The effect of local-scale valley constrictions on flood inundation and catchment-scale sediment delivery in the Fitzroy River Basin, Australia

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Abstract Sediment delivery patterns and rates of sediment accumulation within a basin are significantly affected by features which physically act to prevent and/or enhance the downstream transfer of flow, sediment and attached nutrients. Such features include major within-valley constrictions, or "bottlenecks", which have developed where valley width reduces dramatically relative to the upstream reaches. Several of these features have been previously identified in the Fitzroy River Basin, Queensland. In many of these bottlenecks, channel pattern upstream and downstream of the bottleneck is notably different, with a propensity for change from multi-channel anabranching to single meandering. Using a representative example from the Nogoa sub-catchment, one-dimensional hydraulic modelling is used to describe the affect of the bottleneck on flood inundation and flow routing downstream. Flow hydrographs indicate a spatially and temporally variable flow regime where discharge dominance alternates between the trunk and main channel.

Key words valley constrictions; flood inundation; back-water; HEC-RAS; flood plain storage

INTRODUCTION

The greatest threat to water quality in Australia remains enhanced contaminant delivery, notably sediments, due to accelerated soil erosion in response to climate and land-use changes. Geographically, the most significant contributors to soil loss, water quality decline and offshore pollutant delivery are large catchments, notably but ironically, those lying adjacent to a sensitive marine ecosystem such as the Great Barrier Reef Marine Park (Prosser *et al*., 2001b; McCulloch *et al*. 2003). Enhanced terrestrial pollutants have been detected in the reef record, leading to local government initiatives that have set end-of-valley targets for the reduction of sediment delivery off-shore. Some "connectivity" between upstream and downstream reaches is implied.

Sediment delivery patterns and rates of sediment accumulation within a basin are significantly affected by features which physically act to prevent and/or enhance the downstream transfer of flow, sediment and attached nutrients. Such features include major within-valley constrictions, or "bottlenecks", which have developed where valley width reduces dramatically relative to the upstream reaches. The ability of the channel to transport both coarse and fine particles through these areas, and the temporal pattern of such conveyance, will largely determine the catchments sediment connectivity pattern. Valley constrictions are just one example of a geomorphic feature that can act as a barrier to flood conveyance (Fryirs *et al*., 2007). Previous research in the Fitzroy Basin in Queensland demonstrated that major changes in key variables such as slope, channel pattern, river style were spatially correlated to the location of 46 bottlenecks, where major changes in valley and flood-plain width were noted (Amos *et al*., 2008). The extent of valley width changes was quantified using the valley bottom flatness index (MrVBF) (Gallant & Dowling, 2003) and data verified manually using aerial photos, satellite imagery, digital elevation data and topographic maps. The effect of these features on the routing of both flood waters and associated sediment is largely unknown. The aim of this study is therefore to evaluate their effect on flood inundation patterns using a representative example from Medway Creek in the Nogoa sub-catchment. Data presented here form part of an on-going study into the effect of valley constrictions on flow and sediment transfer in the Fitzroy River Basin, Queensland.

STUDY AREA

The study area of Medway Creek lies within the Fitzroy River Basin in northeastern Australia, a large (144 000 km^2), low relief, catchment, spanning semi-arid to sub-humid climatic zones (MAR 600–700 mm), that discharges into the Coral Sea within the Great Barrier Reef Marine Park. The basin is divided into six subcatchments; Nogoa, Comet, Isaac-Conners, Mackenzie, Dawson and Fitzroy (Fig. 1). One of the most notable valley constriction sites occurs at the confluence of Medway Creek with the Nogoa River (Fig. 1). At the confluence, Medway catchment (1855 km^2) is one sixth the size of the Nogoa catchment (11 820 km^2).

Medway Creek exhibits an anabranching planform which becomes constrained by sedimentary scarps just prior to its confluence with the Nogoa River forming a bottleneck (Fig. 2). The

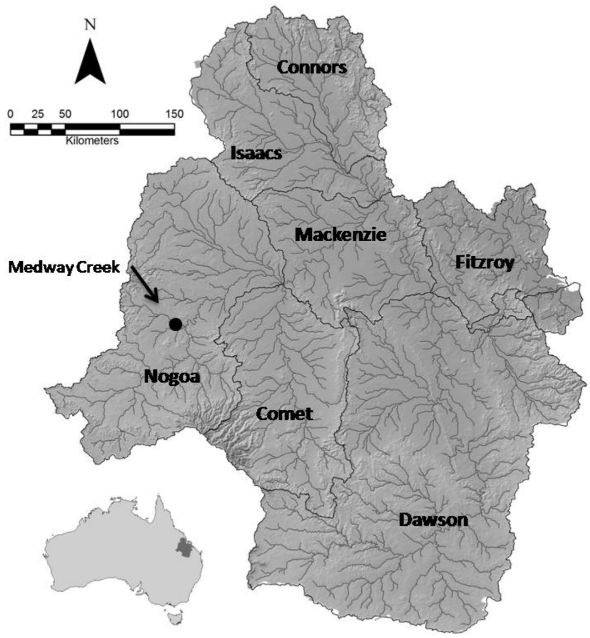

Fig. 1 Major sub-catchments in the Fitzroy Basin and the location of Medway Creek, the selected example chosen for this study in the Nogoa sub catchment.

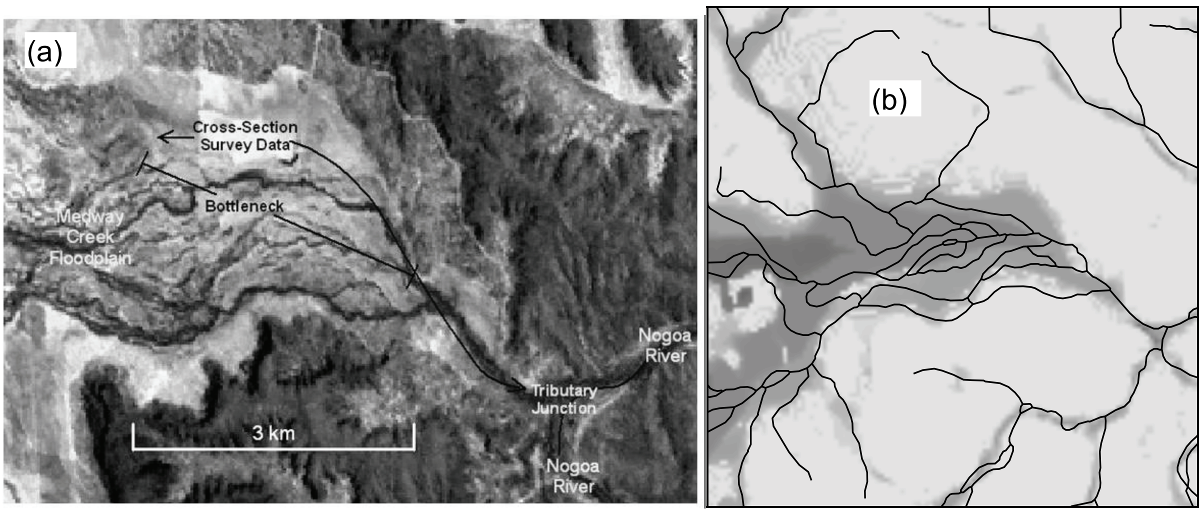

Fig. 2 (a) Image showing the anabranching planform of Medway Creek change to a single confined channel as it approaches the confluence with the Nogoa River. (b) Outlines changes in valley width as determined using MrVBF of Gallant & Dowling (2003).

channel maintains a single channel planform as it passes through this feature and at the confluence with the Nogoa River, multiple distributary channels feed Medway flows into the Nogoa River. The average channel slope is approx. 0.001 m m^{-1} and notable changes in channel bed elevation accompany the change from anabranching to a single-channel planform. This bed elevation fall is ~2.6 metres, approx. 50% of the total bed relief of the surveyed reach. The flood plain sediments of the Lower Medway Creek are composed primarily of mud with a silt:clay ratio of <1:2 (Purvis-Smith, 2007).

Rainfall in the area is strongly seasonal, being derived from the westerly monsoonal circulation in summer and generally falling as intense single-celled storms (0.25–6 h) limited to approx. 30% of summer days (Ciesiolka, 1987). Alternatively, summer tropical cyclones can produce torrential rainfall for extended periods (≤96 h). Winter is typically dry.

METHODS

The flood regimes of the Nogoa River and Medway Creek were investigated through an analysis of hydrographs of maximum daily flow records from three gauges within the study region (Table 1). The period of record from 1972 to 1985 provides 14 years of continuous data common to all gauges. Because the upstream gauges are some distance from the confluence, and there is potential for transmission losses, the data are supplemented with daily rainfall records (1966–2005) from the Rutland Property on the lower Medway catchment adjacent to the confluence. An assumption is made that rainfall at Rutland for the same period of record indicates catchment-wide rainfall. Therefore the Mowbray peak discharge would serve as a conservative estimation of Medway Creek discharge near the tributary junction.

Table 1 Gauge Station details for data sourced from QLD Dept. of Natural Resources and Water.

Gauge name	Station number	Catchment area	Catchment description	Proximity to junction	Stream name	Period of record
Mowbray	130212A	1108 km^2	Upper 60% (1108 km^2) of total MC	~20 km upstream	Medway Creek (MC)	24/10/1972 to 03/11/1988
Raymond	130202A	8308 km^2	The 1855 km^2 MC catchment is 34% of the contributing area between these gauges	~50 km upstream	Upper Nogoa River	10/12/1949 to 06/06/1985
Craigmore	130209A	13786 km^2		~5 km downstream	Downstream Nogoa River	10/02/1972 to present

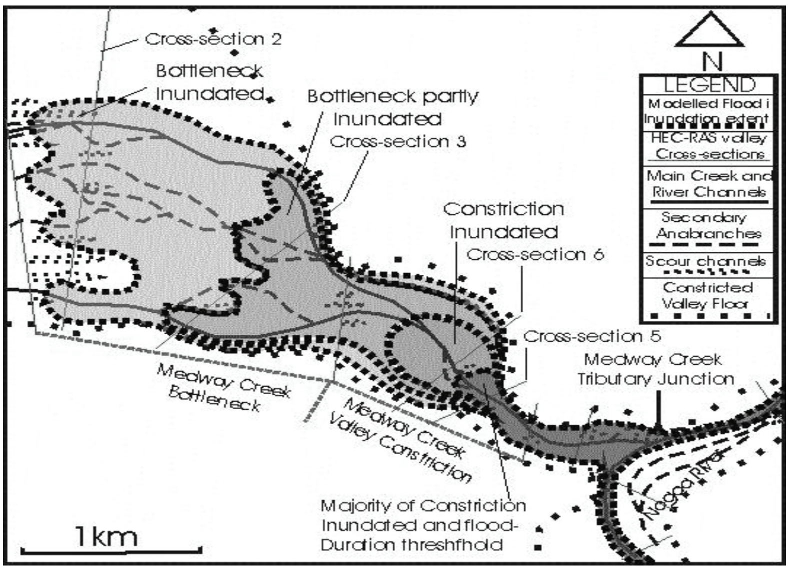

Fig. 3 Definitions used to identify the spatial extent of flood inundation through the study area.

Eight cross-sections were surveyed on Medway Creek, in addition to two upstream and one downstream on the Nogoa River (Fig. 3). Cross-sections 1–4 are subsequently referred to as the *bottleneck reach* while cross-sections 4–8 are referred to as the *constriction reach*, with cross-section 4–5 referred to as *the upper-constriction* (Fig. 3). Data were used to estimate channel geometry, channel and flood-plain slope and flood-plain width as used as input parameters for the one-dimensional flow modelling.

HEC-GeoRAS was used to model flood scenarios through the tributary junction. A 25-m DEM interpolated from a 1:100 000 scale topographical map with a 20 m contour interval is used to derive cross sections for the model. Given the coarse resolution in elevation in the DEM and therefore poor representation of flood plain topography, the modelling serves to illustrate flood scenarios only and does not provide an indication of actual flood depths and velocity (Purvis-Smith, 2007).

RESULTS AND DISCUSSION

Discharge characteristics

HEC modelling indicates bankfull discharges of 90 and 200 $m^3 s^{-1}$ for Medway Creek and the Nogoa River, respectively, representing flow recurrence intervals of between one to two years. Nogoa River floods equal to or exceeding 300 $m^3 s^{-1}$ produce flow over the flood plain. Likewise, discharges equal to, or exceeding, 120 $m^3 s^{-1}$ on Medway Creek produce flood-plain flow. These discharges have been met, or exceeded, 10 times on the Nogoa and 17 times on Medway from 1972 to 1985, the period of gauging data records.

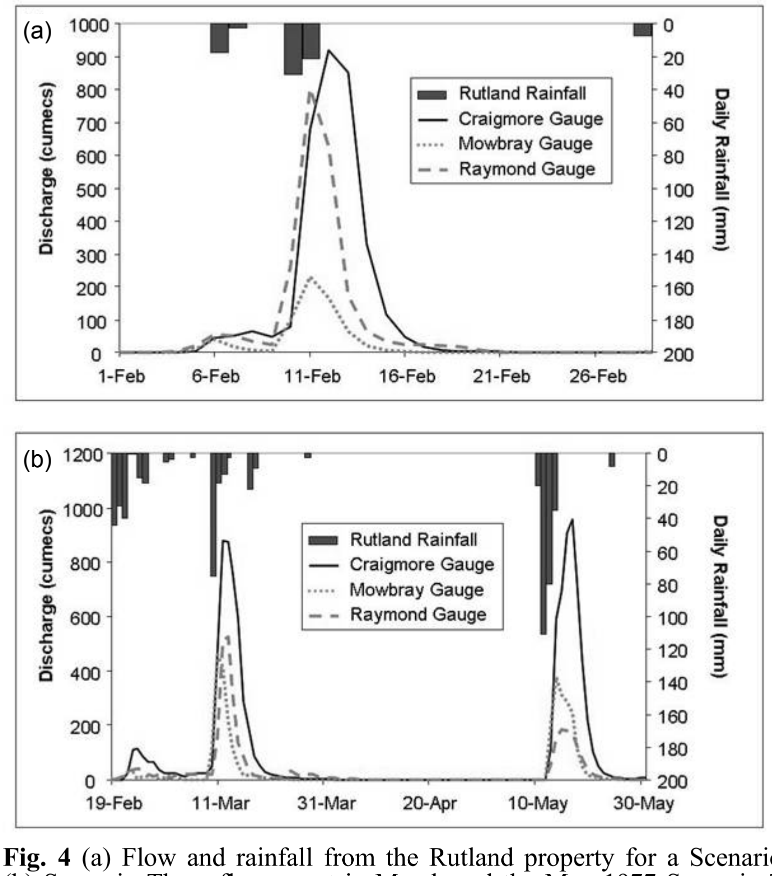

Fig. 4 (a) Flow and rainfall from the Rutland property for a Scenario One event in February 1980. (b) Scenario Three flow event in March and the May 1977 Scenario Two flow event. Dashed line = Nogoa River upstream at Raymond; dotted = Medway Creek at Mowbray; Solid = downstream of the junction at Craigmore.

The hydrographs of flood events over this period indicate three distinct flood scenarios passing the tributary junction. These are: (1) when the Upper Nogoa River is the dominant source of flood discharge downstream of the Medway Creek tributary junction; (2) when Medway Creek is a primary contributor to the Nogoa River discharge downstream of the junction; and (3) when Medway Creek and the Upper Nogoa River synchronously contribute flood waters to the junction.

Scenario One: Nogoa dominant During Scenario One flood events, flow from the Nogoa River will flow into the Lower Medway Creek channels and flood plain. The hydrograph of the February 1980 flood event illustrates the contrast been Medway and Nogoa flows (Fig. 4(a)) and provides a good indication of the lag time for a flood peak to travel from the Raymond Gauge to the Craigmore Gauge, which is a straight-line distance of around 50 km. The flood lag-time is approx. 2 days, the duration extended by one day, and the peak discharge is reduced by about 10% in transit. No rainfall is recorded at the Rutland property and, therefore the discharge at the Mowbray gauge (40 $m^3 s^{-1}$) is likely the total contribution of Medway Creek at the confluence.

S**cenario Two: Medway Dominant** The event of May 1977 (second hydrograph in Fig. 4(b)) provides an example of the occurrence of flood-events that are dominated by Medway Creek. The discharge at the Mowbray Gauge (Q10) on Medway is double that at the Raymond gauge upstream on the Nogoa River. High rainfall (280 mm) was recorded in lower Medway during the event.

Scenario Three: Both systems on the summer of 1973–1974 produced a series of storms resulting in the wettest summer on record for the lower Medway Creek. The resultant hydrographs for Mowbray gauge show sufficient discharge to exceed Q_{bf} in lower Medway Creek four times. Likewise, Raymond gauge indicates sufficient flow to equal or exceed the Nogoa's bankfull capacity near the confluence three times. The hydrographs also indicate sufficient overlap in timing of the flood peaks from Medway and Nogoa to indicate coincidence in peak timing at the confluence.

Modelled scenarios

The three flood scenarios described above were modelled using Q_5 flows for the dominant or "on" channels and 1 $m^3 s^{-1}$ for the "off" channel. HEC-GeoRAS modelling of Scenario One, Nogoa River dominant, illustrates the backwater effect on the lower Medway flood plain with flood waters backing up 3 km (Fig. 5(a)). The modelling results suggest that Nogoa River discharges that are larger than 280 $m^3 s^{-1}$ upstream of the Medway Creek junction will exceed bankfull as they back-up through the constriction. The flood discharge just downstream of the junction frequently

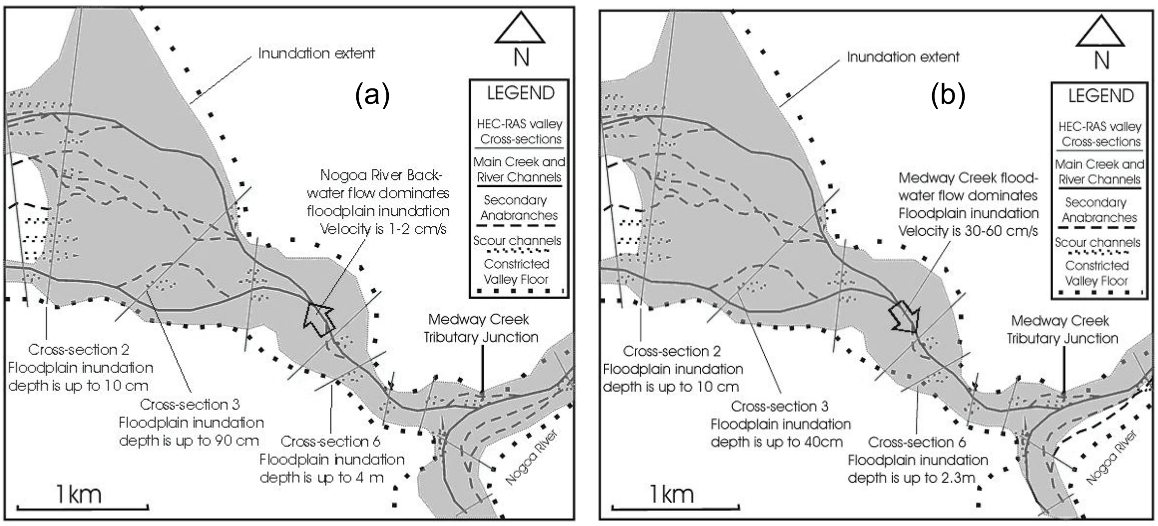

Fig. 5 (a) Back-water inundation modelled from discharges recorded on the 5 May 1983 when the Nogoa River dominates. (b) Modelled inundation extent from the discharge event recorded on the 14 May 1977 when Medway Creek flow dominates. Note direction of arrow denotes flow dominance.

exceeds this magnitude, often with little input from Medway Creek. Therefore, the Nogoa River discharge passing the tributary junction would regularly back-up and spread overbank in the constriction reach of Lower Medway Creek. While all of the flood peaks that were analysed inundated the constriction reach for several days or more, many smaller floods that have not been modelled would also have inundated this reach.

Modelling of Scenario Two, Medway Creek dominant, illustrates the more extensive flooding in the upper reaches. Less extensive flooding is evident in the mid to near confluence reaches as channel and flood-plain slope increase marginally. Water surface slope is also expected to increase near the confluence as flow enters a larger capacity channel which is unimpeded by Nogoa River flows (Fig. 5(b)). Discharges recorded on Medway Creek exceeded the predicted constriction inundation threshold during 26 independent flow events between 1972 and 1985. When both Medway and Nogoa River flood, the model indicates the most extensive flooding of Medway flood plain. While less Nogoa flow can ingress into Medway Creek, the higher water surface elevation of the Nogoa flow at the confluence impedes Medway outflow, reduces its water surface gradient and back-fills Medway Creek beyond the study area. Of the 10 flood-peaks modelled since 1972, only those that occurred in December 1975, March and May 1977, February 1978, April–May 1983 and January–February 1984 inundated the flood plain of the bottleneck reach. Of these, only the February 1978 flood, for 3 days at an average depth of 0.8 m, and the January–February 1984 flood, for 4 days at an average depth of 1.0 m, inundated the bottleneck flood plain to a depth likely to cause sedimentation at the upstream end (cross-section 2).

Model validation

Validation of the model predictions remained difficult up until recently when a series of flow events caused back-water inundation at the junction. For example, in October–November 2005, localized storms resulted in the flooding of a tributary (Vandyke Creek) of the Nogoa River, ~20 km upstream from the Medway Creek confluence. Flood records at Craigmore gauge indicate a peak flood of 77.4 $m^3 s^{-1}$. No rain or flow was recorded or observed in the Medway Catchment (Rutland Property, personal communication, 2006). Overbank sedimentation in the form of a 1-cm thick black clay layer was observed and GPS surveyed on the upstream Nogoa River cross sections. The basalt derived deposit from the eastern side of the Nogoa basin was traceable up the Medway Creek flood plain as a contrasting layer to the grey-cream silty-clay alluvium derived from the catchment's sand-silt- mud-stones and shale lithology. Here, the deposits thinned to 2–5 mm thick and had dried into sand-size pellets. The average survey deposit elevation was 285.3 m on the Nogoa River and 283.1 m in the lower Medway catchment. Within Medway's lower single channel, successive Nogoa flood deposits of black clay resulted in deep cracking beds upon drying.

The October–November 2005 event represented Scenario One, Nogoa on and Medway off. HEC-RAS modelling of the event indicates a significantly larger flood peak (~400 $m^3 s^{-1}$) was required to exceed bankfull to the extent of flood sedimentation on the Nogoa River upstream of the confluence, compared to the broadened peak of 77 $m^3 s^{-1}$ recorded at Craigmore below confluence. This difference can be attributed to the discharge that ingressed into Medway Creek and flood plain and other tributaries along the Nogoa River between Medway Creek and the gauge.

A more recent and larger event occurred in January 2008 when over 700 mm of rainfall fell within the Nogoa sub-catchment. Satellite imagery clearly indicates a Scenario Two flow regime with the Nogoa River backing up well beyond the upper cross-sections previously used in this study (Fig. 6). Communication with the local property owners at Rutland on Medway Creek indicated that the flood waters resided on the lower flood plain of Medway for over a week following this event. Detailed analysis of cores taken in this area is currently under way.

Limitations

Initial analyses in this study were performed using simple one-dimensional flow modelling. It is well recognised, however, that variation in the main river water surface elevations and in the tributary discharge requires unsteady flow modelling to completely analyse the situation. The affect of using bedslope, and not water surface slope, on shear stress and predicted bedload transport rates through the reach have not been investigated and currently are poorly considered in any sediment routing model (e.g. Prosser *et al*., 2001b). Nonetheless, this initial pilot study concluded that increased rates of sediment deposition observed at this bottleneck in the form of thick, dense clay layers were primarily due to the increased residence time of flood waters on the flood-plain surface due to backwater effects. Backwater inundation may be a dominant process in low-gradient, wide flood plain basins and accurate parametisation of this process will greatly improve flood inundation predictions for many areas.

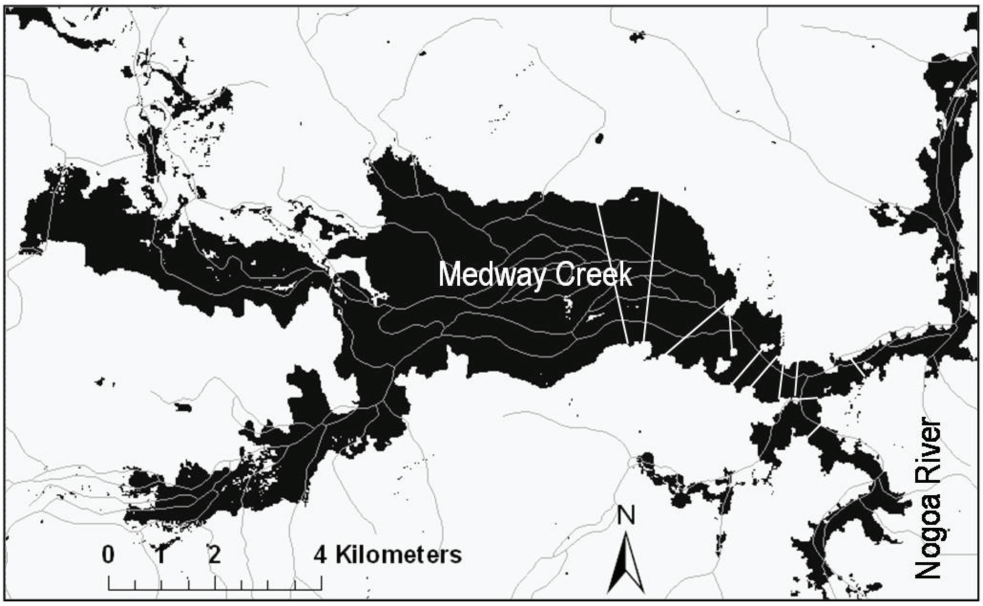

Fig. 6 Spatial extent of inundation from the January 2008 flood event on the Nogoa River.

CONCLUSIONS

Valley constrictions are recognised to form a barrier to flood waters and due to their effect on channel slope and flood plain width, are also likely to have important implications for the proportion of overbank discharge, and the residence times of floodwaters over flood plains. These two factors are well recognised as key controls in determining the proportion of sediment removed from the suspended load of a flood flow (Prosser *et al*., 2001b). Using a representative example of one of the 46 valley constrictions identified previously throughout the FRB, this study reveals some important considerations for the accurate prediction of flood inundation and sediment deposition on flood plains in this basin. Firstly, the timing of flood peaks between the tributary and the main channel was found to vary spatially and temporally, and resulted in the recognition of at least three relevant hydrological regimes: the dominance of tributary inputs only to the main channel; main stem only and a combination of tributary and main channel flow. It is the occurrence of the latter which was found to induce a process of backwater inundation. Due to reduced gradients in the main channel, and conversely over-steepening in the tributary, flood flows from the main Nogoa channel backfill several kilometres up into the tributary. This apparent delay of floodwater transmission through the tributary junction will increase the residence time and, therefore, suspended sediment deposition on the flood plain of Lower Medway Creek. In large semi-arid catchments it is important to consider these factors in the sediment delivery model framework. While it is not feasible to gauge the flood plain discharge above each constriction, residence time of floodwaters may be better predicted if the timing of flood peaks, and increased residence times of back-flow into confined tributary junctions is taken into account.

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