. In a high-flow month, maximum daily average discharges are higher than the average discharge for that month. In a low-flow month, minimum daily average discharges are usually lower than the monthly average flow. The general implication for FDCs is that daily discharges are higher than monthly discharges in the area of low probabilities of exceedence and lower than monthly discharges in the area of high probabilities. At the same time, a strong relationship exists between 1-day and 1-month flows of the same exceedence levels. Smakhtin (2000) explored these relationships for approximately 200 gauged rivers in South Africa and suggested linear regression equations and step-by-step procedures to calculate a 1-day FDC from a 1-month FDC. This procedure could be applied at any site, where monthly flow data are available (or may be simulated) and was also used to calculate 1-day FDCs at the estuarine mouth site. This calculation completes the acquisition of components necessary to generate a continuous daily stream flow time series for an estuary using a spatial interpolation algorithm.

Estuarine Mouth Condition Records versus the Variability of Upstream Inflow

Only a few estuaries in South Africa where observations on mouth condition were conducted in the past have been identified. The required records were acquired from different sources for these sites. However, only a few sets of these data were usable due to their poor quality and/or short records. Different individual estuaries display very different patterns of temporal variability in mouth condition. Figures 16 and 17 display daily inflow to an estuary simulated as described above and the mouth phases for two different estuaries. An estuary open mouth phase is represented in these figures by a dummy non-zero constant (1 or 5) and a closed mouth phase is represented by zero.

The first estuary, Vungu (figure 16), is an example of a non-responsive system. The estuary is located 142 km southwest of the coastal city of Durban in the KwaZulu-Natal Province of South Africa. The upstream catchment is approximately 120 km^2 (Begg 1978), and the estuarine lagoon is about 175 m long with a maximum width of 125 m and an average surface area of 1.13 X 10^{-2} km^2. A few weirs impound the stream upstream of the estuary, but their total capacity (about 2% of natural mean annual runoff) is negligible compared to the natural mean annual runoff (MAR) at the estuary mouth. The estuary lagoon is more than 2 m deep and the mouth is open for most of the year. Mouth closure occurs for short periods during the dry season, but during wet cycles the estuary, and others like it, may remain open for the entire year. The variability in daily inflow does not lead to multiple closures because the flow is usually sufficient to prevent the mouth from closing.

The second estuary, Little Manzimtoti (figure 17), is an example of a much more sensitive system. The Little Manzimtoti river is located close to the Vungu estuary and drains a catchment of approximately 15 km^2. The S-shaped lagoon is about 0.8 km long, with a maximum width of 45 m and an average surface area of 1.5–10^{-2} km^2. The estuary is subject to siltation due to upstream catchment developments and the entire lagoon is shallow (mean depth less then 1.0 m). The estuary opens and closes frequently as the flow increases or decreases. As figure 17 illustrates, even small increases in river flow may cause a mouth opening event and/or increase the duration of the open mouth phase. However, in estuaries such as this, not all mouth behavior may be explained by the variability in river flow, since sea effects (e.g., tidal exchange and sandbar overtopping events) may also play a role (e.g., recorded short-lived open mouth phases shortly after day 50, just before day 200 and around day 300 on figure 17). The sea processes effectively have impacts on all estuaries, but to a different extent.

The examples above illustrate the range of variability in estuarine mouth conditions. They demonstrate that the pattern of observed mouth phases in estuaries is often strongly linked to the simulated inflows.

FIGURE 16.
Example time series of simulated daily inflow and observed daily mouth condition in the Vungu estuary.

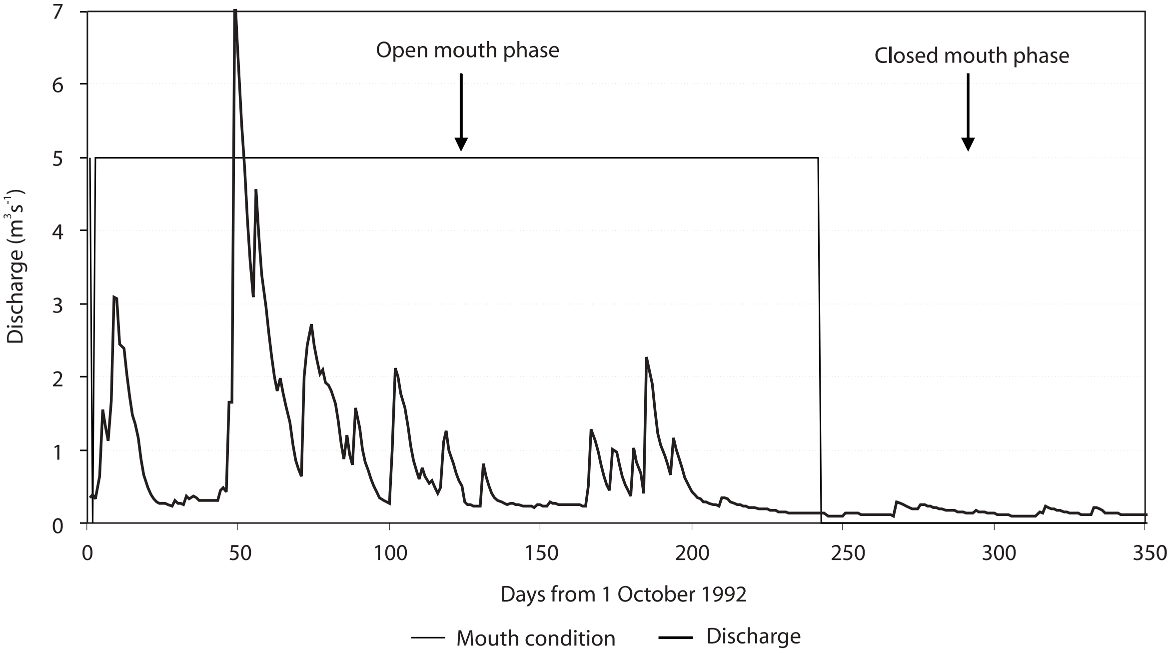
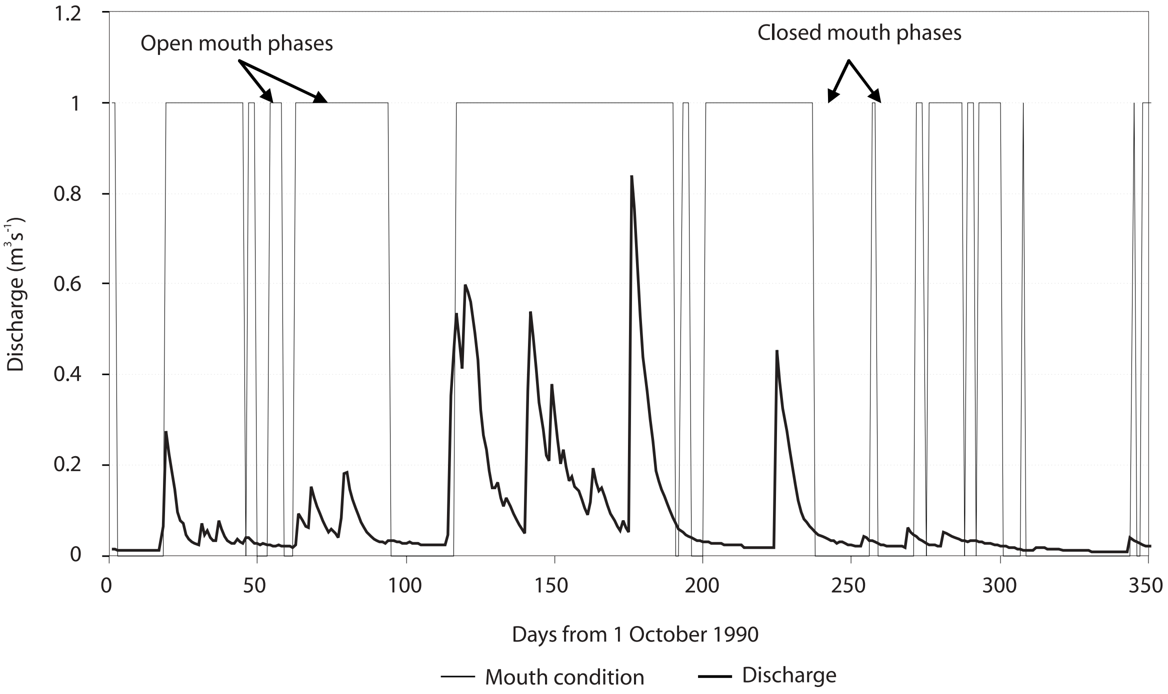


FIGURE 17.
Example time series of simulated daily inflow and observed daily mouth condition in the Little Manzimtoti estuary.



Simulating Estuarine Mouth Conditions

An estuary which is blocked off from the sea by a sandbar effectively represents a reservoir where the sandbar serves as a dam wall. This analogy is used here as the basis for simulating the openings and closures of an estuarine mouth. The “estuarine reservoir” water balance equation is effectively the same as in equation 4, but the percolation term (D) includes the seepage through the sand bar and bed of the lagoon. It is hereafter referred to throughout this section as seepage. The outflow term (O) in equation 4 is the outflow from an estuary into the sea, when the estuary is ‘full’. The description of the inflow from the sea into the estuary was not considered at this stage and it has therefore been assumed that mouth openings are driven exclusively by flow from the inflowing stream. The inflow from the sea refers to marine overtopping into the estuary and not to seepage from the sea. The latter is likely to be insignificant if it occurs at all (A.Whitfield, personal communication). The model forms part of a comprehensive hydrological modeling computer package, which incorporates other models as wells as data pre- and post-processing and display routines. The use of this model in the context of reservoir operation has been described by Hughes and Ziervogel (1998).

In the absence of observed stream flow records, the inflow time series may be simulated using the spatial interpolation algorithm described previously. Daily rainfall time series may be taken from the closet rain gauge to the estuary under consideration. Normally at least one rain gauge with data may be found within a reasonable vicinity of any estuary, even in remote areas. Information on regional mean monthly evaporation values in South Africa is available from Midgley et al. (1994). Daily evaporation values have been approximated by the division of monthly evaporation values by the number of days in a month. Daily rainfall and evaporation values multiplied by the estuarine water surface area form the components of the estuarine water balance. Seepage from an estuary may represent a substantial component of an estuarine water balance. It is, perhaps the least studied process in small temporarily closed South African estuaries. In the absence of detailed information on this process and in the context of the model used, a seepage component is approximated as the total annual water abstraction from an estuary based on synthetic monthly data from Midgley et al. (1994). This annual total is then distributed between calendar months of the year in proportions based on the monthly distribution of inflow. The daily values are calculated by the division of monthly volumes by the number of days in a month.

Outflow from an estuary is assumed to occur if the volume of water stored within it exceeds the estuarine reservoir capacity (a model parameter), and, consequently, the reservoir water level exceeds the “full supply level”. The water level (H, m) at the end of each time interval is estimated using a depth—volume relationship. The outflow from an estuary is calculated using the following equation:

$$O = h^{1.5} * K * W * 86400 \qquad (6)$$

Where h is the depth above the full level of an estuary, averaged over the start and end of the time interval and determined from the depth-volume relationship, K and W are the estuarine ‘spillway’ coefficient and width respectively (model parameters). In the context of the current study, the actual outflow volume is not of primary importance. What is more important is the fact that on certain days outflow does occur. On days when the estuary ‘spills’, the estuarine mouth is assumed to be open. On days when no ‘spillage’ occurs, the estuarine mouth is closed.

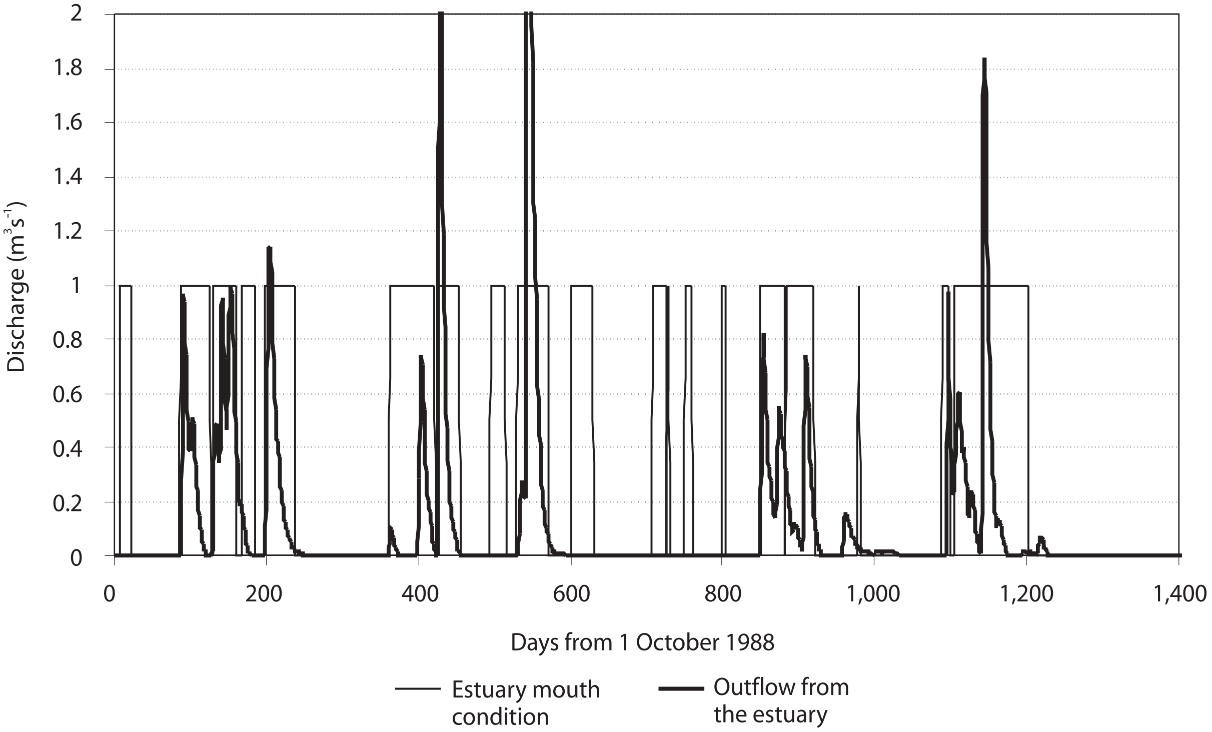
The model parameters which define the characteristics of the estuarine reservoir may be estimated from available literature sources (e.g., Begg 1978; Day 1981a), which often list such variables as length, maximum and minimum width and maximum, minimum, or mean depth of an estuarine lagoon. Alternative sources may include maps or aerial photographs, and databases available from regional environmental or nature conservation agencies and departments. Some parameters may be approximated during the stage of model calibration in cases when such calibration is possible (when at least limited but accurate observed flow data exist close to the estuarine mouth or where observations of estuarine water level are available).

The example used to illustrate the modeling approach described above is the temporarily closed Umgababa estuary in KwaZulu-Natal Province (figure 15). The Umgababa River, some 35 km south of Durban, is about 15 km long and drains a coastal belt catchment of approximately 37 km^2. The S-shaped lagoon is about 3 km long with an estimated surface area of 17.6 X 10^{-2} km^2. It gradually widens from a small stream 20 m across to a maximum width of 150 m (Day 1981b) and has an average depth of about 1.5 m for most of its length. After heavy rains, the water level rises until the sandbar is breached and the estuary becomes tidal until the bar builds up again. The Umgababa estuary is one of the most important on the Natal south coast, and has considerable conservation potential. The estuary appears to have preserved its current environmental character and has an abundance of estuarine life (Begg 1978).

Daily rainfall data from the nearest station (Illovo Mill), located upstream of the estuary was used as input to the model. Figure 18 shows an extract from the time series of simulated daily outflow from Umgababa estuary and observed mouth conditions. The observed data (1988 – 1995) suggests that the estuary is open for approximately 31.6% of the time on average throughout a year (although the lengths of open phases vary from year to year). The quality of these data is however highly questionable and there are multiple periods of missing data, particularly in the latter half of the record. The simulation (carried out for the same period) suggests that the estuary is open for 28.5% of the time, which is close to the value obtained from observed data.

Some observed open mouth phases do not, however, coincide with periods of outflow from the model. In the simulated series there are fewer (13 cases in the whole record) but longer (mean of 50 days) events of the open mouth phase compared to the observed data (28 cases and a mean of 23 days, respectively). The model, however, cannot and has not been properly calibrated against the observed data, as the observed record was very short and inaccurate, as mentioned above. Model parameters have been derived from published sources (Begg 1978; Day 1981a; Midgley et al. 1994). At the same time, the example indicates that even under conditions of very scarce and uncertain data, the pattern of mouth status dynamics could be reproduced by this or a similar pragmatic model and further improved if additional field data on estuarine characteristics, mouth conditions and flow (even obtained through occasional measurements) become available.

FIGURE 18.
Simulated daily outflow and observed mouth condition in the Umgababa estuary.



Conclusions

This report illustrates how simple modeling approaches can be used to generate, analyze and present information for natural hydrological systems in cases where information is extremely scarce and where the availability of data is unlikely to improve quickly. Measured time series are, for example, normally not available for small coastal water bodies. The methods described in this report are capable of producing long-term simulated time series of required hydrological variables (e.g., discharge, water levels, volumes, water surface areas and mouth conditions).

The simulation methods employed in this report include water balance equations and a number of assumptions about the physical processes, system structure and characteristics. They require much less input information and parameters to operate, compared to more complex, distributed, information-consuming and labor-intensive techniques.

Such modeling approaches also have to employ simple, and often, unconventional ways of describing certain processes or components of natural systems, which have not yet been studied and which may remain unmeasured due to limited budgets and time constraints. For example, in the Karagan study the multiple interactions between tanks, crop fields and sub-catchments have been successfully described by a few lumped dummy reservoirs. Similarly, in the Bundala study results of surveys of local residents have been used to derive a hydrological tool (a water level duration curve), which was then used to generate the required hydrological time series.

The study illustrates that simple simulation techniques may be used for a variety of tasks, from the assessment of the future impacts of irrigation and basin development on natural ecosystems, to the establishment of past, reference hydrological regimes, against which to measure the current impacts.

The methods presented and illustrated in the report are not limited to any specific region. The examples described focus on small coastal water bodies, but the techniques could be used in principle for any ungauged natural coastal system or river/stream.

Some of the methods presented in the report have undergone development through new applications. This applies to the spatial interpolation of observed time series. Although it is already widely used in hydrological practice for generation of flows, it has been applied here for the first time to generate lagoon water volumes and levels. Similarly, an unconventional interpretation of an estuary as a reservoir which 'spills' into the sea when the estuary is full, allows the estuarine mouth closures and openings to be simulated without major modifications to the water balance modeling framework.

The outputs simulated by these methods may have many other applications and spin-offs. For example, continuous long-term records of lagoon volumes and water-surface areas may be used in calculating salt concentrations and the dynamics of flooding. Simulations of inflows to estuaries under conditions of different upstream catchment development may facilitate the assessment of changes in the estuarine type (e.g., they could be used to assess whether an estuary might close completely under planned irrigation withdrawal from an inflowing stream). The analysis of water levels using a duration curve allows a summary of hydrological variability to be presented and may suggest ways of linking hydrology with ecology (e.g., changes in the probabilities—assurances—of water levels may be related to recorded or estimated losses of aquatic biodiversity).

Even modeling methods as parsimonious and pragmatic as those illustrated in the report, may point to further research needs. For example, it is clear from the above examples that more experimental data are required to properly quantify such components as percolation and seepage in coastal ecosystems. Therefore, continuous observations of water levels have been established in Karagan Lagoon and its catchment in Sri Lanka. Establishing continuous observations on estuarine mouth condition for at least a few small representative estuaries of different types in South Africa (and other regions, where such systems represent important natural ecosystems) would also help considerably.

Finally, the simulated time series may form the basis for a transparent discussion on matters related to impacts (current or future) of irrigation development. The models may be run interactively at specialist and/or stakeholder workshops in order to illustrate the hydrological impacts of scenarios or to quantitatively interpret the perceptions about current or future development plans.

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