A coupled hydraulic–hydrologic modelling approach to deriving a water balance model for a complex floodplain wetland system

Scott Rayburg and Martin Thoms

ABSTRACT

Wetlands, particularly those in semi-arid or arid environments, are hotspots of biological diversity and productivity. Water resource managers are therefore increasing their efforts to conserve wetlands from environmental degradation. To do this, they require a thorough understanding of the wetting and drying regimes of these wetlands, and how potential land use, climate change and water resource development might affect inundation patterns. Hydrologic models can help to enhance this understanding, and to predict and assess future impacts. However, for semi-arid environments, data to assist in model construction is scarce. This paper presents a new method for developing a water balance model for a semi-arid wetland, the Narran Lakes ecosystem in eastern Australia. This method combines hydraulic (improving our understanding of water movement through a wetland) and hydrologic (improving our predictive capability for inundation levels) models and satellite imagery (acting as calibration and validation data) to produce a predictive model of wetland inundation. We show that this coupled hydraulic–hydrologic model yields inundation patterns commensurate with those that actually occurred over more than 30 years. The model results indicate that current inundation levels are at historical lows, which is most likely associated with a naturally occurring drought and increasing water resource development upstream.

Key words | MIKE21, Narran Lakes ecosystem, remote sensing, water resource management, wetland

Scott Rayburg (corresponding author)
Martin Thoms
Riverine Landscapes Research Laboratory,
University of Canberra,
Canberra ACT 2601,
Australia
E-mail: *scott.rayburg@uts.edu.au*

Scott Rayburg (corresponding author)
Current address: Landscape Stressor Response Group,
University of Technology,
Sydney, New South Wales 2007,
Australia

INTRODUCTION

Wetlands in semi-arid or arid environments are hotspots of biological diversity and productivity as a consequence of their nutrient-rich sediments and the frequency with which they are inundated. In Australia, where approximately 70% of the landscape is classed as either arid or semi-arid, wetlands are biologically important. For example, many of Australia's largest recorded waterbird breeding events occur within wetlands located in semi-arid and arid regions (Kingsford *et al.* 1999). These wetlands fill as a result of highly unpredictable, and spatially and temporally variable, rainfall and streamflow conditions, and typically have irregular and extended wet and dry periods (Stafford Smith & Morton 1990). Given the importance of these systems, and the spatial and temporal complexities of their hydrologic character, it is vital that we develop accurate hydrologic models that are capable of predicting the likely impacts of climate and land-use change and water resource development on the magnitude, frequency and duration of inundation within them. Such knowledge is essential for the effective management of these systems, both as ecological refuges and potential sources of agricultural productivity in otherwise dry landscapes.

There have been many attempts to model the water regimes of lakes, wetlands and floodplains in different

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climatic environments. Models have been constructed for relatively simple systems, such as single lakes (e.g. Jacobson & Schuett 1979; Yin & Nicholson 1998; Jones *et al.* 2001), wetlands (e.g. Arnold *et al.* 2001) or linear sections of floodplain along single river channels (e.g. Overton 2005; Frazier & Page 2006). These have ranged from simple water balance models (e.g. Crapper *et al.* 1996; Sene 1998; Jones *et al.* 2001) to relatively more complex two-dimensional or three-dimensional spatially distributed computer models (e.g. Somes *et al.* 1999; Thompson 2004). Recently, the use of remotely sensed data has significantly improved the accuracy and precision of hydrologic models by providing calibration and validation data for inundated extents (Townsend & Walsh 1998; Campo *et al.* 2006). These data also provide a means for the historical reconstruction of past flood events (Pietroniro *et al.* 1999; Shaikh *et al.* 2001; Todhunter & Rundquist 2004; Frazier & Page 2006) and as a predictive tool for potential future flooding (Overton 2005).

Despite these current advances in hydrologic and hydraulic models, there are still significant modelling challenges to be overcome. Predictive hydrologic models in complex systems (like those in distributary systems or with multiple linked storages) are rare and underdeveloped. Few studies have attempted to integrate hydraulic and hydrologic models in such a way as to capitalise on the strengths of these complimentary modelling approaches. Such a coupling, supported with the judicious use of remotely sensed data, could significantly improve models in complex systems where existing data sources are sparse and the hydraulics of the complex systems are largely unknown.

The aim of this paper is to develop a coupled hydraulic–hydrologic model capable of predicting inundation patterns in a complex floodplain wetland system. The approach developed herein provides a blueprint for building hydrologic models for complex systems in relatively data-poor environments. It incorporates a two-dimensional hydraulic model (to facilitate an understanding of water movement through the system), remotely sensed data (for calibration and validation) and a water balance model (for long-term predictions of lake, wetland and floodplain inundation). The outputs of the model are considered with respect to the medium-term flood history of the Narran Lakes ecosystem, located in eastern Australia, and the suitability of the model in facilitating water resource management decisions is discussed.

STUDY AREA AND DATA SOURCES

Study area

The Narran Lakes ecosystem is a terminal floodplain–lake–wetland complex of the Narran River in north-central New South Wales, Australia (Figure 1). The system is composed of two principal lake complexes: the Northern Lake complex in the north-eastern part of the system and the Narran Lake complex at the southern end of the system. The Northern Lake complex is considerably smaller, both in surface area (approx. 3,000 ha) and volume (approx. 17,500 ML), than the Narran Lake complex (approx. 12,000 ha and 122,500 ML), and consequently both fills and dries more frequently.

The Narran Lakes ecosystem is supplied with water from the Condamine–Balonne Basin and has a catchment area of 143,000 km^2 (Figure 1). The Condamine–Balonne Basin has a single channel for most of its length, but bifurcates into five principal channels downstream of St George: the Ballandool, Bokhara, Culgoa and Narran Rivers and Briarie Creek (Thoms 2003). All five channels are characterised by very low slopes (approx. 0.0002), tortuous planforms ($p > 2.2$), fine sediment loads and bankfull cross-sectional areas that decrease with distance downstream (Thoms 2003). The Narran River is the only one of the five distributary channels that terminates in the Narran Lakes Ecosystem–the other four channels bypass the Narran Lakes ecosystem and flow into the Darling River. Details of the hydro-geomorphology of the regional distributary network are provided by Thoms (2003) and Thoms & Parsons (2003).

The climate of the broader Narran region is hot and dry, with maximum summer and winter temperatures of 50 and 20°C, respectively. Average annual precipitation is 480 mm yr^{-1} in contrast to the average annual potential evaporation of 2,000 mm yr^{-1}. Rainfall is highly variable from year to year, with secular wet and dry periods a feature of the region (Thoms & Parsons 2003). The local catchment

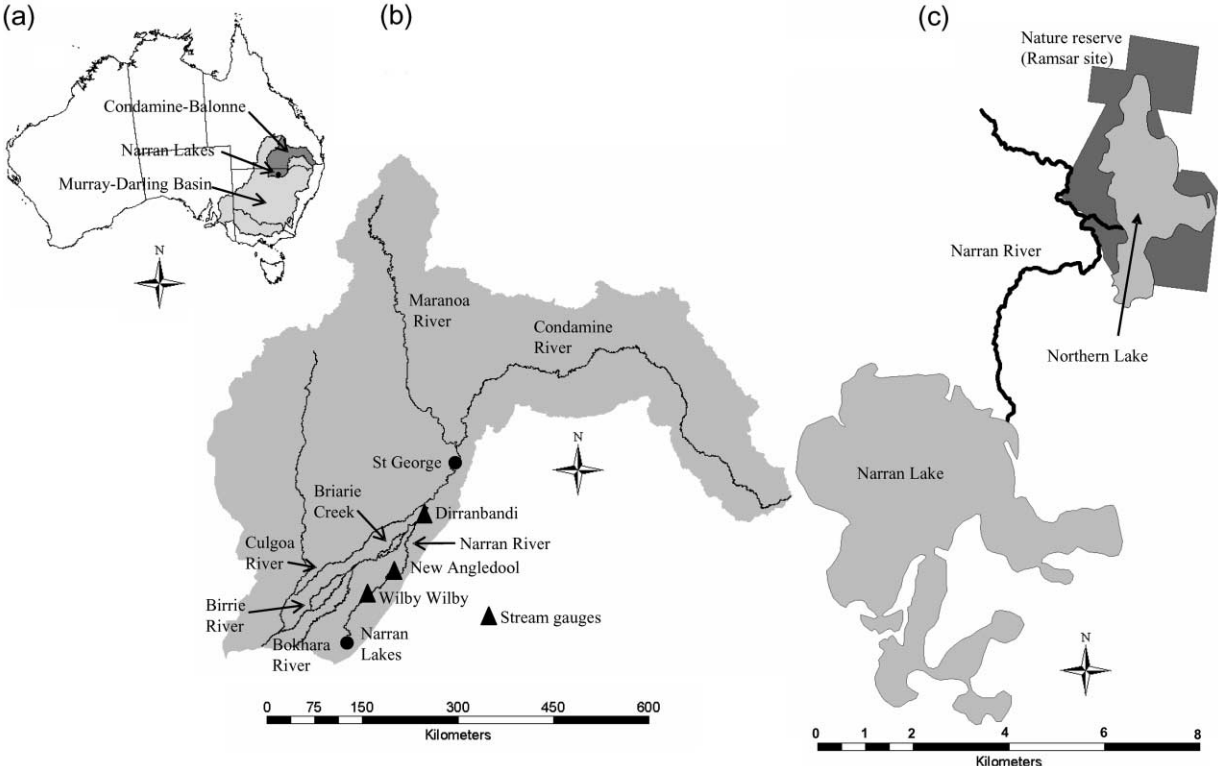

Figure 1 | The location (a) and structure (b) of the Narran Lakes ecosystem.

of the Narran Lakes ecosystem is relatively small (approx. 46 km^2); therefore, this terminal system does not fill as a result of local precipitation, but from flows from the Narran River that are generated in the upper catchment of the Condamine–Balonne Basin. The mean annual flow of the Narran River just upstream of the terminal lakes is 141,000 ML, with a standard deviation greater than 150,000 ML, and periods of no flow occur approximately 60% of the time. The high inter-annual variability of flows in the Narran River ensures that the Narran Lakes ecosystem experiences complex flood inundation patterns with periodic wet and dry cycles (Thoms 2003).

A significant portion (5,500 ha) of the northern section of the Narran Lakes ecosystem was designated as a Ramsar site in June 1999. This area has also been managed as a nature reserve by the New South Wales National Parks and Wildlife Service since 1988. The wetland system is characterised by large areas of the flood-tolerant shrub *Muehlenbeckia florulenta* (tangled lignum) that provides an important breeding habitat for many species of colonially breeding waterbirds. Land use in the surrounding region is predominantly sheep and cattle grazing, and mineral exploration. Further upstream, in the northern part of the Condamine–Balonne Basin, land use is increasingly dominated by intensive crop irrigation that has been associated with expanding water resource development in recent years, which has influenced the catchment's hydrology at a number of scales (Thoms & Sheldon 2002). The development of a hydrologic model is part of a larger investigation into the impacts of altered (natural and anthropogenic) hydrology on the frequency and duration of inundation within the Narran Lakes ecosystem and the likely impacts of these changes on the system's ecology.

Data sources

The development of a coupled hydraulic–hydrologic model is a data-intensive process, requiring information on climate, river flows, topography, inundation extents, infiltration and transmission losses. The sources, applications and methods employed in using or creating the data for this study are summarised in Table 1. Of the seven major data

Table 1 | Input parameters for the hydraulic and hydrologic models

Data type	Data source	Data considerations	Data use
Rainfall	Australian bureau of meteorology	Thiessen polygons constructed from three surrounding rainfall stations with more than 100 years of data (Walgett, Lightning Ridge, Brewarrina)	Input into water balance model
Evaporation	Australian bureau of meteorology	Amalgam of several surrounding evaporation records to form a continuous 60-year record of pan evaporation; data were corrected to evapotranspiration by applying a 1.5 times multiplier	Input into water balance and hydraulic models
Soil losses	Derived	Computed by comparing input flow volumes (from the Wilby Wilby gauge) to the standing water volumes for each flood, as determined by overlaying the inundated areas determined from the satellite imagery with the LiDAR DEM	Input into water balance model
Transmission losses	Derived	Computed by assessing the losses (by distance) between three flow gauges along the Narran River	Input into water balance model
Discharge	New South Wales department of infrastructure, planning and natural resources	40 years of flow gauge data from the Wilby Wilby gauge, approximately 45 km north of the study site	Input into water balance and hydraulic models
Topography	LiDAR	Dedicated flight over the study site, dataset includes 650,000,000 points. with 1 point per m^2; data accuracy of 8 cm, data precision of 1 cm	Input into hydraulic model
Known flood extents	Landsat imagery	Landsat imagery was collected before and after every flood event from 1981–2004, as well as two drying sequences with images gathered every 1–2 months until dry; total dataset includes over 80 images	Calibration for the hydraulic and water balance models; computation of soil losses.

DEM = digital elevation model; LiDAR = light detection and ranging.

types included in the study, three were sourced from existing records (rainfall, evaporation and discharge) and four were newly derived or created datasets (topography, transmission losses, lake infiltration and flood extents from 1981 to 2004).

Topographic data were acquired using a light detection and ranging (LiDAR) aerial survey flown in October 2004. The LiDAR dataset included over 650,000,000 data points spanning an area of about 650 km^2 with one data point per square metre, and internal positional and vertical accuracies of approximately 2–3 cm (Rayburg *et al.* 2009). More than 20,000 points were used to calibrate the LiDAR data, sourced from a 2003 Queensland Department of Natural Resources and Mines differential global positioning system (GPS) survey, which had positional and vertical accuracies of <1 cm. This process was undertaken by AAM Hatch, a commercial LiDAR provider based in Brisbane, Australia and involved comparing the LiDAR-derived topography with that of the 20 000 ground survey points. The calibration data allowed for the identification and rectification of much of the error in the LiDAR data which originated as instrument error (simple errors of the laser rangefinder itself), position and orientation errors (for the integrated GPS), and data handling and processing errors (including interpolation errors). The calibration procedure undertaken here represented an order of magnitude more ground data than typically used for such purposes, resulting in a highly accurate final digital elevation model (in which there was less than 1 cm deviation between LiDAR-derived and DGPS-measured elevations). At the time of the aerial survey, small areas of the Narran Lakes ecosystem were inundated (in particular, there were several deep pools along the Narran River). As LiDAR is unable to penetrate water, a differential GPS survey of roughly 1,000 extra points was conducted to fill these gaps.

The resultant digital elevation model (DEM) of the Narran Lakes ecosystem was then used to produce two sets of hypsometric curves (surface area and lake volume against water surface elevation) for the Narran and Northern Lakes, respectively. These curves were derived for 2 cm elevation increments using the 3D analyst extension of ARCGIS 9.3. Equations to describe these curves were then derived in TableCurve2D and the resultant high-order polynomial equations are used to transform modelled output data between surface area, volume and water surface elevation.

Transmission loss data were calculated from a series of four flow gauges along a 172 km stretch of the Narran River. The Narran River has no major input tributaries along this section and discharge decreases in the downstream direction. Transmission losses (due to infiltration and evaporation) were calculated as the long-term mean difference in flow between each gauge, temporally corrected for the travel time of water between each gauge. This was accomplished by matching peak discharge at each gauging station (all of which provided daily flow data) for floods which had no new water added from tributaries or rainfall as flows moved between stream gauges. Time shifts between gauges were determined as the time between peaks at each successive gauge, which resulted in reasonable travel times commensurate with ground observations and with average stream velocities ranging between 0.5 and $0.8\,\mathrm{m\,s^{-1}}$. Transmission losses were relatively stable between stream gauges with no apparent bias (either for larger or smaller losses) between any two particular gauges. The net result is a value for water loss per kilometre of river length (which amounted to 250 ML for the 45 km between Wilby Wilby and the top of the Narran Lakes Ecosystem). This value was then subtracted from flow data recorded at the long-term gauge closest to the Narran Lakes ecosystem (the Wilby Wilby gauge) to derive an input flow at the point of entry into the system.

Data on lake infiltration volumes and known flood extents were obtained from satellite imagery. Eighty-two cloud-free Landsat MSS, TM and ETM + images of the Narran wetland were acquired for the period February 1972 to April 2004. These images provide a snapshot of the system before and after every flood event since 1981 and data on two extended drying sequences. The optimal time for image acquisition was determined as 2 weeks before the arrival of water and 1 month after the cessation of flow into the system: however, limitations in the return period of the satellites (± 16 d) means there is some variability in the data around this optimum. This image acquisition strategy was adopted to provide the largest pool of data possible, in order to ascertain the inundation response in each lake complex to floods of various magnitudes, at different times of the year and with different antecedent conditions. In addition, the inclusion of two long drying sequences allowed for the calibration and validation of the loss component of the model and, therefore, provides accurate information on the residence time (and future antecedent conditions) of water within the system.

Upon acquisition, each image was reprojected to the Geodetic Datum of Australia 1994 (GDA94), Universal Transverse Mercator (UTM) zone 55 S, which is an appropriate localised projection that minimises spatial distortions (Longley *et al.* 2005). The images were geometrically rectified using a 1:250,000 topographic map as a reference with a minimum of 20 ground-level control points (usually water storage tanks or road junctions). The individual and total root-mean-square errors (RMSE) for each geo-rectified image were approximately one pixel length (30 or 50 m, depending on the resolution of the satellite image).

Water-covered pixels were identified by performing a density slice on Landsat MSS, TM and ETM + Band 5 (Frazier & Page 2000). This near-infrared band (1.55–1.75 μm) returns very low values for water because virtually all radiant flux is absorbed at this wavelength. Conversely, vegetation and soils have a very high return. The resultant images showed water bodies as black areas, and soils and vegetation as bright areas. Classification was accomplished using an ISODATA algorithm within Erdas Imagine that divided the scenes into wet and dry pixels. A more detailed description of the use of density slicing to identify water in Landsat imagery can be found in Frazier & Page (2000) or Overton (2005).

The binary rasters (i.e. the classified images) were then converted to vector format for ‘cleaning’, whereby cloud elements, artificial water storages and unrelated inundated areas were removed. Additionally, expert knowledge was used to reconnect estranged channels, where an evident link had been lost through rasterisation. This process increased the overall accuracy of the flood maps. An example of two final flood images for the Narran Lakes ecosystem are presented in Figure 2. These finalised polygon extents were verified based on field observations undertaken during the 2004 flood event and its drawdown phase. The observations indicate a high level of agreement between water identified in the satellite images and water observed on the ground.

The final raster flood extent files were overlayed on the LiDAR topography map. Next, the 3D analyst extension to ARCGIS 9.3 was used to intersect the rasterised flood extents with the LiDAR topography layer to determine the surface area (i.e. the area of inundated cells) and the volume (i.e. the area of each inundated cell times the depth of each inundated cell) of each flood event. This enabled a highly accurate determination of both the surface area and volume inundated within the Northern and Narran Lake complexes. The volumes determined were then coupled with discharge, evaporation and transmission loss data to ascertain the volume of water lost to the soil during each flood event since 1981. This involved a comparison of the total input discharge at Wilby Wilby (45 km upstream from the Narran Lakes ecosystem), less a standard loss parameter to account for transmission losses between Wilby Wilby and the Narran Lakes ecosystem (determined by comparing the loss in discharge per unit distance for a series of three stream gauges on the Narran River) and less an evaporation component (assessed as the surface area times the evaporation depth per day over the length of the event), to that which was observed as standing water in the Narran Lakes ecosystem at the time of image acquisition. Although there was considerable variability due to antecedent conditions, time of year and the overall size of the flood (and hence which areas were inundated), a mean value for overall soil moisture loss was determined (range: 300–1,100 $\mathrm{L\,m^{-2}}$; mean: 624 $\mathrm{L\,m^{-2}}$). This result was compared to anecdotal data provided by agricultural land holders, who observed comparable soil losses on their properties.

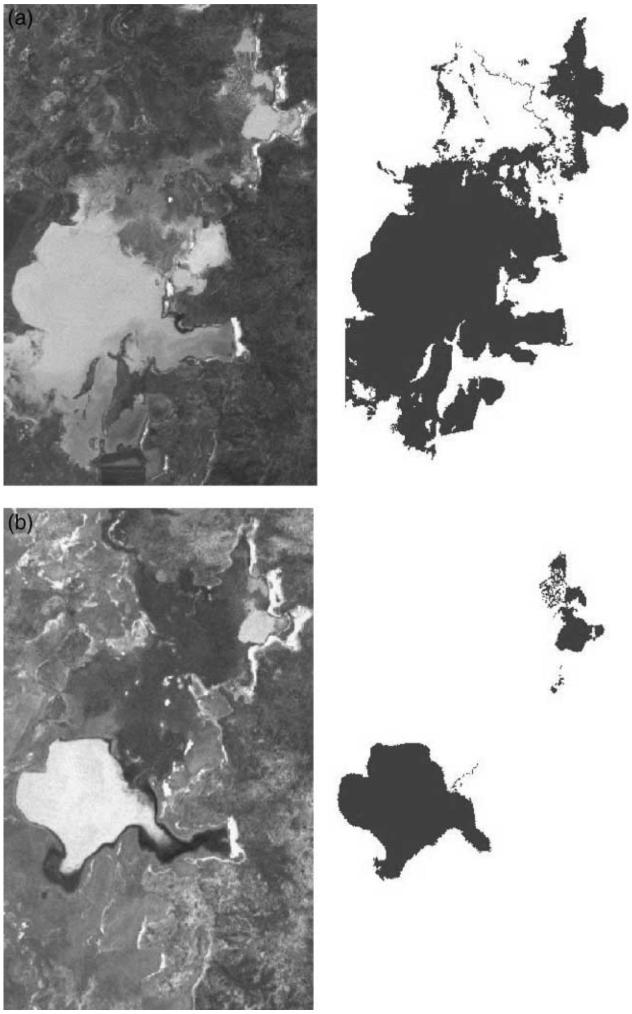

Figure 2 | Examples of the extraction of inundated extents from Landsat imagery for (a) 28 August 1983 and (b) 20 April 1991.

The flood extents determined from the satellite imagery provided the calibration and validation datasets used in both the hydraulic and hydrologic modelling phases of this project. These ‘known’ flood extents were compared to those produced by each model, to verify model performance with respect to predicting the quantity, distribution and residence time of water in both lake complexes.

MODELLING APPROACH

A hydraulic–hydrologic modelling approach was employed to develop a water balance model that could be used to reconstruct the inundation history of the Narran Lakes ecosystem and predict the impacts of natural and anthropogenic changes on hydrology (timing, frequency and duration of inundation). Given the paucity of existing data on the nature of flow, the history of inundation and even the sizes of the lakes within the Narran Lakes ecosystem, a hydraulic modelling approach was deemed a necessary first step to developing a water balance model for the system.

The hydraulic model provides two critical datasets: first, it elucidates the flow pathways by which water moves across the landscape; and second, it provides a quantitative accounting of the proportion of water that travels down each pathway in response to variable input flows. These data provide the core of the hydrologic model in that they define the quantity of water that travels to each lake in response to a given flood event. Although the hydraulic model provides invaluable information on flow pathways and can be used to predict the extent and duration of inundation, it is computationally intensive, with a single years' worth of data requiring 6–7 weeks of model run time. In comparison, the hydrologic model is computationally simple and capable of running more than 100 years of flow data in several minutes. Thus, this model can more easily be used to reconstruct the timing, magnitude and duration of flooding in the Narran Lakes ecosystem (for the period since the beginning of gauge data collection along the river in 1964). In addition, it can be used as a tool to model a variety of flow scenarios in order to ascertain how climate change and water resource development will have an impact on future inundation patterns within the system.

Hydraulic model

The hydraulic model for the Narran Lakes ecosystem was constructed within a commercially available software package, MIKE21, created by the Danish Hydraulics Institute (DHI). The MIKE family of products has a long history and MIKE21 has been widely applied within both scientific and environmental consulting communities to address a range of hydraulic modelling, assessment and/or prediction issues (e.g. Somes *et al.* 1999; Yuanita & Tingsanchali 2008). MIKE21 is a two-dimensional depth-averaged hydraulic model that solves the Reynolds-averaged Navier–Stokes equations. A more detailed description of the equations and components of the MIKE21 model can be obtained from the MIKE21 user guide (DHI 1996). MIKE21 employs one of two simulation options: (1) an unstructured mesh which uses a cell-centred finite-volume solution and (2) a rectilinear model which uses finite differencing techniques to achieve a solution. For the purposes of this study, the latter approach was employed.

The inputs into the MIKE21 model for the Narran Lakes ecosystem occupy four distinct categories:

- domain and time parameters,
- initial conditions,
- boundary conditions,
- calibration factors.

Domain and time parameters refer to two types of data—bathymetric data, and the simulation length and time step. The bathymetry for the model was derived from the LiDAR dataset. In its original form, this dataset was too detailed for the model, generating model run times of the order of one model-day per actual-day. To reduce the run times it was necessary to reduce the resolution of the bathymetry layer. Several resolutions were attempted and a final resolution was selected according to the competing ideals of minimum run times and the preservation of all potential flow pathways within the system. The optimal spatial resolution of the bathymetry layer was 25 m, which maintained all of the important topography within the system while improving run times to approximately eight model-days per actual-day. Thus, the model was composed of a rectilinear finite element grid with grid elements having a spatial resolution of 25 m. The final mesh had dimensions of 1,024 cells in the N–S direction and 680 cells in the E–W direction, resulting in a final mesh comprising 696,320 individual elements.

The second component within this first input category is the simulation length and time step. These parameters have significant impacts on both the length of modelling runs and the overall stability of the model. The simulation length selected for this modelling exercise (after the calibration and validation runs were completed) coincided with the largest recorded flood in the Narran Lakes ecosystem since 1964. This flood (in 1983–4) was exceptionally large and had three distinct flood peaks separated by several weeks to months of minimal or no flow. To minimise run times, all intervening periods of minimal or no flow were removed, thereby producing a flood of reduced duration, but with realistic peak flow levels and rise and fall times. Even with the reduced simulation length, the final model run took more than 4 months to complete. The second time parameter to be set is the time step. The time step and the resolution of the bathymetry layer, along with the velocity of flow, determine the Courant number which is a condition for convergence while solving certain partial differential equations numerically. The Courant number, therefore, should be near or below 1 for the model to run successfully (i.e. attain convergence). Thus, the spatial resolution of the bathymetry layer determines the ideal time step. This was set at 8 s for the present study, yielding a maximum Courant number of 1.0007.

The initial conditions category for a MIKE21 model includes an initial water surface level and an initial x and y component of velocity. Given that the Narran Lakes ecosystem dries periodically and was dry prior to each model run, both of these parameters were set to 0. Thus, the initial model condition is a dry basin and the movement of water into and through the system can be predicted as each modelled flood progresses.

The boundary conditions category for a MIKE21 model includes the water level and/or discharge. These two parameters are tied and either one can be used to route flow into the system. The input flows included in the present study were derived from the flow gauge at Wilby Wilby, approximately 45 km upstream of the Narran Lakes ecosystem, corrected for transmission losses as previously described.

The 2004 flood event was used to calibrate the hydraulic model. This event lasted approximately 3 months, with a total discharge of approximately 45,000 ML, which is a small flood within the Narran Lakes ecosystem. The short duration of the event enabled multiple model runs to proceed over a relatively short period of time, thus facilitating the calibration of several input parameters. The most important of these were eddy viscosity and bed resistance, for which both single-value and spatially variable models were trialed. The bed resistance is given by the Manning equation and can be either constant or spatially variable. Given that the primary output for this modelling exercise is relative discharge past particular points of interest, it was not necessary to generate an accurate determination of velocity within the Narran Lakes ecosystem. In addition, velocity was not verifiable due to a lack of available data. Although a number of Manning's n values (both constant and spatially variable) were trialed, a constant value of Manning's n was used (0.05), which produced a stable model and predicted inundated areas commensurate with those observed on the remotely sensed imagery. In addition, a Manning's n value of 0.05 was deemed appropriate for this site in that this roughness value accounts for both natural channels with brush-covered banks and tall grass or shrub-covered hillslopes, two conditions that are common in the Narran Lakes ecosystem. The second calibration parameter, the eddy viscosity, can be based on either flux or velocity formulations. The velocity-based formulation is more accurate, but can create instabilities in the model. However, because the accuracy of the eddy viscosity term was deemed sufficiently important (see Wu & Tsanis 1994), a velocity-based formulation was adopted in the present study. A constant value for eddy viscosity was chosen, based on early calibration and validation model runs that showed close agreement between the observed and predicted distributions of water within the Narran Lakes ecosystem.

Once the hydraulic model input parameters were finalised, the model was validated using the 1994 flood event, which lasted approximately 126 d, had a total discharge of approximately 145,000 ML (approximately equal to the mean annual discharge) and inundated both the Northern and Narran Lake complexes. This event was considered to be a medium-sized flood. The validation results showed close agreement between the predicted and observed inundated areas for both principal lake systems (± 5–10%).

For both calibration and validation purposes, the model was calibrated against satellite-derived surface areas. Several images were available for each event, which enabled the timing and extent of the initial flood and subsequent redistribution of water within the system to be verified. It should be noted that the modelled flow velocities were consistent with limited field observations during the 2004 flood event, with velocity measurements from the Narran River stream gauges and with anecdotal evidence. Thus, although a complete velocity-based calibration and validation process was impossible due to the paucity of velocity data, the velocities modelled here were physically possible and realistic, and yielded flood extents consistent with the multi-temporal satellite flood extents used to calibrate and validate the model (ranging from −7% to

+9% for the Narran Lake and −5% to +6% for the Northern Lake).

Once calibrated and validated, the hydraulic model was used to simulate a single large event of sufficient magnitude and duration to activate all possible flow pathways within the Narran Lakes ecosystem. Thus, the simulation event both identified the flow pathways and provided a mechanism for quantifying the relationships between input flows and flows along each primary, secondary and tertiary flow path (Figure 3(a)). In total 28 locations (pathways by which water moves across the floodplain and through channels) were extracted from the hydraulic model for further analysis and these defined all the major and minor pathways of flow through the system. Each of these hydraulic control points (or major or minor flow pathways) is represented by a solid black line in Figure 3(b).

An example of how the relationship between input flows and the flow down a major flow pathway is derived is provided in Figure 4. This illustrates one of the more important flow pathways; the main pathway by which water is routed into the Northern Lake complex which is designated as line 1 (out of the total of 28 lines or flow pathways). Figure 4(a) illustrates the hydrograph for the inflows into the Narran Lakes ecosystem as a whole and that which travels down this primary flow pathway. Importantly, this pathway has a maximum flow transport capacity (a threshold flow value of $10\,\mathrm{m^3\,s^{-1}}$) above which all additional flow volumes are routed down alternative flow pathways to the Narran Lake complex. This is evident in Figure 4(b) which plots the relationship between inflow discharge and the discharge past line 1. Using only the portion of the flow less than $10\,\mathrm{m^3\,s^{-1}}$ therefore, it is possible to develop a statistical relationship between inflows and flows past line 1 which represents the proportion of the inflow that moves down this primary flow pathway (Figure 4(c)). Alternative flow pathways into the Northern Lake complex are only triggered in the largest floods (i.e. those above $25\,\mathrm{m^3\,s^{-1}}$) and flows into the complex cease when the lake becomes fully inundated, at which point all water is diverted into the Narran Lake complex.

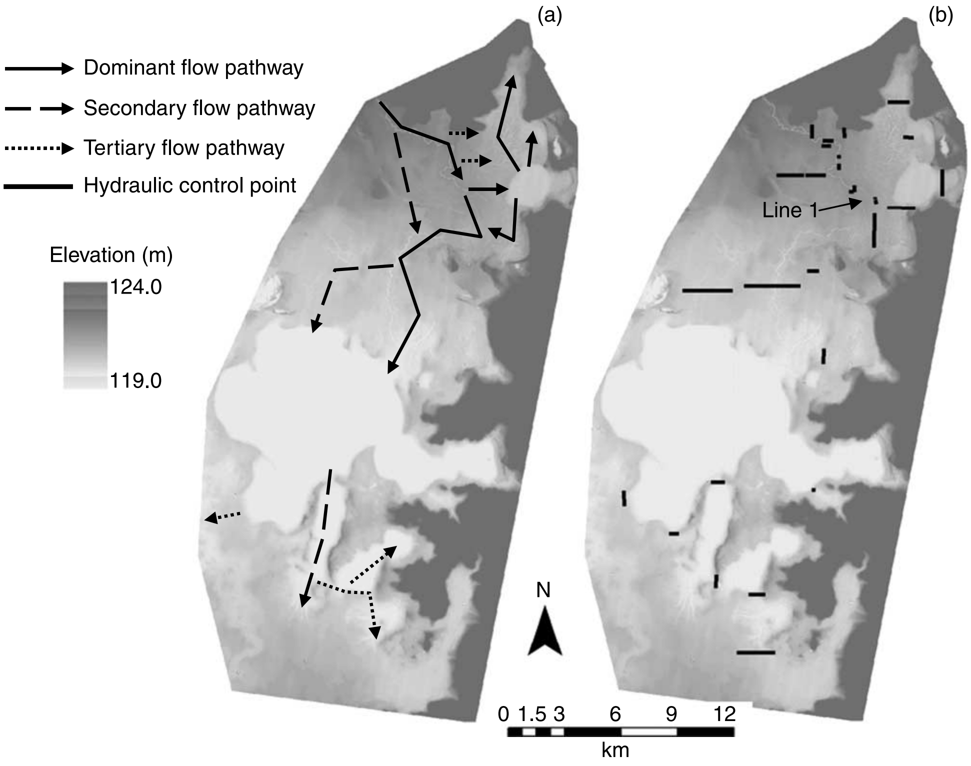

Figure 3 | Major and minor flow pathways in the Narran Lakes ecosystem (a) and the locations of hydraulic model data extraction points (b). Note: line 1 represents the main off-take channel from the Narran River to the Northern Lake complex and is used as a reference point for Figure 4.

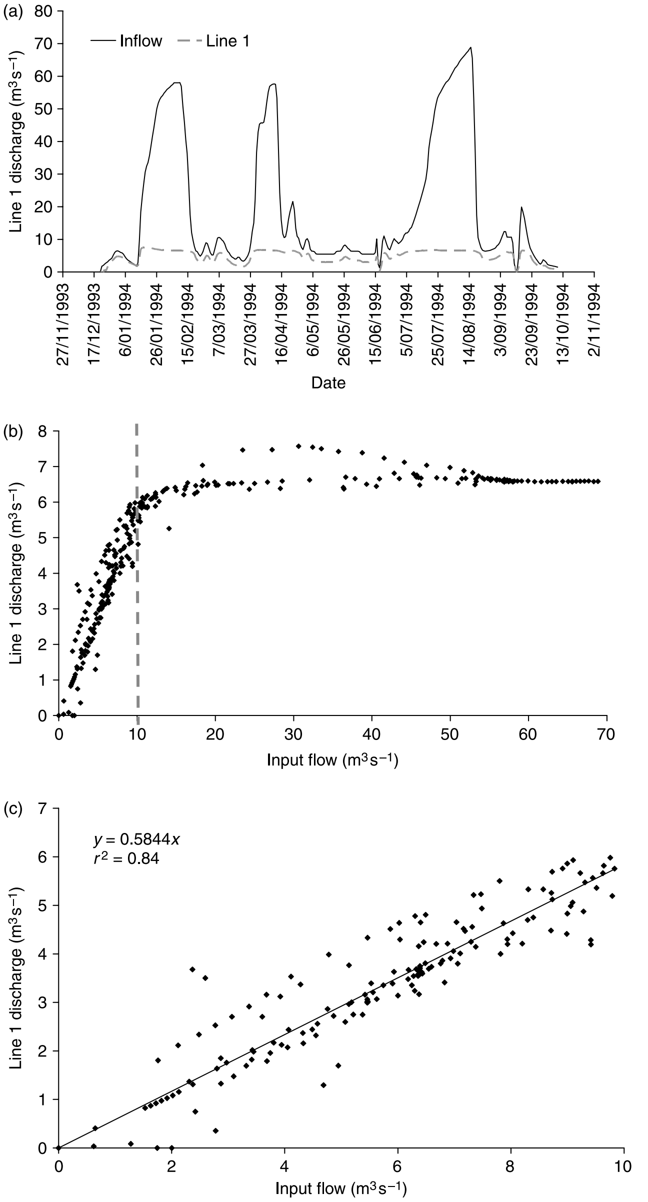

Figure 4 | The method employed to extract hydraulic data from the MIKE21 hydraulic model for use in the hydrologic model. (a) Input flows at the top end of the Narran Lakes ecosystem and flows at Line 1, the major inflow to the Northern Lake complex; (b) the relationship between input flow magnitudes and flow magnitudes at Line 1, showing the cutoff point for maximum flow through Line 1; (c) the relationship between input flows and flows at Line 1 for the linear portion of the relationship only. The regression equation developed here suggests that roughly 58% of the input flow (up to $10\,\mathrm{m}^3\,\mathrm{s}^{-1}$) flows past Line 1.

Hydrologic (water balance) model

The water balance for a lake or wetland can be written as

$$\frac{\mathrm{d}V}{\mathrm{d}t} = (Q(t) - T(t) - I(t) + P(t) - E(t)) \quad (1)$$

where V is the volume of the lake, t is time, Q is inflow discharge, T is transmission loss, I is infiltration into the lake bed, P is precipitation and E is evaporation. The water balance for the Narran Lakes ecosystem includes all of these major parameters, with the two storages, the Northern Lake complex and Narran Lake complex, being modelled independently, but with linked flow inputs. The water balance model is a daily time-step model with inputs and outputs computed on a daily basis.

The linked water balance model for the Narran Lakes ecosystem may be computed in the following iterative fashion:

(1) The transmission-loss-adjusted inflow discharge from Wilby Wilby is routed into the top end of the Narran Lakes ecosystem.
(2) A check is made of the input flow level against threshold values for each of the flow pathways into the system.
(3) For any pathway on which the commence to flow level has been exceeded, the proportion of the input flow that travels down the pathway is determined from the relationships defined by the hydraulic model (refer to Figure 4 for an example of this procedure).
(4) The total flow input into Northern Lake (via all functioning flow pathways) is determined. (Note: the flows into the Northern Lake complex are determined first because once this lake fills it alters the amount of flow delivered to the Narran Lake complex).
(5) The input flows into the Northern Lake complex are adjusted for lake bed infiltration and internal transmission losses by subtracting a fixed volume of 250 ML (which amounts to in-channel infiltration) and an additional 12.5% (which accounts for overbank water losses) of the flow down each pathway.
(6) The running discharge (i.e. the cumulative discharge for a given flood event) is calculated based on the adjusted input flows.
(7) The volumetric daily loss/gain is computed as the rainfall (determined using a Thiessen polygon approach incorporating three surrounding rain gauges) minus evaporation (multiplied by a correction factor of 1.5 to account for transpiration as well as evaporation) multiplied by the surface area of standing water from the previous time step.

(8) The adjusted Northern Lake volume is determined by first querying the current standing water volume of the lake to see if it is full. If so, all additional flow inputs are routed to the Narran Lake complex. If not, the new volume of the lake is computed by taking the volume of the lake during the previous time step minus the loss/gain value plus the input discharge.

(9) The adjusted discharge is converted into a surface area based on the hypsometric curves for the Northern Lake complex.

(10) The flow to the Narran Lake complex is determined by subtracting the total input discharge at the top of the system from the (pre-adjusted) flow into the Northern Lake.

The flow input from Step 10 is then routed into the Narran Lake complex and a water balance is computed using Steps 5–9 with one exception; rather than removing water from the input flows to account for lake-bed infiltration and internal transmission losses (Step 5) a standard loss of 1,100 $\mathrm{L\,m^{-2}}$ is applied to this complex. Although this value is at the top of the range defined for lake-bed infiltration, it captures both lake-bed infiltration and transmission losses. As a large proportion of the water that flows into the Narran Lake complex flows overland, rather than in channels, these combined losses are quite large.

The water balance model was calibrated and validated using the 50:50 method (Refsgaard 1997). One-half of the known flood extents (1981–92) were used to calibrate the model, while the remaining known flood extents (1993–2004) were used to validate the model (Figure 5). As mentioned above, although the Northern and Narran Lake models are linked, each lake has been modelled separately. Therefore, each lake complex has its own unique calibration and validation. For both lake complexes, there was a high level of agreement between the calibration and validation data, with the model outputs for the Northern and Narran Lake complexes (Figures 6(a, c)) reporting r^2 values of 0.87 and 0.88, respectively, for the actual to predicted surface area inundated when all known flood extents are considered.

When the full range of 78 remote-sensing-derived calibration and validation flood extents were considered against the modelled flood extents, the RMSE for the Northern Lake was 139 ha (or 4.6% of the full level), while the RMSE for the Narran Lake was only 156 ha (or 1.3% of the full level). Overall the modelled surface area for the Northern Lake was equal to the actual surface area 14 times, larger than the actual surface area 28 times and lower than the actual surface area 36 times, with the sum total of all 78 predicted surface areas (90,855 ha) 10.4% larger than the sum total of all actual surface areas (82,291 ha). Meanwhile, in the Narran Lake, the predicted surface areas were equal to,

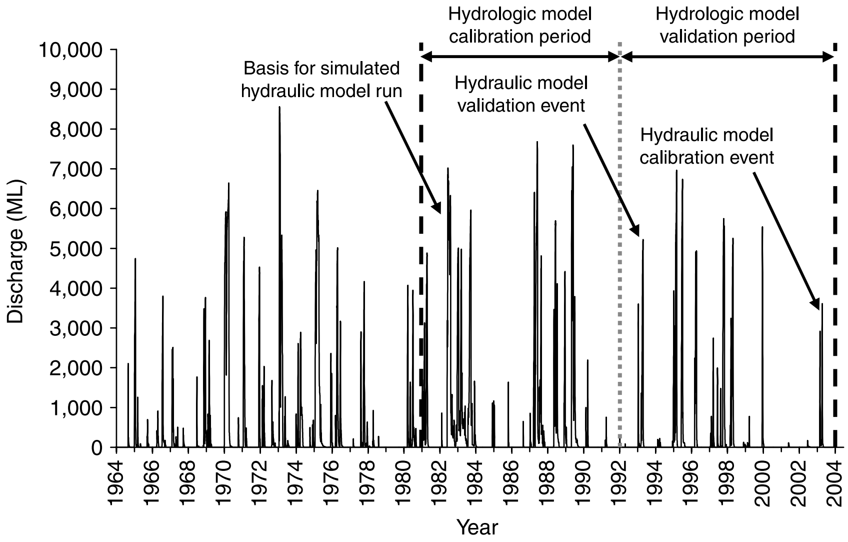

Figure 5 | Streamflow records at the Wilby Wilby gauge on the Narran River and the flood events used to calibrate and validate the hydraulic and hydrologic models.

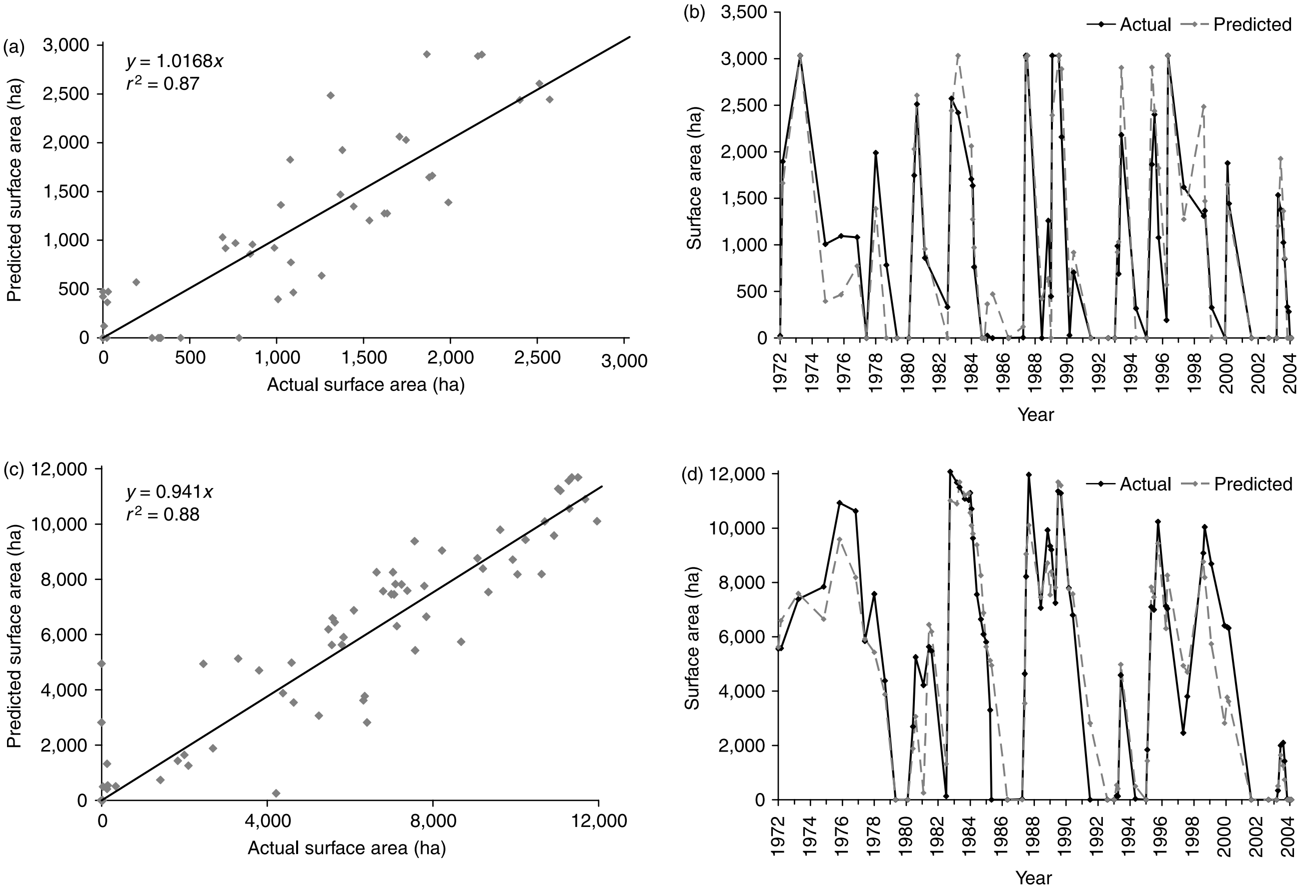

Figure 6 | Model evaluations for the predictive hydrologic (water balance) model of the Narran Lakes ecosystem. (a) Regression plot showing actual against predicted surface areas for the Northern Lake; (b) time series of actual against predicted surface areas for the Northern Lake; (c) regression plot showing actual against predicted surface areas for the Narran Lake; (d) time series of actual against predicted surface areas for the Narran Lake.

larger than and smaller than the actual surface area 25, 24 and 29 times, respectively, with the sum total of all 78 predicted surface areas (403,147 ha) 3.2% smaller than the sum total of all actual surface areas (416,570 ha).

The validity of the model outputs can be further examined through a consideration of the time series of predicted against actual inundated surface areas for both lake complexes (Figures 6(b, d)). These plots show a high degree of correlation between the actual and predicted flow levels, with all of the major and minor inundation and drying events being captured by the model. In addition, since there is no systematic error in the model (in that the actual inundation level exceeds the predicted level as often as the predicted exceeds the actual) it is clear that the model is not prone to either over- or under-prediction. Therefore, long-term predicted flow levels are highly correlated with those that actually occurred, and the total predicted and actual lake volumes for the period of record are very close (between 3% and 10%) for both lake complexes.

MODEL UNCERTAINTY

There are many potential sources of uncertainty within the water balance model that could account for the variability between the predicted and actual surface areas. Effectively, every input parameter within the model has a level of uncertainty associated with it, although some input parameters are significantly more uncertain than others. The highest levels of uncertainty are found within the infiltration and transmission loss parameters. Because there are no data available on these values within the Narran Lakes

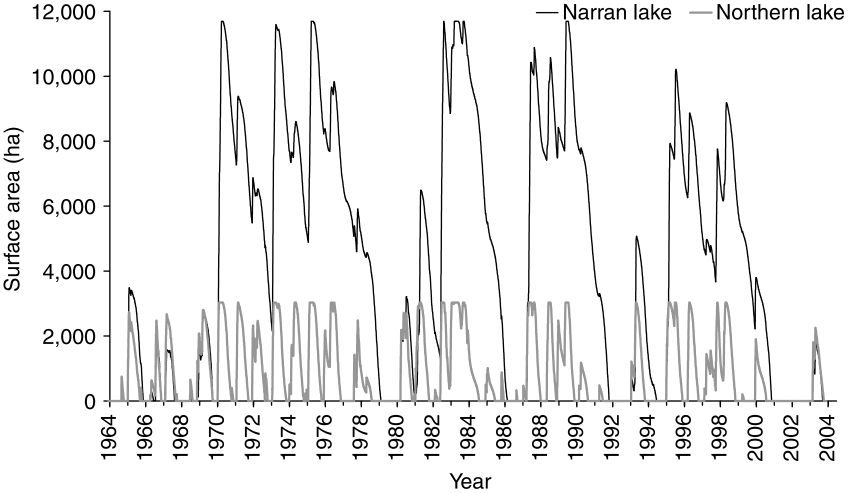

Figure 7 | Predicted surface area for Northern and Narran Lakes over the period for which discharge data are available from the Wilby Wilby gauge.

ecosystem, they are used largely as calibration factors, with their limits defined according to the previously described procedures.

The precipitation and evaporation data also have a degree of uncertainty, particularly with respect to the daily values occurring directly over the lakes. Although the data themselves are of high quality, the spatially variable nature of rainfall within this semi-arid environment means that the actual value over each lake could be considerably different (on a daily basis) than that derived from the Thiessen polygon approach. However, these errors will be mitigated over the longer term, as the average rainfall and evaporation over the area are relatively constant. Therefore, the overall impact on the model results will be negligible for the long term, but could be significant over the scale of several days to several weeks. An additional level of uncertainty applies to the evaporation data in the conversion of pan evaporation to open-water evaporation. As no evaporation data are available over the lake surfaces, this correction is based on standard Australian Bureau of Meteorology data and, therefore, may also be inaccurate over short timescales.

The input flows to the system are another potential source of error, particularly during the largest flood events. Although the Wilby Wilby gauge is considered to have good quality data, some of the water in the Narran River flows overland during the largest flood events and is beyond the extent of the rating curve for the Wilby Wilby gauge. Therefore, the gauge discharges recorded during these events do not necessarily represent the total discharges potentially entering the Narran Lakes ecosystem.

Finally, a small degree of error is also possible in the actual flood extents, as derived by the satellite imagery. Although the band 5 density slice technique is an established method of determining the inundated extents of wetlands as measured by Landsat imagery, and field observations were conducted to verify several flood extents in 2004, there is still the possibility of misclassifying wet soils as inundated soils using this technique. In addition, the inundation that occurs from secondary flood peaks can often be obscured by the tremendous vegetative response to inundation that occurs within the Narran Lakes ecosystem. Thus, there is the possibility of error within the input and the calibration data for the water balance model.

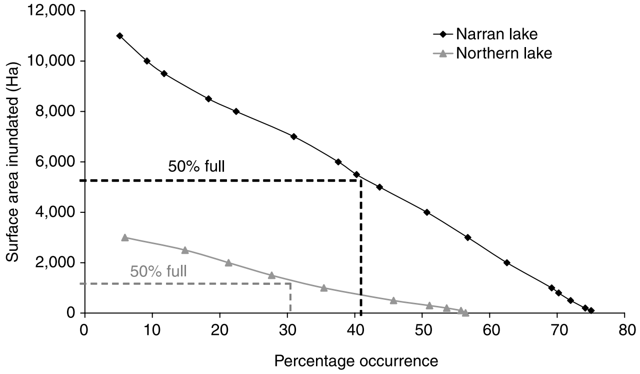

Figure 8 | Inundation–duration curves for the Northern and Narran Lakes derived from modelled surface areas from 1964–2004.

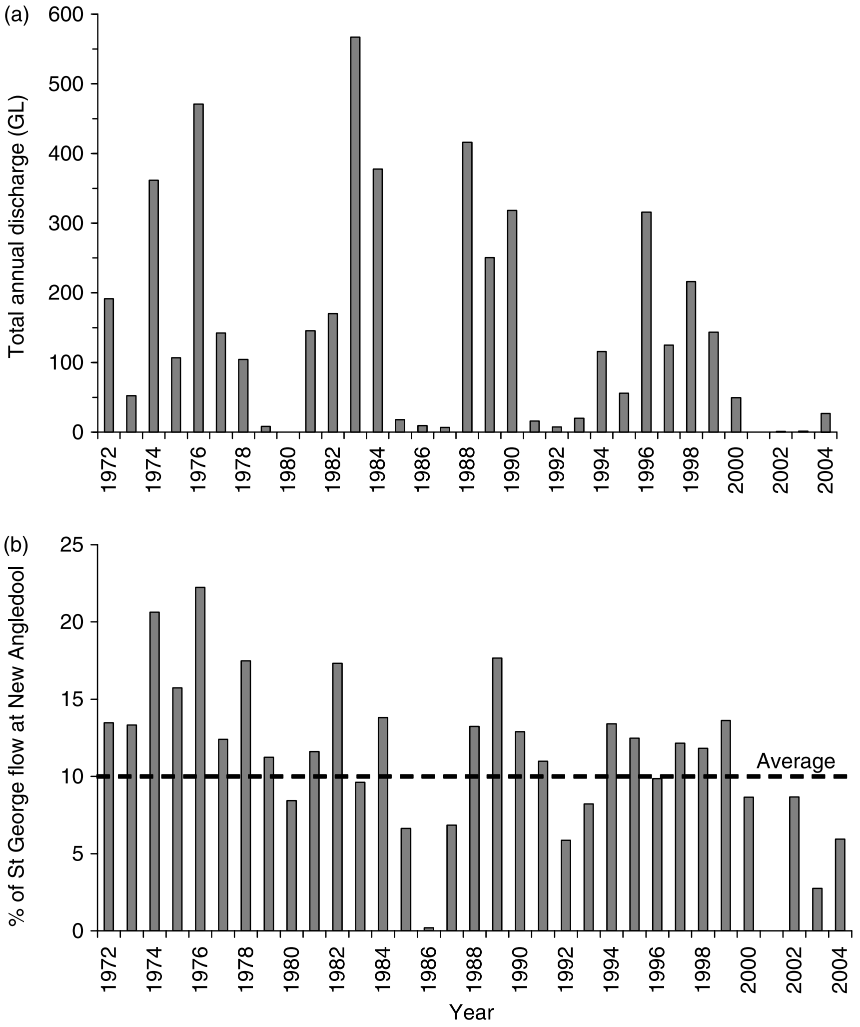

Figure 9 | Annual flows at the Wilby Wilby gauge for the period from 1972 to 2004 (a) and the proportion of flow past the St George gauge that reached the Narran River (b).

Despite these numerous sources of error, the close correlation found in the present study between the actual and predicted inundated areas indicates that the model is robust and capable of predicting inundation within the Narran Lakes ecosystem with a high degree of accuracy.

MODEL OUTCOMES AND MANAGEMENT PERSPECTIVES

The output of the water balance model is a reconstruction of the flood inundation history of the Narran Lakes ecosystem from 1964–2004 (Figure 7). From these results, an inundation–duration curve for each lake system was produced (Figure 8). These results show that both lake systems have some water in them more than 50% of the time, and the Narran Lake system is wet more than 70% of the time. In addition, there is a significant amount of water within each lake (>50% full) 31% and 41% of the time for the Northern and Narran Lake systems, respectively.

The number of unique inundation events is much higher in the Northern Lake system as a consequence of its smaller size and subsequent shorter residence times for water. In most cases, the Northern Lake system is wet for less than one year at a time. The Narran Lake system, however, retains water for very long periods of time, so that the frequent top-up events maintain the water level within the lake system for many consecutive years. For example, the Narran Lake system retained water for a 9-year period between 1970 and 1979 (supported by eight flood events), while the Northern Lake system had eight unique wetting and drying phases during this same period. Historically, periods where both lakes were devoid of water have been infrequent and of short duration. However, in recent years (2000 to the present) the lakes have both undergone significant dry periods. The last Northern Lake filling event occurred in 1999 and the last Narran Lake filling event occurred in 1991. These are the longest intervals between filling events over the period of record.

There are two possible causes for the recent declines in lake filling events in the Narran Lakes ecosystem. The first is drought. Recent inflows (post-2000) into the Narran Lakes ecosystem have been quite low (i.e. less than $50\,\mathrm{GL\,yr^{-1}}$) (Figure 9(a)). This may be caused by a reduction in the amount of runoff being generated from within the Condamine–Balonne Catchment. Indeed, there has been a persistent and ongoing drought in the region over the last several years. However, the proportion of the water received at St George (upstream of the bifurcation of the Condamine River into four river channels) that subsequently reaches the Narran River has declined. The level is now typically below the long-term average, since the onset of major water resource development in the area post-1992 (i.e. below average in 8 out of 13 years since 1992 as opposed to 4 out of 20 years prior to 1992) (Figure 9(b)). Consequently, it can be inferred that both climatic and human impacts are currently affecting flows into the Narran Lakes ecosystem, and consequently the magnitude, frequency and duration of inundation of the two principal lakes within the system.

The model presented here has the potential to provide evidence for possible impacts of climate and/or land use change and water resource development on future inundations in the Narran Lakes ecosystem. Therefore, it can be used to inform management decisions as to the volume and timing of water extractions from the Narran River. In addition, knowledge of the past, current and potential pattern of inundation within the Narran Lakes ecosystem can be used to define and establish links between wetting and drying, and ecological responses within the system. Such knowledge will be vital to ensure the long-term viability of the Narran Lakes ecosystem as ecological refuges by maintaining minimum environmental flow requirements in the face of an uncertain climatic regime and an ever-increasing demand for water resources.

CONCLUSIONS

Hydrologic models can be important water resource management tools in semi-arid lakes and wetlands, as they can help to predict the impacts of climate and land use change, and water resource development, on the magnitude, frequency and duration of inundation. However, in data-poor environments or complex systems (containing multiple storages and or many potential flow pathways) an incomplete knowledge of the hydrology of these systems can lead to inadequate models that fail to capture the true nature of inundation within the wetland.

This study presents a new method for developing a predictive water balance model in a complex semi-arid wetland. It incorporates a coupled hydraulic–hydrologic model with remotely sensed imagery to overcome the challenges associated with the morphologic complexity of the wetland and hydrologic data scarcity. The coupled hydraulic–hydrologic model uses the strengths of the hydraulic model to identify important flow pathways, and the trigger flows and proportion of input flows that travel down each pathway as a result of variable flow inputs. These data are used as key inputs into the hydrologic (water balance) model that routes flows through the complex system according to these hydraulic controls, while simultaneously dealing with storage volumes and water losses throughout the system.

Both models are shown to be successfully calibrated and validated through the use of a series of satellite images taken before and after each inundation event over a period of more than 25 years. The overall accuracy of the model is very high, generating RMSE of less than 5% (of full volume) for the system as a whole, and predicted against actual surface areas within 10% (and with $r^2 > 0.9$) over the same time period. Model results show that the Narran Lakes ecosystem has been wet more than 70% of the time between 1964 and 2004, but that recently the frequency and duration of inundation are at 'period of record' lows. This record dryness can be attributed to a combination of natural (prevailing drought conditions) and human-made (increasing water resource development) influences. The ability to place current water levels within a historical context and to identify potential drivers of these water levels means that this model will be useful for water resource managers.

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REFERENCES

Arnold, J., Allen, P. & Morgan, D. 2001 Hydrological model for design and constructed wetlands. *Wetlands* **23**(2), 167–178.
Campo, L., Caparrini, F. & Castelli, F. 2006 Use of multi-platform, multi-temporal remote-sensing data for calibration of a distributed hydrological model: an application in the Arno basin, Italy. *Hydrol. Process.* **20**, 2693–2712.
Crapper, P., Fleming, P. & Kalma, J. 1996 Prediction of lake levels using water balance models. *Environ. Softw.* **11**(4), 251–258.
Danish Hydraulics Institute (DHI) 1996 *MIKE21 User Guide and Reference Manual*. DHI, Horsholm, Denmark.
Frazier, P. & Page, K. 2000 Water body detection and delineation with Landsat TM data. *Photogramm. Eng. Remote Sensing* **66**(12), 1461–1467.
Frazier, P. & Page, K. 2006 The effect of river regulation on floodplain wetland inundation, Murrumbidgee River, Australia. *Mar. Freshwater Res.* **57**, 133–141.
Jacobson, G. & Schuett, A. 1979 Water levels, balance, and chemistry of Lake George, New South Wales. *BMR J. Aust. Geol. Geophys.* **4**, 25–32.
Jones, R., McMahon, T. & Bowler, J. 2001 Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c. 1840–1990). *J. Hydrol.* **246**, 159–180.
Kingsford, R., Curtin, A. & Porter, J. 1999 Water flows on Cooper Creek determine 'boom' and 'bust' periods for waterbirds. *Biol. Conserv.* **88**, 231–248.
Longley, P. A., Goodchild, M. F., Maguire, D. J. & Rhind, D. W. 2005 *Geographic Information Systems and Science*, 2nd edition. Wiley, Chichester.
Overton, I. 2005 Modelling floodplain inundation on a regulated river: integrating GIS, remote sensing and hydrological models. *River Res. Appl.* **21**, 991–1001.
Pietroniro, A., Prowse, T. & Peters, D. 1999 Hydrologic assessment of an inland freshwater delta using multi-temporal satellite remote sensing. *Hydrol. Process.* **13**, 2483–2498.
Rayburg, S., Thoms, M. & Neave, M. 2009 A comparison of digital elevation models generated from different data sources. *Geomorphology* **106**, 261–270.
Refsgaard, J. 1997 Parametrisation, calibration and validation of distributed hydrological models. *J. Hydrol.* **198**, 69–97.
Sene, K. 1998 Effect of variations in net basin supply on lake levels and outflows. *Hydrol. Process.* **12**, 559–573.
Shaikh, M., Green, D. & Cross, H. 2001 A remote sensing approach to determine environmental flows for wetlands of the Lower Darling River, New South Wales, Australia. *Int. J. Remote Sensing* **22**(9), 1737–1751.
Somes, N., Bishop, W. & Wong, T. 1999 Numerical simulation of wetland hydrodynamics. *Environ. Int.* **25**(6/7), 773–779.
Stafford Smith, D. & Morton, S. 1990 A framework for the ecology of arid Australia. *J. Arid Environ.* **18**(3), 255–278.
Thompson, J. 2004 Simulation of wetland water-level manipulation using coupled hydrological/hydraulic modelling. *Phys. Geogr.* **25**(1), 39–67.
Thoms, M. 2003 Floodplain-river ecosystems: lateral connections and the implications of human interference. *Geomorphology* **56**, 335–350.
Thoms, M. & Parsons, M. 2003 Identifying spatial and temporal patterns in the hydrological character of the Condamine-Balonne River, Australia, using multivariate statistics. *River Res. Appl.* **19**, 443–457.
Thoms, M. & Sheldon, F. 2002 An ecosystems approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology. *Geomorphology* **47**, 153–168.
Todhunter, P. & Rundquist, B. 2004 Terminal lake flooding and wetland expansion in Nelson County, North Dakota. *Phys. Geogr.* **25**(1), 68–85.
Townsend, P. & Walsh, S. 1998 Modelling floodplain inundation using an integrated GIS with radar and optical remote sensing. *Geomorphology* **21**, 295–312.
Wu, J. & Tsanis, I. K. 1994 Pollutant transport and residence time in a distorted scale model and numerical model. *J. Hydaulic. Res.* **34**, 583–598.
Yin, X. & Nicholson, S. 1998 The water balance of Lake Victoria. *Hydrol. Sci. J.* **43**(5), 789–811.
Yuanita, N. & Tingsanchali, T. 2008 Development of a river delta: a case study of Cimarut river mouth, Indonesia. *Hydrol. Process.* **22**, 3785–3801.

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