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DISCONNECTING THE FLOODPLAIN: EARTHWORKS AND THEIR ECOLOGICAL EFFECT ON A DRYLAND FLOODPLAIN IN THE MURRAY–DARLING BASIN, AUSTRALIA

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ABSTRACT

Globally, dams and water extractions are well-recognised disruptors of flow regimes in floodplain wetlands, but little is known of the hydrological and ecological impacts of floodplain earthworks constructed for irrigation, flood mitigation and erosion control. We mapped the distribution of earthworks with high-resolution SPOT (Système Probatoire d'Observation de la Terre) imagery in an internationally recognised Ramsar wetland, the Macquarie Marshes of the Murray–Darling Basin, Australia. There were 339 km levees, 1648 km channels, 54 off-river storages and 664 tanks (0.5–5 m high), detected within the 4793 km^2 floodplain study area. Earthworks reduced localised flooding compared with undeveloped sites. The most pronounced disconnection of the original floodplain (73.0%) occurred where earthworks were most concentrated compared with areas with few earthworks (53.2%). We investigated relationships between hydrological connectivity and mortality of the perennial flood-dependent river red gum *Eucalyptus camaldulensis* at 55 floodplain sites (225 × 150 m). Over half of the river red gums were dead at 21.8% of the sites. Earthworks blocked surface flows to flood-dependent vegetation and drowned vegetation in artificially inundated off-river storages. Mortality was due to impacts of earthworks and potentially exacerbated by effects of river regulation, water extraction and climate. River red gums were healthiest in narrow river corridors where earthworks confined flows and flows could recede freely. Rehabilitation of flood-dependent ecosystems should focus on reinstating lateral connectivity and protecting environmental flows. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: earthworks; hydrological connectivity; floodplain wetlands; irrigation infrastructure; water resource development; riparian vegetation; river red gum; *Eucalyptus camaldulensis*

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INTRODUCTION

Hydrological connectivity is essential for rivers and their floodplains, providing variable spatial and temporal pathways for water (Freeman *et al*., 2007). Flow transfers energy, matter and organisms (Amoros and Roux, 1988, Thoms *et al*., 2005, Jenkins and Boulton, 2003), uniquely shapes floodplains (Ward and Stanford, 1995), links aquatic habitats (Jenkins and Boulton, 2003) and drives biotic patterns and processes (Freeman *et al*., 2007) including dispersal, survival, reproduction, growth and recruitment of riparian vegetation (Bacon *et al*., 1993, Nilsson and Svedmark, 2002).

Development for agriculture, irrigation, drinking water and electricity has fragmented over half of the world's largest rivers (Nilsson *et al*., 2005), affecting wetlands and subsistence agriculture around the world (Lemly *et al*., 2000). Dams have changed hydrological connectivity in floodplains, reducing magnitude and frequency of overbank flooding (Gergel, 2002, Gergel *et al*., 2002). Hydrological connectivity can also be severed by earthworks built directly on the floodplain (Kingsford, 2000, Opperman *et al*., 2009) that reshape surface morphology and affect the spatial distribution of flows (Thoms *et al*., 2005). There are four types of floodplain earthworks: (i) levees (also known as embankments or dykes), physical earth barriers for controlling water for storage, protecting agricultural land or redirecting water within or outside the floodplain; (ii) artificial channels (also known as canals, ditches or trenches), open waterways transporting water for irrigation or around the wetland. Channels are below or above ground level, usually flanked by levees; (iii) off-river storage units, used to store rainfall or irrigation water diverted from a watercourse or pumped from ground water; and (iv) tanks (also known as farm dams, ring dams or turkey nests) for livestock and domestic water. Earthworks exist in most agricultural floodplains of the world, including USA with an estimated 25 000 miles (40 234 km) of levees (FEMA, 1992), Europe (viz. Carluer and Marsily, 2004, Lagacherie *et al*., 2006), Middle East (viz. Hritz and Wilkinson, 2006, Jones *et al*., 2008), Asia (viz. Xu, 1993, Tsujimoto *et al*., 2006) and Australia (viz. Callow and Smettem, 2009, Kingsford and Thomas, 2002). Despite this preponderance and the importance for hydrological connectivity and ecological processes, most

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ecological research has focused on ecological effects of in-stream structures (Ward and Stanford, 1995). A Web of Science (Thompson Reuters, 2009) database search (17/5/2010) returned 1054 publications containing 'dam', 'reservoir' or 'weir' and 'river' within the title, compared with only 49 publications containing 'levee', 'ditch', 'embankment' or 'earthwork' and 'river'. With poorly understood ecological effects, policy and management for earthworks has also lagged, with legislation for many rivers in Europe and Australia not adequately recognising floodplains until the 1990s (Monstadt and Moss, 2008, CSIRO, 2000). This accompanied increasing realisation that health of floodplain vegetation was deteriorating (Jolly *et al*., 1996).

The distribution and health of perennial floodplain vegetation usually reflects hydrological connectivity. Worldwide, floodplain vegetation segregates along a spatial gradient of hydrological connectivity (Auble *et al*., 1994, Gergel *et al*., 2002, van Looy *et al*., 2003) with the most water-tolerant plants occupying the best connected core of the wetland, whereas terrestrial flood-intolerant vegetation inhabit peripheral parts of the floodplain (Galat *et al*., 1998). When natural flow regimes are disrupted, hydrological connectivity changes, affecting vegetation distribution and health (Bren, 1992). River red gums *(Eucalyptus camaldulensis*) occur in monospecific stands in watercourses and floodplains in tropical, temperate and semi-arid regions of Australia (Di Stefano, 2001, Chippendale, 1988), considerably influencing floodplain biodiversity (Leslie, 2001) vegetation community structure (MDBC, 2003) and terrestrial and aquatic food webs (Baldwin, 1999). River red gums rely on natural flow regimes or access to groundwater for recruitment and survival and are sensitive to hydrologic change (Bacon *et al*., 1993, Kingsford, 2000, Horner *et al*., 2009). Flood frequency and seasonality affect the ability of river red gums to facilitate ecosystem processes, including nutrient cycling (Glazebrook and Robertson, 1999) and primary production (Robertson *et al*., 2001). Water-stressed river red gums in Australian wetlands shed leaves, reduce growth rate, accelerate senescence, increase mortality and have little regeneration (Bacon *et al*., 1993). Excess water due to building dams equally affects vegetation health by depleting soil oxygen and drowning river red gums dependent on an intermittent flooding regime (Lemly *et al*., 2000, Chesterfield, 1986). Loss or declining health of river red gums can cause irreversible shifts in biodiversity, structure and function of ecosystems.

We investigated the extent and distribution of earthworks on the Macquarie floodplain in the Murray–Darling Basin and their impact on lateral surface flows and river red gum health. The Macquarie Marshes are a wetland of international significance but considerably affected by reduced flows from river regulation upstream (Kingsford and Thomas, 1995, Ren *et al*., 2009, Thomas *et al*., in press). We had three main objectives: (i) to develop a technique to identify the extent of levees, channels, off-river storage units and tanks on a large floodplain; (ii) to assess how earthworks altered hydrological connectivity; and (iii) to quantify impacts on river red gums, a representative species of flood-dependent vegetation in the Macquarie Marshes (Paijmans, 1981, Brander, 1987). Finally, we evaluated management implications of floodplain policies and regulations around the world and particularly in the Murray–Darling Basin where 40% of Australia's gross agricultural production occurs (CSIRO, 2008b).

STUDY AREA

The Macquarie River (460 km) in southeast Australia flows through a catchment (73 000 km^2) with headwaters in the Great Dividing Range (Figure 1). It is regulated by two large dams, Burrendong [1 154 000 megalitres (ML)] and

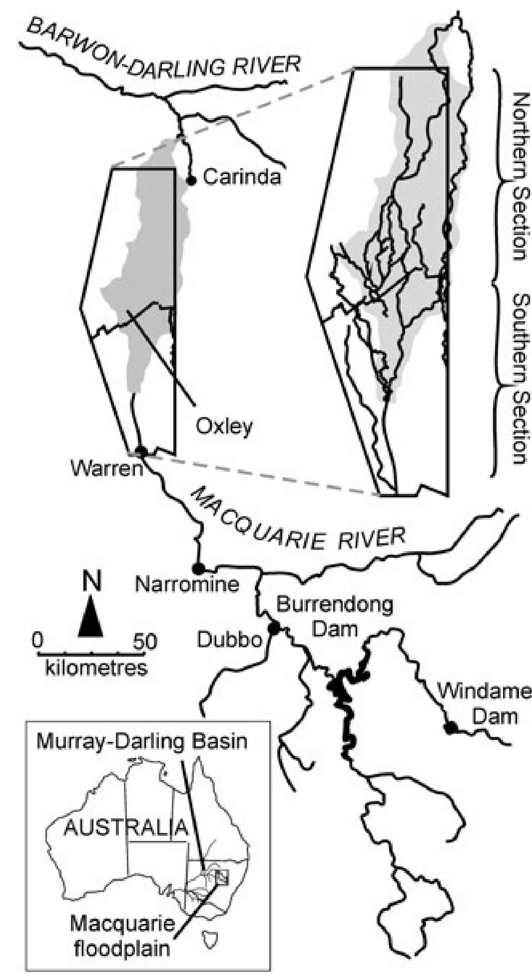

Figure 1. The location of the Macquarie River catchment showing the study area, major tributary rivers, distributary creeks, large dams and the Macquarie Marshes floodplain in the Murray–Darling Basin, Australia

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Windamere (361 000 ML). As the river reaches the Macquarie floodplain (Figure 1), the well-defined channel breaks down into a maze of interconnected streams, ephemeral lagoons, distributary creeks and anabranching channels of the Ramsar-listed Macquarie Marshes. Potential evapotranspiration [1 800 mm yr^{-1} (DWR, 1991)] exceeds average annual rainfall on the floodplain [432 mm yr^{-1} (Paijmans, 1981)], so frequent and complex flood pulses from the upper catchment are essential for semipermanent wetlands and their dependent vegetation. Between flood events, the natural footprint of hydrological connectivity shrinks until low regulated flows are confined to channels and waterholes that may become disconnected (Rayner *et al*., 2009).

Nine major regulatory dams of the Macquarie catchment can capture and store 2 100 000 ML of water for flood control and irrigation (Johnson, 2005). Surface water entitlements total 738 793 ML yr^{-1}: 156% of annual yield (Johnson, 2005), though average extractive use ranges from 100 000 to 550 000 ML (CSIRO, 2008a) largely for irrigated farming, predominantly cotton (Lemly *et al*., 2000). A further 260 000 ML is currently allocated annually for the environment. The volume of flows captured on the floodplain for irrigation remains unaccounted (Johnson, 2005). Part of the Macquarie floodplain (~11%) is a conservation reserve (22 260 ha), whereas most of the floodplain is privately owned (>177 000 ha) and is used for irrigated agriculture, dryland cropping and pastoralism (predominantly cattle).

METHODS

Original floodplain

To determine the extent of the floodplain before river regulation, we merged hydrological, geomorphological and flood-dependent vegetation data using Geographic Information System technology. The hydrological surface included a vector watercourse layer (GA, 2006), and the largest recorded flood event (3744 km^2; 1955) compiled from aerial photography, government records and interviews with landholders (Sinclair Knight and Partners, 1984). The geomorphological surface was based on floodplains, ephemeral lakes and artefacts of fluvially-formed levees (Northcote, 1966), from 1960s soil mapping (BRS, 2000). Eight existing vegetation maps of the Macquarie Marshes were integrated to define 13 flood-dependent vegetation communities. Several tanks and low channels present in 1949 aerial photography were overtopped by flows in the 1955 flood and were unlikely to affect flood boundary. We divided our study area, between the towns of Warren and Carinda (4793 km^2), into a Northern and Southern Section (Figure 1), aligning with the boundary used for floodplain management policy exclusive to the Southern Section (DECC & DWE, 2008).

Satellite image analysis

We identified four types of earthworks within the Macquarie floodplain, using SPOT satellite imagery (2.5 m resolution; January and February 2005) (SPOT Image, 2005). Water storages were easily differentiated by size (off-river storage units >0.02 km^2, tanks ≤0.02 km^2). Roads, bank stabilisation, dredging, vegetation clearing and natural geomorphological features were not identified. Levees, channels, off-river storage units and tanks were visually classified cell-by-cell (1 km resolution) and digitised as vector lines and polygons (GDA 94 MGA Zone 55 projection) using ArcGIS 9.2 (ESRI Inc., 2006). The classification was iteratively informed by a preliminary (100 km^2) pilot assessment using high-resolution aerial photography (NSW Department of Lands, 2004) reference data. We differentiated roads from linear channels using a road map (1:10 000 scale). Additional low, narrow levees were subsequently GPS-tracked from a helicopter. To provide unbiased ground truthing of the SPOT classification, we surveyed 116 randomly stratified ground control points from a helicopter, at least 500 m apart, to minimise spatial autocorrelation. GPS location and earthwork class were photographed while the helicopter hovered at a height of about 150 m. Heights of 20 random levees and 55 random channels were visually estimated from the air and classified as less than 0.5 m, 0.5–1 m, or >1 m by comparison with fence lines of known height.

Earthwork density analysis

We estimated differences in earthwork density between irrigated and nonirrigated areas by sampling 13 large quadrats (10 × 11 km) between 1949 and 2005. Quadrats were randomly stratified by flow frequency (nine in the Southern Section, four in the Northern Section). First, a 1994 earthworks map was produced by removing earthworks from the 2005 map, absent from 1994 Landsat Thematic Mapper (TM) imagery (25 m per pixel). The process continued using available grayscale aerial photography from July 1981 (scale of 1:50 000), then September 1972 (scale of 1:84 350), then November 1949 (scale of 1:30 000) and calculating earthworks length at each date. Several narrow, low levees (<1 m) in the Northern Section (Figure 2) were difficult to identify from satellite imagery so were dated using local knowledge. A mixed effects model was used for fixed (irrigated/nonirrigated) and random (quadrat, time) variables. Earthworks were assumed to be permanent landscape features. Variability among quadrats was normal according to a Shapiro–Wilk test ($W = 0.96$, $p = 0.08$).

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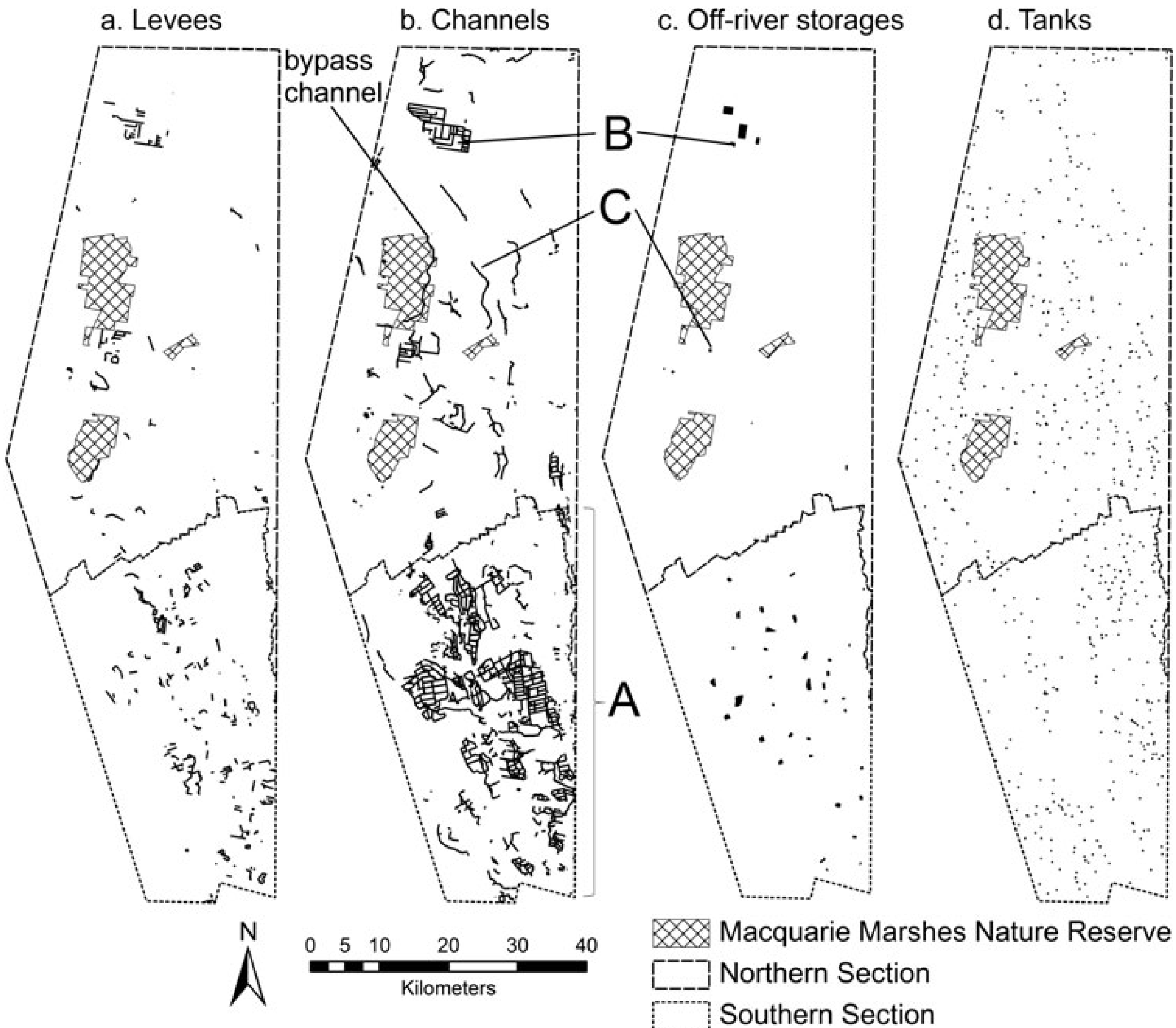

Figure 2. Distribution of (a) levees, (b) channels, (c) off-river storage units and (d) tanks on original Macquarie floodplain including the Nature Reserve within the study area, divided into the Northern and Southern Section. Most irrigation development is in the Southern Section (A), with the exception of two other clusters of irrigation development, B and C in the Northern Section. The 18.5 km bypass channel circumvents wetlands in the Northern Nature Reserve for downstream supply

Hydrological effects

We tested whether earthworks affected localised flooding by comparing the extent of dry ground between inner (riverside) and outer sides of earthworks over 28 years. Paired quadrats (500×100 m) were placed on either side of the 25 randomly chosen earthwork sites and 29 randomly chosen control (undeveloped) sites. At earthwork sites, the inner and outer quadrats were aligned parallel with the straight edge of the earthwork, whereas at control sites, the two quadrats were aligned parallel with the nearest river channel to account for the natural drying patterns that increase distally from the channel. Dry ground was derived from an inundation frequency map (resolution 25 m^2 per pixel, 7297 km^2 total mapped area) for the study area, where every pixel showed flood frequency based on annual Spring inundation (Sept–Nov) from Landsat satellite imagery Multispectral Scanner (MSS) and Thematic Mapper (TM) between 1979 and 2006. Landsat imagery for 1998 was unavailable and excluded, two images were included in 1990 to correspond with flood events and nearest available cloud-free images to Spring were selected for 1989, 1996 (Aug) and 1987, 2000 (Dec) (Thomas *et al.*, in press). Paired quadrats were spaced less than 50 m apart to minimise confounding effects of spatial variation that increase with distance. All tests relied on differencing the surface area of dry ground (zero flow), of the inner quadrat from the outer quadrat, to yield the dependent variable of difference in dry

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surface area between paired quadrats. The Shapiro–Wilk normality test (Shapiro and Wilk, 1965) showed the data were not normal ($W = 0.897$, $p < 0.001$). Log and power transformations failed to normalise data so we used the nonparametric Kruskal–Wallis test on all data. A two-tailed test was chosen because the direction of flooding was unknown and water may have pooled behind earthworks. We compared the full extent of recent flooding (1979–2006) (Thomas *et al.*, in press) to original floodplain area.

River red gums

To determine if earthworks potentially affected the river red gum health, we modelled mortality in relation to hydrological connectivity. Fifty-five random river red gum sites (225x150 m) were selected across a range of inundation frequencies in the entire study area, spaced more than 500 m apart for spatial independence. Sites were randomly stratified by flow frequency producing a higher concentration in the Southern Section where flow frequency was more varied (50 in the Southern Section, five in the Northern Section). Each site was photographed (50 mm focal length, 150 m height, eight-bit colour) during helicopter surveys in May 2007, when healthy river red gums have fully formed leaves. Photographs were visually subsampled and classified using 100 random points as live (leaves/live branches), dead (leafless dead branches), water or soil. The dependent variable was the number of dead and live points per site, interpreted as river red gum mortality (% of dead trees). Three independent variables were used as hydrological connectivity indices: lateral flow distance; inundation frequency; and earthwork density. Lateral flow distance was the shortest distance water could travel from the nearest natural watercourse to each river red gum site, modelled around any interfering levees. Inundation frequency was derived from a commonly used unsupervised spectral classification of wetted areas (Ozesmi and Bauer, 2002) in annual Landsat imagery captured between 1979 and 2006 (Thomas *et al.*, in press). Earthwork density was earthworks within a 3 km radius of each 10 m resolution pixel. Nonuniform spatial distribution of earthworks within each neighbourhood was accounted for using a spatially-dependent kernel function (ESRI Inc., 2006).

We used a multivariate generalised linear model to determine whether river red gum mortality was correlated with the three independent variables. Binomial logistic regression was used because the data were homoscedastic, the response variable was binary (live versus dead) and the explanatory variables were ratio scaled. The fit of the logistic regression was assessed using the D^2 statistic and Akaike's Information Criterion. We quantified the likelihood of river red gum mortality with the independent variables and their interactions using odds ratios (OR), calculated as the exponential of the logistic regression coefficient ($OR = e^{coeff.}$). To examine potential nonparametric relationships, we re-analysed the data using a generalised additive model. Geographically Weighted Regression (GWR) was used to determine whether the derived global relationship from the logistic regression exhibited geographic trends or spatial autocorrelation. The GWR calculates a local statistic by disregarding sites that are greater than 5 km away and weighting sites within a 5 km radius according to a gaussian distribution (Charlton *et al.*, 2003). A 5 km radius best captured spatial variation without excess noise compared with other radii we examined (1, 10, 25 and 50 km). Local relationships derived for each site were interpreted by looking at the parameter values with an estimate of significance such as the *t*-value or the goodness-of-fit. All statistical analyses were conducted in R software (R Development Core Team, 2009).

RESULTS

Extent and distribution of earthworks

There were 2320 km of earthworks distributed across the study area including 338 km levees and 1648 km channels (Table 1). Most levees and channels were in the Southern Section (max. density 3400 m km^{-2}), arranged as enclosed regular shapes, tessellated in compact grid-like clusters or rings (Table I; Figures 2a and 2b). Earthworks in the Northern Section were sparse, isolated curvilinear features, with the exception of two clusters of earthworks (B and C, Figures 2b and 2c). Sampled channel heights ranged between 0.5 and 3 m and most levees were less than 0.5 m unless they bounded off-river storages (<5 m; Table 1). There were 54 off-river storage units and 664 tanks on the Macquarie floodplain (Table 1; Figures 2c and 2d). Most off-river storage units were in the Southern Section for irrigation. Tanks were uniformly dispersed across the study area (Table 1, Figure 2d), primarily for stock and domestic water supplies. Classification accuracy for the complete study yielded a Kappa statistic (K_{HAT}) of 0.661, an improvement (>4%) on the pilot study. Errors arose from falsely classifying channels as levees (Appendix A), resulting in reclassification of 33.8 km of levees as channels. Average omission accuracy was 82.5%, average commission accuracy was 81.6%, and overall accuracy of the final classification was about 77%. There were 119 km of levees classified uncertain, requiring further ground truthing.

Earthwork density analysis

Earthwork density was significantly higher in irrigated areas compared with nonirrigated areas (662.71 m km^{-2} $\pm$ SE 98.78, $t = -6.7$, $p < 0.01$) between 1949 and 2005 (Figure 3). In irrigated areas (Southern Section and B and C in Northern

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Table I. Lengths, areas enclosed and average densities of earthworks within the original Macquarie floodplain in the Northern (N) and Southern Section (S) of the study area (Figure 1)

Earthworks	Section	Length (km)[a] <0.5 m	Length (km)[a] 0.5–1 m	Length (km)[a] >1 m	Total length km (%)[b]	Quantity	Enclosed area (km^2)[c]	Av. density ($m\,km^{-2}$)
Levees	North	70	38	0	108 (32)	—	—	38.9
	South	150	80	0	230 (68)	—	—-	114
	Subtotal	220	118	0	338	—	—	
Uncertain levees[d]	North	41	22	0	63 (53)	—	—	22.7
	South	36	20	0	56 (47)	—	—	27.7
	Subtotal	77	42	0	119	—	—	—
Channels	North	277	148	22	447 (27)	—	—	161.4
	South	745	396	60	1201 (73)	—	—	595.1
	Subtotal	1022	544	82	1648	—	—	—
Off-river storage units	North	0	0	37[e]	37[e] (28)	12 (33%)	6 (22%)	13.3
	South	0	0	92[e]	92[e] (72)	42 (67%)	13 (78%)	45.6
	Subtotal	0	0	129[e]	129[e]	54	19	
Tanks	North	0	0	51[e]	51[e] (59)	402 (62%)	0.5 (61%)	18.4
	South	0	0	35[e]	35[e] (41)	262 (38%)	0.3 (39%)	17.3
	Subtotal	0	0	86[e]	86[e]	664	0.8	
Total	North	388	208	110	706	414	6.5	254.7
	South	931	496	187	1614	304	13.3	799
	Total	1319	704	297	2320	718	20	1054.4

[a]Height estimated from sample where: 65% of levees were less than 0.5 m, and 35% were 0.5–1 m; 62% of the channels were less than 0.5 m, and 33% were 0.5–1 m and 5% were 1–3 m. Off-river storage units and tanks were enclosed by levees greater than 1 m.
[b]Percentage of length within Northern and Southern Sections per earthwork class.
[c]Area enclosed on all sides by earthworks.
[d]Features with ambiguous classification requiring further ground truthing.
[e]Levees bounding off-river storage units or tanks.

Section, Figure 2) there were an estimated 284 $m\,km^{-2}$ of earthworks in 1949 in our 13 sample quadrats. By 1981, the length of earthworks had doubled (577 $m\,km^{-2}$), then tripled by 1994 (864 $m\,km^{-2}$) and there were over four times more earthworks in 2005 (1182 $m\,km^{-2}$), compared with 1949. Earthwork density in irrigated areas was four times higher than nonirrigated areas in 1994 (819 $m\,km^{-2}$ and 199 $m\,km^{-2}$) and twice as dense in 2005 (1137 $m\,km^{-2}$ and 518 $m\,km^{-2}$).

Hydrological effects

Less than half (38.4%) of the original floodplain was inundated at least once, during spring 1979–2006. Compared with the original floodplain based on hydrological, geomorphological and vegetation layers, inundated area during this 28 year period was only 46.8% in the Northern Section and 27.0% in the Southern Section. There were 632 km of earthworks within areas inundated during the 28 year period. Of these, most earthworks (609.5 km; or 96.4%) were in infrequently flooded regions (inundated 50% of years or less), whereas the remaining earthworks (22.6 km; or 3.6%) were in areas flooded more than half of the 28 years. Based on the results of the floodplain frequency analysis, floodplain sites near earthworks were significantly drier than undeveloped sites with no earthworks (Mann–Whitney $U = 508$, $p = 0.012$). Earthworks exacerbated the natural tendency for the floodplain to become dry distally from the channel.

River red gum mortality

All river red gums were dead at 9.1% of the sites, including two sites within off-river storage units (1.4 km^2, 0.4 km^2) circumscribed by levees. At 21.8% of the sites, over half of the trees were dead (Figure 4). The relative probability of observing a live or dead tree (logarithm of the odds) depended linearly on the lateral flow distance, inundation frequency and earthwork density:

$$\begin{aligned}\mathrm{Logit(P)} &= \mathrm{Log(P/(1-P))}\\ &= -0.0005\mathrm{FD} - 0.0746\mathrm{IF} - 0.7263\mathrm{ED}\\ &\quad +0.0001(\mathrm{IF} * \mathrm{FD}) - 0.1387\end{aligned}$$

where P = probability of a dead river red gum tree, FD = lateral flow distance from nearest river channel, IF = inundation frequency and ED = earthwork density. Variables were

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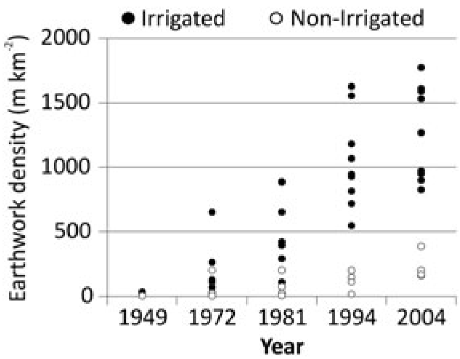

Figure 3. Earthwork density within 13 quadrats (10 × 11 km) on the Macquarie floodplain, derived from historical aerial photography and satellite imagery captured in 1949, 1972, 1982, 1994 and 2006. Earthwork density associated with irriga

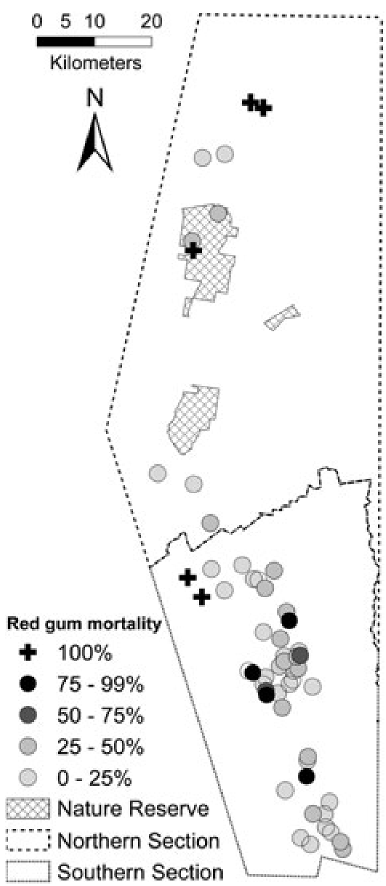

Figure 4. Condition of river red gum at 55 sites in the study area. Mortality was based on aerial photography classification and calculated as the percentage of dead red gums, displayed within five categories: 0%–25%; 25%–50%; 50%–75%; 75%–99% and 100%

independent (correlation coefficients: ED–FD: 0.069; FD–IF: 0.119; and ED–IF: −0.123) and all regression coefficients of independent variables including the interaction term were significantly different from zero ($p < 0.01$), except the constant. Earthwork density was a key explanatory variable for river red gum mortality. Well-connected river red gums within narrowed floodways bounded by dense earthwork clusters (Southern Section) were among the healthiest (Figure 5a), where flows were confined and river red gums frequently wetted. Conversely, well-connected river red gums within open wetland tracts of low earthwork density (Northern Section) exhibited high mortality. Every unit increase in earthwork density decreased the odds of river red gum death by half ($OR = e^{\text{coeff. of ED}} = 0.48$; where OR < 1, was a reduced likelihood of dead river red gums), with inundation frequency and lateral flow distance held constant. Lateral flow distance was not a strong explanatory variable ($\text{OR} = e^{\text{coeff. of FD}} = 1.00$; an equally likely chance of live or dead river red gums) with all other variables held constant. For every unit increase in inundation frequency, there was a slight increase in the likelihood of survival ($OR = e^{\text{coeff. of IF}} = 0.93$). Interaction between inundation frequency and flow distance was not a strong explanatory variable ($OR = e^{\text{coeff. of FD}} = 1.00$). The logistic model explained 58.6% of the deviance ($D^2 = 0.586$). The model with all three variables emerged as the best model with the lowest Akaike's Information Criterion value (FD/IF/ED: 645.12) compared with other models explaining drivers of river red gum mortality (FD/IF: 725.58; ED/IF: 708.1; FD/ED: 696.12). Statistical significance of generalised additive model variables was similar to logistic regression ($p < 0.01$ for all variables), so we retained the logistic regression as it was a simpler model.

Our local GWR identified 24 out of 55 sites with significant spatial nonstationarity in one or more independent variables ($t < -2$, $t > 2$; Appendix B). Vegetation mortality and lateral flow distance (Appendix Ba) were positively correlated throughout most of the Southern Section and negatively correlated in the Northern Section near the two parts of the conservation reserve, with the exception of two sites adjacent to irrigation areas. The GWR reinforced the global relationship between inundation frequency and river red gum survival (Appendix Bb), except in several sites in the Southern Section and in the Northern Nature Reserve. In the Northern Section, earthwork density was highly positively correlated with river red gum mortality in three sites (Appendix Bc), a difference that the global regression model failed to detect. In the Southern Section, the GWR suggested that river red gum mortality decreased with increasing earthwork density, a relationship fluctuating in strength (−0.59 to −0.02) across the Southern Section, although this relationship was not significant. The Gaussian distribution was better at calculating the goodness-of-fit using red gum mortality likelihoods than the logistic regression and the Pearson's R^2 statistic of goodness-of-fit was excellent in some regions ($R^2 = 0.99$) but not others ($R^2 = 0.34$).

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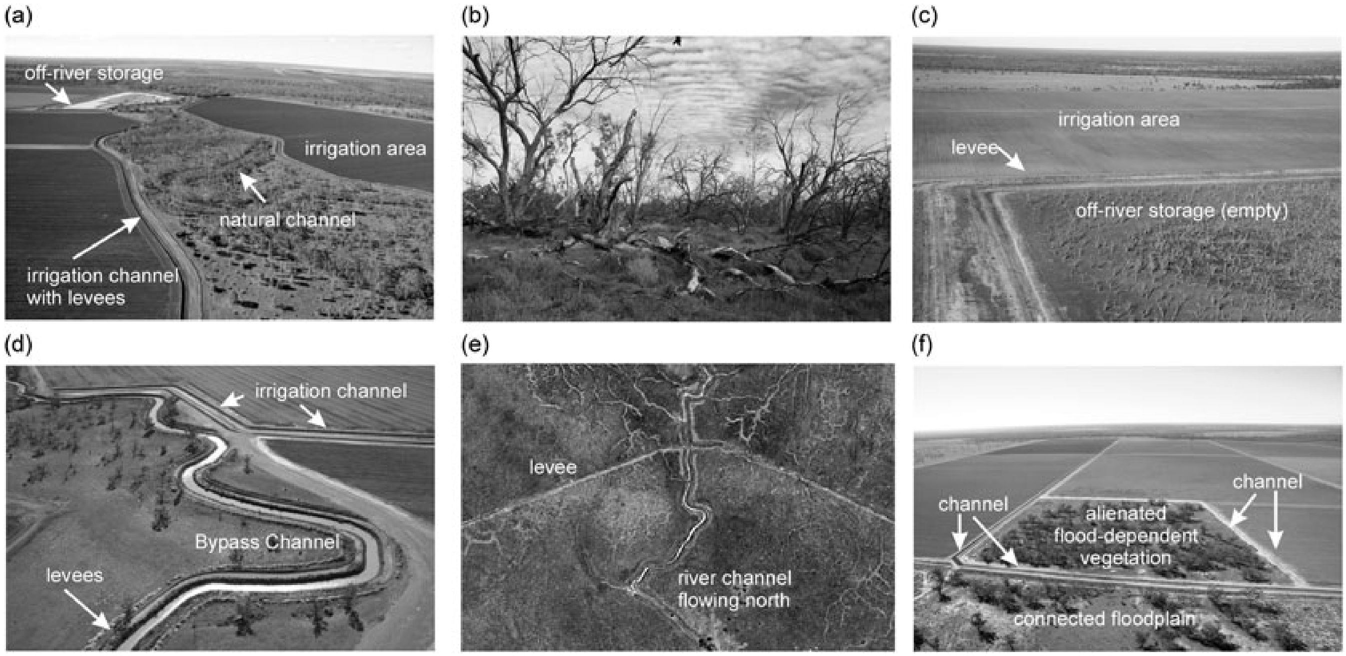

Figure 5. Ecological effects of earthworks varied according to landscape position and orientation. (a) Healthy river red gums in a narrow stretch within the floodway network where earthworks confined flows. (b) Dead river red gums in the Northern Nature Reserve, despite being hydrologically connected with the channel. (c) Increased saturation in off-river storage kills 1.56 km^2 of river red gum in the Northern Section. (d) Bypass Channel flanked by levees preventing overbank flow. (e) Levee designed to capture and spread environmental flows. (f) Channels prevent overbank flows from reaching flood-dependent vegetation in the Southern Section, isolating 0.13 km^2 of floodplain

DISCUSSION

The ecological effects of earthworks on the world's floodplains and their dependent ecosystems are poorly known, largely because identifying their extent and impacts present considerable technical challenges (Gergel, 2002). Most of our understanding of the ecological problems of rivers comes from research on the effects of dams, weirs and diversion of water upstream of wetlands (Bunn and Arthington, 2002, Lemly *et al*., 2000, Nilsson *et al*., 2005). This ignores the fundamental complexity of major rivers and their complex spatio-temporal floodplain interactions (sensu Junk *et al*., 1989, Walker *et al*., 1995). Some temperate and semi-arid floodplains have been almost entirely disconnected from their channel by floodplain levees: 80% of the Middle Elbe River floodplain (Leyer, 2004); 90% of the Lower Mississippi floodplain (Kesel, 2003); 90% of the Lower Missouri floodplain (Galat *et al*., 1998) and 59% of the Lower Murrumbidgee floodplain (Kingsford and Thomas, 2002). Much of this development is associated with agricultural development on floodplains, whether for irrigated agriculture or mitigation of flooding so agricultural crops can be grown. There are increasing efforts to rehabilitate rivers throughout the world, mainly focusing on improving the natural flow regime through environmental flows (Poff *et al*., 1997). Without clear identification of the spatial extent of earthworks and their effect on localised flooding, the full extent of ecological impacts from earthworks and opportunities for rehabilitation may be thwarted. We showed earthworks altered hydrology and subsequently affected floodplain ecology in one of the more significant wetland systems in Australia, the Macquarie River floodplain.

Using a rigorous visual detection technique, we identified more than 2000 km of floodplain earthworks from satellite imagery (Figure 2; Table 1). Earthworks that interacted with flow on the semi-arid Macquarie floodplain were site-specific flow controllers, modifying and constraining natural flow pathways supplying the internationally listed Ramsar wetland site. Some earthwork sites produced localised drying over a 28 year period. We estimated at least 632 km of earthworks could have interfered with hydrological patterns on the Macquarie floodplain between 1979 and 2006 (Figure 3), potentially preventing overbank flows from spreading laterally across the floodplain, impeding surface flooding and isolating regions from fluvial processes. Similar effects occur on other floodplains (Thoms, 2003, Gergel *et al*., 2002). Such severance of hydrological connectivity limits intrinsic wetland functions including water filtration and flood control (Walling and He, 1998).

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In some areas, earthworks constrained flows (Figure 5a) and probably magnified flood stage (Criss and Shock, 2001), potentially increasing hydroperiod within confined riparian habitats (Gergel, 2002). Such earthworks limit flood extent until levees are breached and hydrological impacts are mitigated (Gergel, 2002).

Floodplain earthworks acted as anthropogenic boundary controls and reduced inundation extent at a floodplain scale. The upper Southern Section of the Macquarie Floodplain experienced greater hydrological disconnection (73.0% of the original floodplain) compared with the downstream Northern Section (53.2% of the original floodplain) during the 28 year period (1979–2006). Disconnection was likely due to high earthwork abundance in the Southern Section (A) and two small irrigation areas in the Northern Section associated with irrigation (B, C, Figures 2 and 3). Earthworks for flood mitigation and irrigation water delivery oriented parallel to flow direction were likely to confine flows (Figures 2 and 5a). By contrast, earthworks elsewhere in the Northern Section were mainly low levees on pastoral properties perpendicular to flow direction, designed to spread water rather than constrict flooding or harvest water (Figures 2 and 5e). Spatially heterogeneous hydrological responses (Appendix B) because of landscape position (Callow and Smettem, 2009, Larsen *et al*., 2006) and geomorphological changes (Ralph and Hesse, 2010) may have contributed to the difference in disconnection between the Northern and Southern Sections.

Assessing the ecological impact of earthworks is challenging because of the accretive nature of earthworks as a press disturbance over a long period of time. The most obvious ecological impacts were to perennial vegetation, including floodplain eucalypts. Other effects on biota are largely transitory, leaving no signature unless measured at the time. We focused on river red gums because these long-lived eucalypts depend primarily on frequent overland flows for recruitment and survival although they also occasionally access ground water sources (Bacon *et al*., 1993, Kingsford, 2000). Over half of the sampled river red gums in 21.8% of sample sites (225x150 m) were dead because of multiple disturbances including earthworks (this study), river regulation, upstream water extractions and drought (Kingsford, 2000, Kingsford and Thomas, 1995, Horner *et al*., 2009) that had fragmented or completely blocked inundation (Figure 5b). River red gums in the Northern Section are highly characteristic of the Macquarie floodplain with significant areas that are in poor condition (Kingsford and Thomas, 1995, Thomas *et al*., in press), so our sample sites, randomly stratified according to earthwork density, focused sampling effort predominantly in the Southern Section. River red gums were killed by prolonged inundation if they were within an off-river storage circumscribed by levees (Figure 5c). Off-river storage units were morphologically simple with generally high and stable water levels. Some natural water courses are replaced by constructed irrigation channels but these were poor ecological substitutes because of limited overbank flows, reduced geomorphic complexity and potential to convey contaminants or invasive species (Figure 5d; Carluer and Marsily, 2004, Steiger *et al*., 1998). Artificial channels may also reroute flows to other parts of the floodplain. Our global logistic model explained 58.6% of the deviance in river red gum mortality, with inundation duration, ground water availability, soil moisture, tolerance of river red gums to desiccation and spatial effects likely contributing to unexplained variance. Limited distribution of river red gums on the floodplain margins meant sampling was restricted within confined flow corridors where river red gums were healthy. River red gums are usually found in the most frequently inundated areas, with other more xeric floodplain species tolerating less frequent flooding (Bren, 1992). Sampling additional vegetation communities would provide further information of hydrological disconnection caused by earthworks.

The effects of upstream river regulation and local effects of floodplain earthworks are changing vegetation communities of the Macquarie floodplain significantly (Brander, 1987, Kingsford and Thomas, 1995), indicative of an ecosystem in transition to a water regime altered in distribution and quantity (Thomas *et al*., in press). On the river Murray, river red gums invaded hydrophytic grass communities in floodplains after flow regulation reduced flood frequency (Bren, 1992). As flooding extent recedes, floodplain vegetation communities change successionally in distribution and composition (van Looy *et al*., 2003). Parts of the Macquarie floodplain have already been invaded by endemic terrestrial plant species (e.g. chenopods) in areas usually occupied by flood dependent species (Brander, 1987), reflecting increased desiccation due to hydrological disconnection. This will probably continue to occur, given the cumulative effects of river regulation, flow diversions, hydrological impacts of climate change and impacts of earthworks identified in this study.

Despite significant ecological and hydrological effects of earthworks on fluvial processes and ecosystems, there is poor policy and management throughout Australia for regulating their construction, placement or potential effects on environmental flows. Prescribed development zones in the Macquarie floodplain were designed for conveyance of floods and property risk minimization (WRC, 1978, WRC, 1982) and failed to prevent levees from encircling a flood-dependent vegetation community (Figure 5f) or from confining environmental flows laterally and isolating peripheral flood-dependent vegetation from flows. The 2008 Macquarie floodplain management plan (DECC & DWE, 2008) was designed primarily around

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mitigating flood risk to agricultural crops and maintaining longitudinal, not lateral, connectivity through floodways. Rehabilitation of parts of the floodplain may be possible through re-alignment of development zones and earthwork alteration or removal to reconnect fragmented floodplains (Galat *et al*., 1998). Such management of earthworks may be as important as ensuring environmental flows are released for regulated rivers (Poff *et al*., 1997), allowing large flows to pass without flood risk but allowing for reconnection of floodplains (Thoms, 2003, Criss and Shock, 2001, Opperman *et al*., 2009). Economic incentives may also be important, including voluntary purchases of easements on floodplain properties and subsidising modification of earthworks as alternatives to zoning regulation. Globally, insurance companies discourage floodplain development by raising premiums, denying insurance coverage and preventing repetitive payouts to promote relocation (Birkland *et al*., 2003). Not all earthworks are ecologically damaging. Earthworks can facilitate a triage approach to wetland management (Brooks *et al*., 2006), using channels to direct water to high priority sites for rehabilitation and levees to prevent localised flooding of low value assets. Earthworks may be used to control erosion by preventing overland flow and consequently rill formation. Excavation of floodplain sediments can enlarge retention areas and generate bare ground for vegetation regeneration (Geerling *et al*., 2008).

Besides fragmentation, there is an additional ecological problem dependent on positioning of earthworks; lateral placement of levees and channels can redirect overbank flows and increase illegal diversion of environmental water from rivers to irrigated agriculture. Limits on diversions from rivers were set to 1993/1994 levels of development by Federal and State Governments in the Murray–Darling Basin (MDBC, 2004) but these failed to account for ongoing construction of earthworks that harvest water from distributaries or the floodplain. In our sample of 27% (1,320 km^2) of the original floodplain, we found 240 km of levees and channels and two off-river storage units on the lower Macquarie floodplain that were built after 1993/1994, which potentially increased water extraction from rivers. In an effort to further rehabilitate river systems of the Murray–Darling Basin, Federal and State Governments are buying back water entitlements for environment flows ($AUD3.1 billion), but these flows may be intercepted via floodplain earthworks, compromising environmental objectives and posing a risk to the future integrity of water access entitlements. There is a need to protect environmental flows by regulating floodplain harvesting through licencing and monitoring activity using water metres, satellite imagery or helicopter assessments at peak irrigation times.

Our conceptual and practical understanding and management of rivers and the importance of lateral flows to floodplains lags behind our knowledge of the longitudinal importance of flow (see Junk *et al*., 1989), as has our understanding of anthropogenic impacts to floodplain ecosystems. Early river models from temperate forest streams of the northern hemisphere inadequately recognised the ecological importance of lateral connectivity (see Vannote *et al*., 1980, Thorp and Delong, 1994) and complexity of ecological processes at the land-water interface (Gregory *et al*., 1991). So, many floodplains were defined solely by administrative or legal conveniences usually related to preventing flood damage. The main river channel was the focus, not the broad ecosystem that encompassed the floodplain. A planning decision to designate the northern Macquarie Marshes as a floodplain (DWR & NPWS, 1986) only protected part of the floodplain from earthworks (Figure 2). This occurred despite similarities in hydrology and flood-dependent ecological communities between the now predominantly developed south and largely intact northern part of the Macquarie floodplain.

CONCLUSIONS

The development of earthworks continues in many river systems of the world with insufficient knowledge of local and floodplain scale impacts on hydrological connectivity. As flood dynamics underpin structure and functioning of freshwater wetlands (Junk *et al*., 1989), preserving channel-floodplain linkages (Sparks, 1995) and connectivity between floodplain patches (Thoms *et al*., 2005) is fundamental for ecosystem integrity. Conceptual models of the importance of connectivity across the floodplain (Amoros and Roux, 1988, Junk *et al*., 1989) need to be recognised within planning and management frameworks as well in theoretical understanding. Earthworks need to be a critical management focus, as the hydrological and ecological impacts of earthworks may be as severe as the impact of dams, weirs and extractions.

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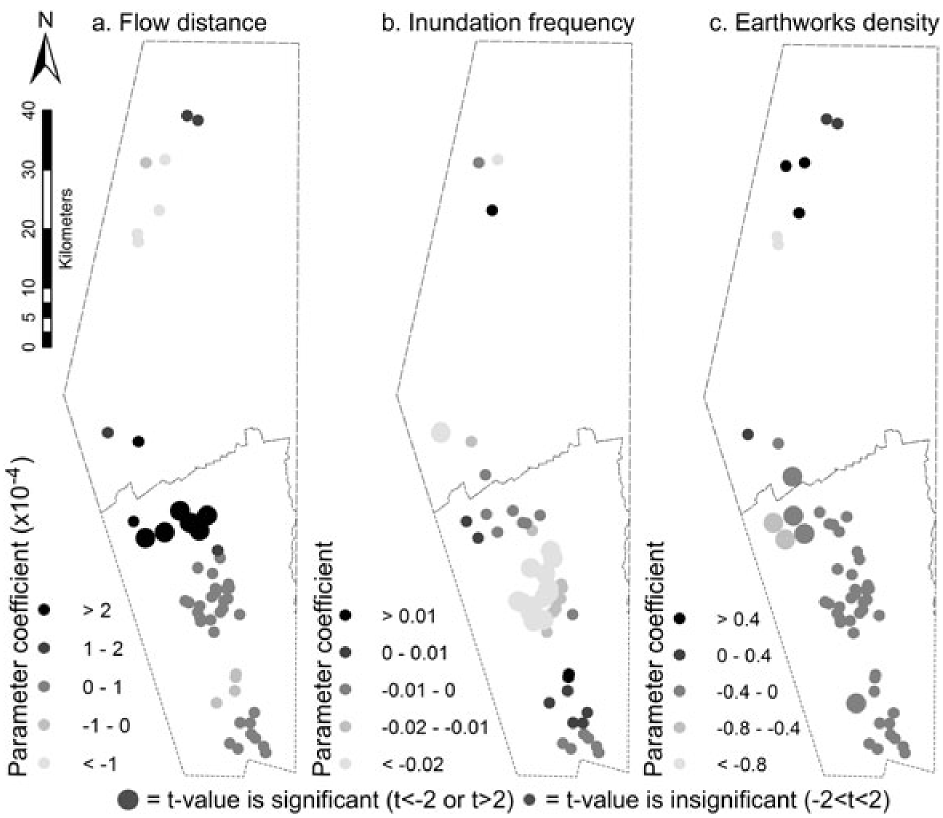
APPENDIX A. Accuracy assessment of earthworks mapping from SPOT imagery (2005), using aerial photographs (55 floodplain sites, 225 × 150 m) from a helicopter survey (2007) as reference.

Class	Levee	Channel	Storage	Tank	Undeveloped	Unsure	Total	Commission Error (%)
Levee	2	9	0	0	6	0	17	11.76
Channel	0	27	0	0	1	0	28	96.43
Storage	0	0	6	0	0	0	6	100
Tank	0	0	0	5	0	0	5	100
Undeveloped	0	0	0	0	49	0	49	100
Unsure	1	6	0	0	4	0	11	0
Total	3	42	6	5	60	0	116	
Omission Error (%)	66.67	64.29	100	100	81.67	Overall accuracy:	76.72	

APPENDIX B. Parameter coefficients from a geographically weighted regression at 55 sites on the Macquarie floodplain. Parameters were flow distance (a), inundation frequency (b) and earthworks density (c). Circle shading represents the parameter coefficient and size represents significance.



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