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Hydraulic Modelling of the spatio-temporal flood inundation patterns of the Koondrook Perricoota Forest Wetlands - The Living Murray

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Abstract: Hydraulic modeling of the Koondrook Perricoota Forest (KPF) wetlands adjoining the River Murray in southeastern Australia was performed for historical flooding conditions using MIKE FLOOD in three stages progressively moving from simple to more complex forms. Validation data sets for model implementation were prepared from remote sensing study, field work, mapping of the inundation area from airborne surveys, reconnaissance surveys and local knowledge. Knowledge of the KPF flood inundation processes was improved in each stage to better formulate more complex model forms. It was considered mandatory to commence simulations with simple model forms using MIKE 11 (quasi-2D) and then conduct targeted simulations using MIKE 21 (2D) and MIKE FLOOD (combined 1D flow in the runners and 2D flow in the floodplain). On the basis of results from MIKE 11, MIKE 21 and MIKE FLOOD models, it is concluded that up to flow of about 28000 ML/d, all three hydraulic models provide similar estimates of the inundation area in the range 0-10%. As flow increases further, results from the models tend to differ. Relationships between complexity of the hydraulic models and accuracy of the wetland inundation areas predicted by each model form under a range of hydrological conditions are developed and discussed. Results from complex hydraulic modeling were synthesised into simple and practical tools designed for use by water managers and for the application of basin-scale hydrological models incorporating the effects of environmental flow diversions in large wetlands.

Keywords: *Wetlands, Runoff, MIKE 11, MIKE 21, MIKE FLOOD, Inundation*

1. INTRODUCTION

The Living Murray (TLM) initiative was established in 2002 by the Murray Darling Basin Ministerial Council in response to concerns about the environmental and economic health of the River Murray system (MDBC 2006). The six Icon sites that will benefit under the TLM initiative are: Barmah–Millewa Forest; Gunbower–Koondrook–Perricoota Forests; Hattah Lakes; Chowilla Floodplain and Lindsay–Wallpolla Islands; the Lower Lakes, Coorong and Murray Mouth; and the River Murray Channel. This paper deals with hydraulic modeling of the Koondrook–Perricoota Forest (KPF) to support development of the environmental watering plans and engineering design of the structural works at this Icon site. The study explores the relationship between river flow and inundation area for large wetlands, as determined from application of the MIKE suite of hydraulic models (DHI, 2007), and shows that these relationships are hysteretic (Tuteja et al., 2007). The proposed hysteretic inundation response model for large wetlands is consistent with Beven's (2006) suggestion of including the effects of hysteresis in the storage–outflow analysis. The proposed concepts for simplifying a complex hydraulic problem into a simple hydrological problem warrant consideration and can help environmental water managers in managing wetlands and environmental flow. This work has formed the basis of ~$40M worth of investment under the Living Murray initiative for supporting design of the structural works for diverting environment flow into the KPF wetlands.

2. STUDY AREA

The study was carried out for the Koondrook Perricoota Forest (337 km^2) located north of the River Murray floodplain in south-eastern Australia, between Torrumbarry Weir to the east and Barham to the west (Figure 1). In the north, on the right bank of the Murray, there are eight inlet locations where water can naturally enter the KPF from the Murray. In the south, on the left bank of the Murray, there are five inlet locations where water can enter the Gunbower Forest when flow in the Murray exceeds 17000 ML/d. The KPF inlets are: Swan Lagoon upstream, Swan Lagoon downstream, Horseshoe Lagoon, Dead River Lagoon, Black Gate, Penny Royal, Upper Thule and Lower Thule. The Gunbower inlets are: Deep Creek, Broken Creek, Spur Creek, Barton Creek and Yarren Creek. Five outlets where water can potentially leave the KPF are: Barbers Outflow, Barbers Creek, Cow Creek, Calf Creek and Thule Creek. Thule Creek outflow is located on the northern boundary of the KPF, whereas the remaining outflow points are located towards the western boundary of the KPF. Typically, water enters the KPF and Gunbower from within the inlet cross-sections and not from the banks of the Murray directly onto the floodplain (Lindsay Johnson, pers. comm.). In general, the inlet runners (channelled flow paths) merge with the forest floodplain within ~50 to 300 m. Conveyance of the runners declines gradually, and water in excess of the runner capacity spills out into the KPF floodplain.

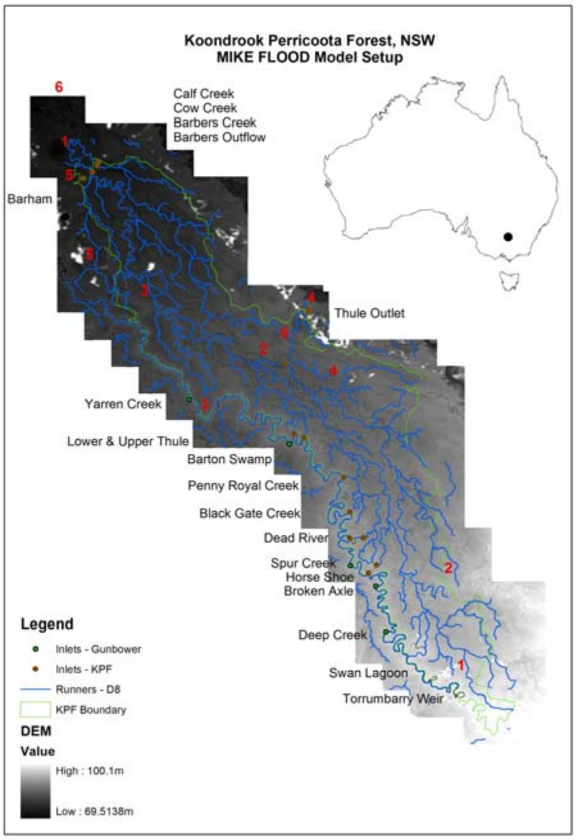

Figure 1. Location map and the KPF floodplain model developed from LiDAR DEM at 1 m grid cell resolution. Six runners (1–1 to 6–6) were used to define 809 runner cross-sections of 200 m width at an average spacing of 226 m, as well as eight KPF inlets and five KPF outlets.

3. MODELLING METHODOLOGY

To develop the KPF hydraulic model, the MIKE 11, MIKE 21 and MIKE FLOOD models were applied to three historical flood events (Figure 1). The MIKE FLOOD hydraulic model consists of three sub-models: MIKE 11, MIKE 21 and a coupling model that links MIKE 11 and MIKE 21 (see DHI, 2007 for details). MIKE 11 is based on one-dimensional solution of the Saint Venant equations along the channel whereas MIKE 21 solves two-dimensional form of the Saint Venant equations along the floodplain. The MIKE FLOOD model combines the strengths of 1D modelling using MIKE 11 for adequate representation of the channel conveyance and floodplain modelling using MIKE

21 to properly represent 2D effects in the out-of-bank flows. The model allows for dynamic exchange internally in both directions between the 1D channel and 2D floodplain flow components. Flow through the MIKE 11 domain into the MIKE 21 domain, and vice-versa, is via a lateral boundary that is applied to MIKE 21 via a source term. Flow through the link is dependent on a structure equation and the water levels in MIKE 11 and MIKE 21. Flow through the link is distributed among several MIKE 11 water level points and several MIKE 21 grid cells. Lateral links can be specified along the centre line, the left levee line or the right levee line of the MIKE 11 cross-sections.

Validation datasets for inundation areas were prepared by using remote sensing analysis of 12 Landsat Thematic Mapper (TM) images across the three historical events (1991, 1993 and 2000) and the mapped flood extents of the 1946 flood event. A coarse quasi 2D MIKE 11 model was initially implemented for preliminary assessment of the flood inundation processes. MIKE 21 was then implemented at a 40-m grid-cell resolution, and model simulations for each historical flooding event were performed with 10-s time steps. MIKE FLOOD, comprising this MIKE 21 model and a comprehensive MIKE 11 model, was also applied to the KPF.

Inundation areas simulated by MIKE 11, MIKE 21 and MIKE FLOOD models were compared with the results of remote sensing analysis and used to develop the inundation response of the KPF wetlands to variation of flow in the Murray. A hysteretic concept of the KPF floodplain inundation process was proposed and a simplified parametric form developed. Results from the KPF hydraulic modelling were synthesised to develop a relationship between storage in the wetland and outflow. These simplified and robust functional relationships in parametric form demonstrate that the floodplain inundation responses obtained by applying complex hydraulic models can be used to incorporate the effects of large wetlands into river basin hydrological models. These simplified parametric forms are currently being implemented in the Murray model BIGMOD/MSM.

4. MODEL SETUP AND IMPLEMENTATION

4.1 MIKE 11 (quasi-2D)

A coarse quasi-2D MIKE 11 floodplain model was setup for the KPF. This type of modelling involves 1D simulation of the water surface profiles using wide cross-sections aligned perpendicular to the direction of flow for representation of the floodplain geometry in MIKE 11. Simulated water levels at a given instance of time are draped over the DEM to produce inundation maps of the floodplain. The coarse quasi-2D MIKE 11 setup includes a combined reach length of about 82415m. A total of 100 geo-referenced cross-sections were used with an average reach length of 824m. Link channels were provided between runners to include the effects of flux transfer between the runners in either direction. Flood hydrographs for 1991, 1993 and 2000 events at each KPF inlet were used as the specified flux (inflow) boundary condition. At the downstream end of the outlets from KPF, a system dependent boundary condition was used by specifying the rating curve and the model estimates flux (outflow) depending on the dynamic water levels. Setting up of the coarse MIKE 11 model across large wetlands requires a moderate effort and simulation times tend to vary between 15 to 30 minutes.

4.2 MIKE 21 (2D)

MIKE 21 simulations were performed at 40-m grid cell resolution and 10-s time steps in order to constrain the Courant number to less than 1 and to keep simulation times within a practical range (5 to 15 days on an Intel Dual-Core PC with 2.13 GHz processor speed and 3.25 GB RAM). The Courant number represents how fast a fluid is travelling through the computational domain relative to the velocity of the fluid. See Tuteja et al. (2007) for a detailed discussion on numerical complexity and accuracy in hydraulic modelling of the wetlands. Two types of boundary conditions were used in setting up the MIKE 21 model. Each of the eight KPF inlets was treated as a point source (Figure 1), and simulated hydrographs at each inlet location, obtained from the MIKE 11 model for the Murray for 1991, 1993 and 2000, were used to describe the source terms (Tuteja et al., 2007). A constant head boundary condition was used at the western boundary (Barbers Creek outflow) and the northern boundary (Thule Creek outflow). The respective water levels maintained in the simulations were 73.2 m and 74.2 m. These were obtained from the representative elevations and conveyance at the respective outflow boundaries. A surface infiltration rate grid was prepared by using the soils map and the measured surface infiltration rates across the KPF. The potential evaporation rate was used to specify evaporation from the (dynamic) inundated areas within the model domain. A Manning’s n value of 0.05 was considered appropriate for the KPF floodplain modelling on the basis of sensitivity analysis and model calibrations (Tuteja et al., 2007).

4.3 MIKE FLOOD (combined 1D and 2D)

Coarsening of the DEM at 40 m resolution because of numerical constraints (Tuteja et al., 2007) results in substantial smearing of the runners; the conveyance of the runners in MIKE 21 is thus under-represented. There are parts of the KPF floodplain where, even under high flow conditions, water will be channelled into the runners and will likely move faster through the forest. This situation is not represented adequately in the MIKE 21 model, and it was therefore expected that the inundation areas simulated by MIKE 21 would be somewhat higher than those obtainable from a model that captures runner dynamics in addition to accounting for floodplain behaviour. The MIKE FLOOD model was implemented to overcome these limitations.

The MIKE 21 model used in MIKE FLOOD is the same as that developed at 40 m resolution. A comprehensive MIKE 11 model was developed at a fine resolution to capture inundation dynamics and flow exchange between the runners and the floodplain. A total of six runners delineated by the D8 terrain modeling method were used (Figure 1); 809 geo-referenced cross-sections up to 200 m width, described at 1-m intervals and with an average spacing of 226 m, were used in MIKE FLOOD. Critical cross section locations were included where there were substantial changes in cross-section geometry. The D8 method assigns flow directions from each grid cell to one of its eight neighbours, either adjacent or diagonally, in the direction with steepest downward slope.

In view of the very long simulation times with MIKE FLOOD (up to 50 days), only two historical events for 1991 and 1993 were simulated. The boundary conditions, spatially variable surface infiltration rate (temporally constant), temporally variable potential evaporation rate (spatially constant) from inundated areas and Manning's n used in the MIKE 21 component of the MIKE FLOOD model were exactly the same as those described in the MIKE 21 application. A Manning's n of 0.042 was used for all six runners in the MIKE 11 component of MIKE FLOOD.

All inflows at the KPF inlets in MIKE FLOOD were included as point sources in MIKE 21. The upstream end of each runner in MIKE 11 was specified with a zero-flow boundary condition. Runners 2, 3 and 5 connect with Runner 1 at the downstream end, which in turn connects with Runner 6 (Figure 1). Therefore, at the downstream end of Runners 4 and 6, a system-dependent boundary condition was used by specifying the rating curve; the model-estimated flux (outflow) depended on the dynamic water levels at the downstream boundary. In MIKE FLOOD, water is permitted to leave the model domain through the outflow boundary as channel flow (Runners 4 and 6) as well as overland flow from the northern boundary (Thule outflow) and western boundary (Barbers Creek outflow).

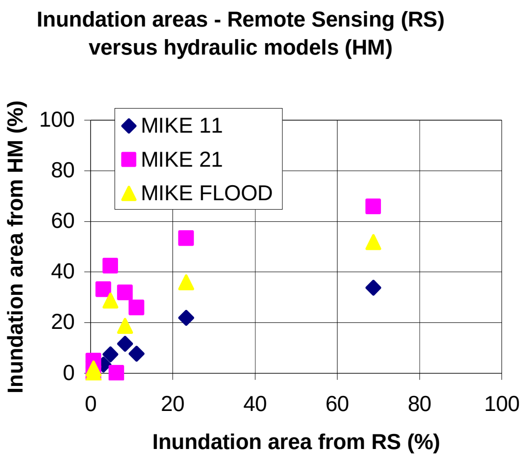

Figure 2. Comparison of inundation area estimates from hydraulic models and results from the remote sensing analysis.

Lateral links along the left and right banks of the MIKE 11 cross-sections were included for each runner throughout the reach length. A cell-to-cell method was used for flow exchange between each reach length described by the MIKE 11 cross-sections and the overlapped MIKE 21 grid cells. MIKE 11 cross-sections were derived from a 1-m DEM at an average spacing of 226 m. Therefore, MIKE FLOOD includes a good description of the runners and floodplain geometry through the use of lateral links between MIKE 11 and MIKE 21.

5. RESULTS AND DISCUSSION

5.1 Hydraulic modelling

Results of MIKE FLOOD simulations for the historical flood events of 1991 and 1993, along with the MIKE 11 and 21 results for the 1991, 1993 and 2000 events, are shown in Figures 2 and 3. Multiple lines of evidence were used to develop confidence in the results of the model. Simulated inflow volumes into the KPF compared very well with measured downstream flows in the Murray (Tuteja et al., 2007). Good agreement was obtained between the inundation-area estimates obtained from the remote sensing analysis (wetting/drying) and those from the reconnaissance survey data (Figures 2 & 3). All simulations showed that up to ~28000 ML/d flow in the Murray, the results from MIKE 21 closely matched those from the remote sensing analysis (Figure 3a). Thereafter, the results from MIKE 21 showed markedly higher inundation areas than those from the remote sensing analysis (Figure 3a; see Figure 3b–d for enhanced clarity of the remote sensing data for low flows). When flow in the Murray is 28000 ML/d, about 2000 ML/d flow enters the KPF through the inlets. Analysis of the variation of conveyance of the runners in the KPF showed significant variation among different parts of the KPF; up to 2000 to 2500 ML/d, flow was largely constrained in one dimension along the fringes of the runners in a north-west direction. Thereafter, the overland flow process became 2D, and transverse hydraulic gradients had a substantial impact on the inundation patterns (Figure 3b). The overland flow process and the inundation patterns for very high flow conditions in the Murray (greater than 50000 ML/d) were better represented in the fully 2D model (MIKE 21) than were the low to medium flow conditions (Figure 3a). However, MIKE 11 (quasi 2D) grossly underestimates the inundation areas at medium to high flows due mainly to imposition of the 1D solution on a 2D floodplain problem.

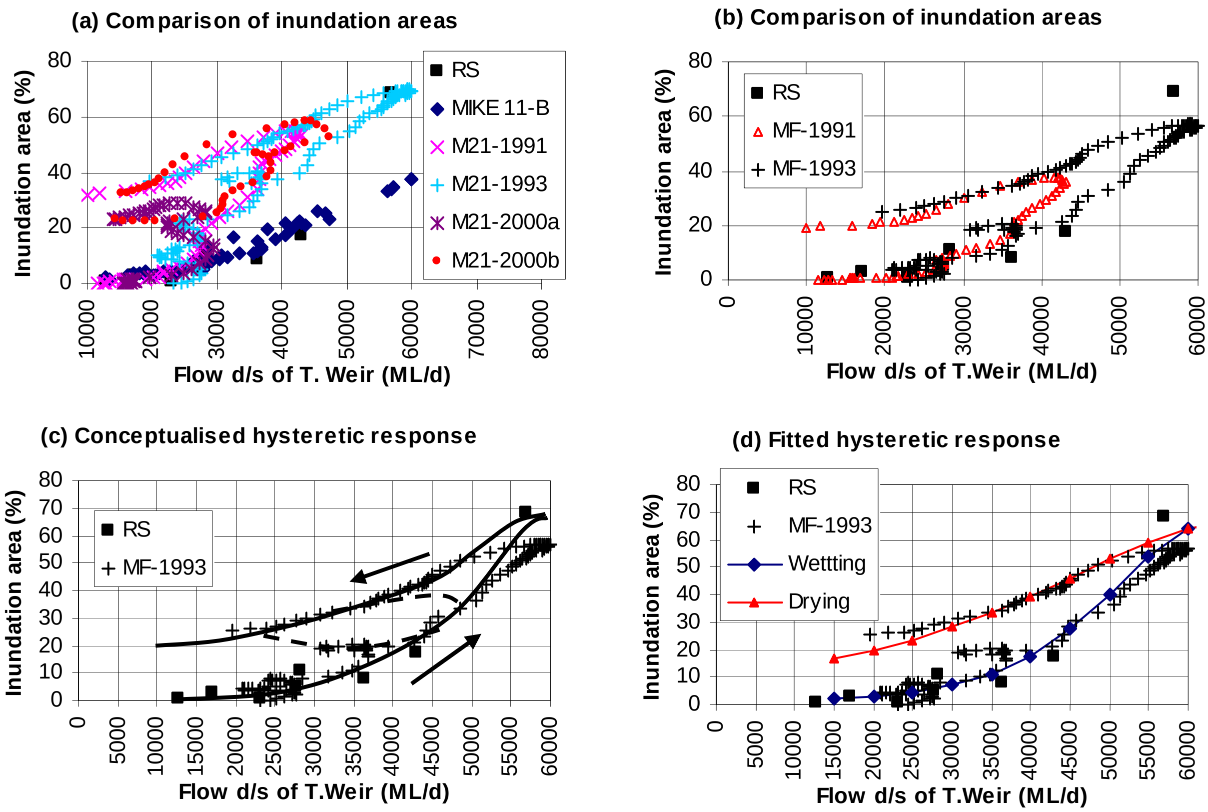

Figure 3. (a–b) Comparison of the inundation area estimates from remote sensing analysis (RS) with results from MIKE 21 (M21) and MIKE FLOOD (MF) hydraulic models (d/s: downstream; T.Weir: Torrumbarry Weir); (c) conceptualised hysteretic inundation response relationship between floodplain inundation area versus flow in the Murray; and (d) fitted parametric forms of the wetting and drying phases of the hysteretic KPF flood inundation response to variation of flow in the Murray.

The inundation area versus flow relationship simulated by MIKE FLOOD showed substantial reductions in the inundation area estimates in comparison with those simulated by MIKE 21 (Figure 3a–b). MIKE FLOOD simulations for the 1993 (1991) event showed a reduction of about 12.3% (17%) in the maximum inundation area of 69.3% (54.8%) simulated by MIKE 21. The numbers in the bracket indicate corresponding values for the 1991 event. The reduction in the inundation area estimate by MIKE FLOOD was the result of appropriate representation of the conveyance of the runners; this conveyance was not represented in MIKE 21. The 1991 flood event began on about 15 August, with a single peak, and the Landsat TM image for 4 October 1991 corresponded to a peak flow of 43055 ML/d. Comparison of the spatial inundation patterns on 4 October 1991 obtained by remote sensing analysis and by MIKE FLOOD revealed good agreement (see Figure 3b, corresponding to a flow of 36000 ML/d). During high flows (in excess of 50000 ML/d, a lot of debris from dead trees during high flow events constrains flow in the runners; therefore, the inundation process is biased towards 2D floodplain inundation as represented in MIKE 21. Flood inundation patterns from MIKE 21 compared better with those from remote sensing and the mapped 1946 flood event than did those from MIKE FLOOD (Figure 3a-b). The total inundation area of 65.9% during wetting phase estimated by MIKE 21 for 23 September 1993 also compared well with the 68.8% inundation area from the remote sensing study, as against the 51.9% simulated by MIKE FLOOD.

On the basis of these findings, the accuracy of the alternative hydraulic model forms and the associated numerical complexity represented by simulation times can be conceptualised as in Figure 4. The conceptualised relationships provide a good indication of the numerical costs associated with more complex hydraulic model forms and these need to be considered against the objectives of the floodplain modelling in large wetlands and the desirable levels of accuracy.

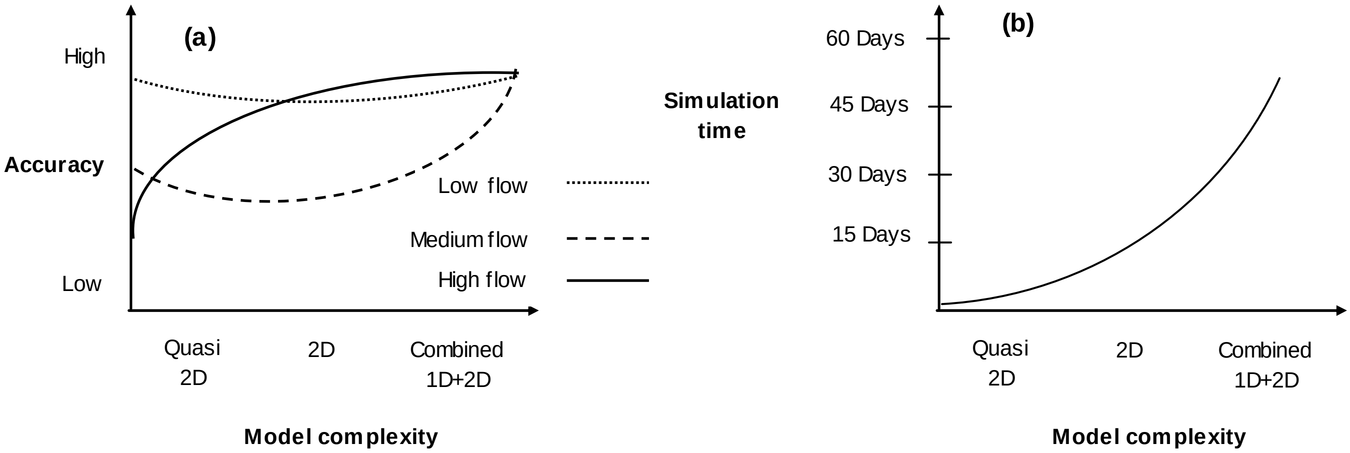

Figure 4. Conceptualised relationships between complexity of the floodplain model forms MIKE 11 (Quasi 2D), MIKE 21 (2D) and MIKE FLOOD (Combined 1D+2D) and accuracy of the simulated inundation areas (4a), and simulation times (4b). (Results from model implementations on a Intel (R) dual core ™ PC with 2.13 GHz processor speed and 3.25 GB RAM for study area of about 337 km^2)

5.2 Wetland inundation response

The hysteretic inundation response of the KPF can be expressed in a simplified parametric form, as described by equation 1:

$$A = \begin{cases} A_r + \dfrac{A_s - A_r}{\left[1 + \left(\alpha(Q_s - Q)\right)^n\right]^m} & Q < Q_s \\ A_s & Q \geq Q_s \end{cases} \quad (1)$$

where, A = (inundation area/total area) (m^2/m^2), Q = flow (ML/d), Q_s = upper bound of the KPF inflow (ML/d), A_r = residual inundation area fraction (m^2/m^2), A_s = saturated inundation area fraction (m^2/m^2), α, *n* and *m* are empirical parameters affecting the shape of the inundation response curve and $m = 1 - 1/n$.

Table 1. Parameters of the fitted KPF hysteretic inundation response curve.

	Wetting phase	Drying phase
A_r (m^2/m^2)	0	0
A_s (m^2/m^2)	0.7367	0.74168
α (d/ML)	0.00002	0.0000175
n (–)	7.78819	4.49187
Q_s (ML/d)	100000	100000
R^2	0.993	0.988

The form of the inundation response curve described by equation 1 is analogous to the van Genuchten (1980) equation used extensively in soil physics to describe the relationship between soil moisture and matric suction. The parameters in equation 1 were optimised for the wetting and drying phases of the conceptualised KPF inundation response in Figure 3c. The fitted parameters are shown in Table 1 and the fitted models are shown in Figure 3d. The fitted models compared very well with the inundation response curves simulated from the hydraulic models. R^2 values of 0.993 and 0.988 were obtained for the wetting and drying phases, respectively. Using the example of a complete hillslope hydrological unit as a representative elementary watershed (REW), Beven (2006) has argued the need to develop and include the effects of hysteresis in storage–outflow analysis. Beven suggested the use of primary drying and wetting curves connected with secondary scanning curves in the REW analysis. The proposed inundation response model in parametric form is consistent with the hypothesis proposed by Beven (2006). Implementation of the lumped conceptual model requires the storage-outflow relationship and estimate of the evaporation loss term, both of which can be obtained from this implementation under any hydrological flooding regime in the KPF.

6. CONCLUSIONS

On the basis of the results of application of the MIKE 11, MIKE 21 and MIKE FLOOD models and the remote sensing analysis, it was concluded that, up to a flow of about 28000 ML/d, all hydraulic models provided similar estimates of the inundation area in the range 0% to 10%. As flow increased further, the results from the models tend to differ. When implemented at 40 m resolution (the grid cell resolution adopted because of the significant computational overheads), MIKE 21 overestimated the inundation area because of lack of representation of the conveyance of the runners. MIKE FLOOD simulations for 1991 and 1993 events showed reductions of about 17% and 12.3%, respectively, in the respective maximum inundation areas of 54.8% and 69.3% simulated by MIKE 21. Up to 45000 ML/d flow and 45% inundation area, MIKE FLOOD provided better estimates of the inundation area and patterns by suitably accounting for conveyance of the runners and transition from a 1D runner-dominated flow process to a 2D floodplain process. Thereafter, high flows up to 70000 ML/d could potentially involve constraints in the runners due to debris and were better simulated by MIKE 21.

For the KPF a hysteretic inundation response model was proposed, comprising flow in the Murray versus percentage inundation area. The accuracy of the calibrated parametric form of the response model was about 99% (Figure 3c–d, equation 1). The proposed inundation response model consisted of primary wetting and drying curves that defined the lower and upper bounds of the wetland inundation. All possible wetland inundation processes dependent on hydrological conditions in the Murray could be defined by the secondary wetting and drying curves. The parametric form is robust and applicable to any wetland (especially Murray wetlands). If developed further and extended to other areas, this model could greatly assist water managers in assessing the ecological benefits of environmental watering of wetlands. These simplified parametric forms are currently being implemented in the Murray model BIGMOD/MSM.

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