Potential impacts of levee construction in the Lockyer Valley

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Key Points

- Natural levees occur along 48 km of the lower Lockyer Creek
- The natural levees have reached threshold set up conditions for channel avulsion
- Post-flood land management has seen the construction of bank-top levees on existing natural levees
- Artificial levee bank construction can increase specific stream power and sediment transport capacity, decrease overbank deposition and lead to increased sediment delivery to end of catchment

Abstract

Natural levees are formed by the process of overbank flood sedimentation. In laterally-stable rivers, the height of levee development is assumed to reach some maximum whereby continued aggradation reduces overbank flooding. Large floods are required to overtop the levees and such events increase the risk of significant geomorphic change such as bank erosion, removal of inset floodplains/benches and channel avulsion. Lockyer Creek is a water supply catchment for Brisbane and managing the catchment for water quality as well as quantity to supply the local horticultural industry is critically important. Natural levees have evolved over the lower third of the main trunk stream, but since the recent floods of 2011 and 2013, uncontrolled artificial levee construction has occurred for flood protection. Terrain analysis showed natural levees occurring along 48 km of the lower Lockyer. Here, the natural levees have reached threshold set up conditions for channel avulsion. A one-dimensional (1-D) hydraulic model was constructed to assess the flow hydraulics of bankfull discharge along the lower Lockyer Creek under scenarios of both natural and artificial levees built on top of the natural levees to explore potential changes in hydraulics and sediment dynamics. Results show that increased channel capacity due to levee enhancement has increased bankfull mean specific stream power from 123 to 153 Wm^{-2}, but at a number of locations the specific stream power produced by the enhanced levees meant that the flow exceeded the threshold for geomorphic change (300 Wm^{-2}). The reduced flooding of the floodplain will decrease overbank sediment storage, thereby potentially increasing catchment sediment delivery to the mid-Brisbane River.

Keywords

Levees, avulsion, stream power, channel-floodplain connectivity, legislation

Introduction

Queensland was exposed to extensive flooding between November 2010 and April 2011 leading a State-wide natural disaster declaration. In this period, the Lockyer catchment was subject to a catastrophic flood causing significant loss of life and damage to infrastructure (QFCI, 2012). Buildings and towns built on floodplains were inundated and/or washed away. Meanwhile, in other Queensland catchments the towns of Goondiwindi, St George, Thallon, Mungindi and Dirronbandi were protected from floodwaters by artificial levee banks. The perceived effectiveness of these structures in mitigating against flooding has subsequently seen considerable ad hoc artificial levee construction along creek banks in the Lockyer catchment. The Queensland Floods Commission of Inquiry (henceforth QFCI) (QFIC, 2012) recognized the role of artificial levee banks in floodplain management, but also acknowledged their potential to cause damage and called for government to regulate their construction.

Within this context, the aim of this paper is to explore the potential geomorphic effects of artificial levees if the current ad hoc built levees are continued to be constructed along the lower Lockyer. In doing so, we start by describing the system on which the artificial levees are likely to be constructed. Specific questions addressed are (1) what are the characteristics of natural levees in the Lockyer? (2) Could 1m high artificial levees constructed on top of natural levees cause significant increases in specific stream power leading to geomorphic channel change? (3) What are the likely consequences of artificial levee construction on sediment delivery?

Thompson, C., Croke, J., & Dent, C. (2014). Potential Impacts of levee in construction in the Lockyer Valley, in Vietz, G; Rutherfurd, I.D, and Hughes, R. (editors), Proceedings of the 7th Australian Stream Management Conference. Townsville, Queensland, Pages 109-115.

Background

Natural levees

Natural levees are elevated topographic features forming the interface between the channel and floodplain. They form sinuous ridges of coarse sediment, relative to the floodplain, and display a triangular cross section (Brierley et al., 1997). The topographic high point of the levee is proximal to the channel forming the bank top. The distal side of the levee has a lower gradient as it slopes down towards the floodplain. Levees typically form as a result of rapid loss of flow competence, hence sediment deposition, once flow exits the channel. Deposition rate is greatest adjacent to the channel and decreases with distance; this is reflected in a fining of sediment distally (Tornqvist and Bridge, 2002). The presence of levees can influence flow routing and sediment dispersion on floodplains (Brierley et al., 1997) and frequently contain a valuable record of past flood events by representing the sediment and stream flow regime over medium time scales ($10^{2\text{-}3}$y) (Hudson, 2005).

Levees can be found in straight, sinuous, anastomosing, braided, unconfined and confined reaches/rivers and can occur on both banks, alternate from side to side or favour the outside of meander bends (Brierley et al., 1997). In meandering rivers, levees tend to have low preservation potential as the cutbank removes the levee as the river migrates across the valley floor. If the migration rate is similar to the levee accretion rate then the levee height can be maintained in a steady-state condition in the medium time scale (Hudson, 2005). Alternatively, in laterally stable channels, levee accretion will attain some elevation at which overbank flooding is reduced thereby decreasing channel connectivity to the floodplain. Increasing flood magnitudes are required to breach the levee and with this is the increasing risk of channel avulsion, which describes the abandonment of a channel in favour of a new course (Tornqvist and Bridge, 2002).

Artificial levees

The construction of artificial levees for flood mitigation has a very long global history. One of the most reported systems is the Mississippi River in the United States which by 1812 had approximately 160 km of levee constructed, increasing to about 1600 km by 1855 (Changnon, 1998). In the mid-1800s a ‘levee only’ policy was implemented and the federal government became increasingly involved in flood control and levee design. However, larger floods continued to occur breaching levees resulting in ever more significant social and economic costs. The 1927 catastrophic flood caused a policy shift to a multi-structure (e.g., levees, off channel storages, reservoirs) approach. By the 1950s it became widely accepted that a structural approach was inadequate and federal focus shifted to managing land use on the floodplains and introducing floodplain insurance (Changnon, 1998). The history of flood control and levee development along the Lower Missouri and Lower Mississippi Rivers has led to 90% of their respective floodplains becoming disconnected (Kesel, 2003). The Mississippi River now delivers ~750 million tonnes of sediment to the Gulf of Mexico annually (Tarbuck and Lutgens, 1984) which is exacerbated by floodplain disconnection by levees which increase flood stage and sediment transport capacity (Remo et al., 2012).

Levee bank legislation in Queensland

In Queensland, the first legislation introduced to regulate levee (and contour) bank development was *the Water Resources Act 1989* which sought to protect riparian vegetation and the physical integrity of a water course. The Act required the acquisition of a licence for levee or contour bank construction. In 2002 the *Water Act* replaced the *Water Resources Act 1989* which no longer regulated floodplain management and all existing licences for levee banks were repealed. Instead the Act focused on maintaining the physical integrity of a water course by controlling in-stream works and extraction of riverine material; and also managed the allocation of water resources.

Responding to the devastating 2011 southeast Queensland (SEQ) floods, QFCI was formed and made five recommendations for the regulation of levees with the aim of developing a consistent regulatory approach to address the impacts and risks associated with the construction of levees, including the potential for levees to increase the risk of flooding and thereby cause damage to the built environment and neighbouring lands (QFCI, 2012). In late 2012 an amendment to the Water Act 2000 was passed defining a levee [*as an artificial embankment or structure which prevents or reduces the overland flow water onto or from land. Excluded are farming related structures and fill that is no greater than 1m in height relative to the natural ground level at any point along its length*] and specified that the diversion of overland flow was an assessable development [requires submission of a development proposal] under the *Sustainable Planning Act 2009* (SPA). The new levee code became law on 16 May 2-14 and considers three levee categories: Category 3 – typically protecting urban areas (impact assessable), Category 2 – typically a rural/agricultural levee (code assessable), and Category 1 – small scale levee around an individual’s house or property (self-assessable).

Study area

The Lockyer Valley lies to the west of Brisbane and is a 3000 km^2 subcatchment of the Brisbane River (Figure 1). The headwaters drain the Great Dividing Range (~800m Australian Height Datum,AHD) delivering water and sediment to the wide (2 – 13 km) floodplain which supports one of Australia's most productive horticultural regions with a Gross Region Product of $166 million in 2011/12 (LVRC, 2013).

The catchment geology comprises Main Range Volcanics (Olivine basalt) on the divide. The headwaters have incised down to, and flow across, the Marburg subgroup (Jurassic sandstones, siltstones, shale). Quaternary terrace and floodplain alluvium deposits commence near Helidon enveloping the main channel down to the Brisbane River confluence. This study focuses on the lower Lockyer downstream of Gatton which has been described as an expansion reach (Croke et al., 2013a) as the 2011 flood waters breached their banks along much of this section inundating the floodplain. Here, the channel planform alternates between low sinuosity reaches and tight meandering bends which have incised into bedrock (Marburg subgroup). Natural levee soils are dark clay loam to light clay with dark brown neutral to alkaline structured subsoil (Powell, 1987). Floodplain soils surrounding the levee are generally described as dark self-mulching, cracking medium to heavy clay.

The January 2011 flood event has been rated as the second highest flood of the past 100 years, after January 1974 in the Brisbane River catchment (BOM, 2011). A detailed account of the event's meteorological and hydrological characteristics is provided elsewhere (Jordan, 2011). Measured flood peak discharges in the Lockyer ranged from 361.5 m^3s^{-1} in the headwaters (Spring Bluff GS) to 3642 m^3s^{-1} in the mid-valley (Helidon GS) and 1453 m^3s^{-1} in the lower Lockyer (Rifle Range Road GS). In January 2013 ex-tropical Cyclone Oswald delivered further flooding rains to the catchment, this time mainly impacting the southern tributaries and lower Lockyer with peak discharges of 41 m^3s^{-1}, 433 m^3s^{-1} and 1238 m^3s^{-1} at Spring Bluff, Helidon and Rifle Range Road gauges respectively leading to overbank flooding along lower Lockyer Creek.

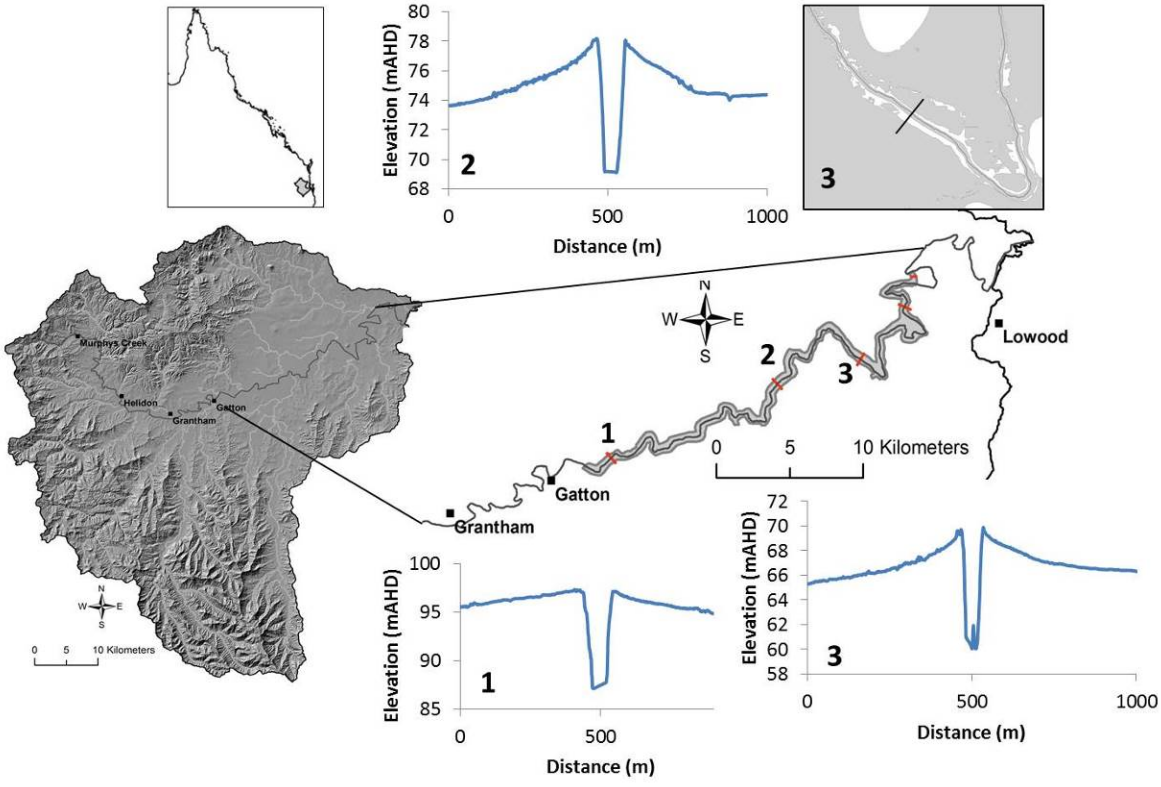

Figure 1. Lockyer Creek catchment in southeast Queensland showing the lower lockyer reach with natural levee extent (grey polygon along channel) and representative XS profiles. Numbering relates to XS number along the main channel. An example of non-inundated (white) and inundated levee/floodplain (grey) is shown in top left inset at XS 3. Flow from left to right

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Methods

To evaluate the two main objectives of this paper, terrain analysis of high resolution spatial and temporal topographical data has been conducted. This was used as input data to a one-dimensional (1D) hydraulic model HEC-RAS which investigated changes in key variables with- and without levee enhancement.

High resolution topographic data

This study uses LiDAR data acquired for approximately 1300 km^2 over the Lockyer Valley in 2010 and an entire catchment capture (~3000 km^2) following the floods in January and February 2013. For the purposes of this study, a subsection encompassing the lower Lockyer main channel has been selected (Figure 1). The cleaned, error-reduced point cloud data were used to construct 1m DEMs for both time periods. The accuracy of both DEM surfaces was quantified using a detailed statistical analysis of the probability of error. Natural levee attributes were derived from cross sections (XS) created in HEC-GeoRAS used to define the hydraulic model geometry (see below). Slope ratio was calculated as the levee slope towards the floodplain divided by the mean downstream slope of the floodplain. Normalised super elevation was calculated as the levee height (elevation difference between levee top and edge of levee progradation) divided by bank height. To determine changes to levee banks between 2010 and 2013, a DEM of Difference (DoD) was computed by subtracting the 2010 DEM from the 2013 DEM. The DoD was error rectified according to procedures outlined in Croke et al. (2013b). Estimates of levee change were quantified from the DoD by classifying positive elevation change (deposition) along the channel banks (≥ 0.4 m).

Hydraulic modeling

Hydraulic assessment was undertaken using the 1-D HEC-RAS model to determine bankfull flow capacity (Q_{bf}) and specific stream power (ω, Wm^{-2}) for three scenarios; (1) replication of the pre-flood (2010)channel-floodplain geometry with natural levee, (2) a 1m increase to natural levee elevation for the model length (artificial levee), and (3) a break in artificial levee. The model was also used to assess the number of locations (cross sections, XS) the levee was overtopped for natural levees and artificial construction (+1m). The model was run over a 30 km reach starting at the first upstream occurrence of natural levees on the main channel. The 2010 DEM did not cover the full extent of levee development downstream. In HEC-GeoRAS, 225 XSs at an average spacing of 130 m were created. Natural levee alignment was digitised to provide a lateral barrier to prevent the model from dividing the flow out onto the topographically low floodplain areas until the levee was breached. Manning's *n* was based on Chow (1959) with values of 0.06 selected for the channel area and 0.035 for the floodplain to reflect a mosaic of vegetable crops, fallow ground, lucerne and pasture. Upstream boundary condition was set to the critical depth, downstream to the normal depth and the model was run as a steady model in mixed flow regime mode.

Results

Natural levee characteristics in the Lockyer catchment

Natural levees occur from 22 km to 70 km above the Brisbane River confluence between Gatton and Lowood, along both straight and meander sections (Figure 1). This 48 km levee section appears relatively continuous on both banks except for tributary junctions and road crossings. However, flood inundation modelling showed variations in levee elevation relative to water surface elevation illustrated by numerous flood breakout points along the levee (e.g. Figure 1 XS 3). Levee widths range from 65 m to 3.7 km, depths between 1 to 9 m and gradients towards the floodplain of between 0.2 to 4.6 % (Table 1). The average floodplain slope along the modelled reach is 0.11 % and 0.09 % for the left and right overbank areas respectively. This resulted in mean slope ratios (across floodplain to downstream along the floodplain) > 6. The ratio of levee to bank height (normalized super elevation) varied from 0.1 to 0.8 %.

Table 1. Characteristics of levee form along lower Lockyer Creek extracted from DEM cross sections.

Attribute	Left bank		Right bank	
	Mean (±σ)	Range	Mean (±σ)	Range
Levee width (m)	1130 (871)	114 – 3722	931 (797)	65 – 3105
Levee height (m)	5 (2)	1 – 9	4 (1.4)	1 – 8
Slope ratio	6.4	1.8 – 11	8.9	1.1 – 16.7
Normalised super elevation	0.4 (0.2)	0.1 – 0.8	0.3 (0.1)	0.1 – 0.6
N	135		142	

Artificial levee construction

The ad hoc bank top artificial levees have been constructed by either earthmoving machinery pushing up channel bank and floodplain soil, or trucks dumping off-site soil. Both methods deliver linear topographic features approximately 4m wide at the base, narrowing to 2m at the top, and 1m high of unconsolidated soil. Analysis of the DoD showed only 7.6 km of levee building between 2010 and March 2013. However, this is likely to be a very conservative estimate for two reasons. Firstly, a new geoid was used for the 2013 LiDAR leading to as yet unquantified changes in vertical projection across the catchment. Secondly, field visits have shown that much of the artificial levee construction has taken place after the LiDAR capture in June 2013.

Hydraulic analysis of bankfull flood conveyance

The main channel Q_{bf} with natural levees decreased from 1710 m^3s^{-1} at the top of the modelled reach near Gatton, down to 1000 m^3s^{-1}. The artificial levee scenario produced a Q_{bf} of 2230 m^3s^{-1} at the top of the modelled reach, and showed a decreasing trend down to 1230 m^3s^{-1}. Specific stream power for natural levee and the artificial levee scenarios varied considerably along the reach with a mean ω of 123 Wm^{-2} (σ 59) for natural levees and 153 Wm^{-2} (σ 75) for the artificial levee (N= 213) (Figure 2). Results of a paired *t*-test showed the increase in ω for the artificial levee scenario was significant ($p < 0.05$). The artificial levee scenario also resulted in a number of XS (at 55 km, 68 km, 70 km) with ω exceeding 300 Wm^{-2}. Similarly, the levee break scenario resulted in ω exceeding 300 Wm^{-2} in the main channel at the break point at 60 km (Figure 2).

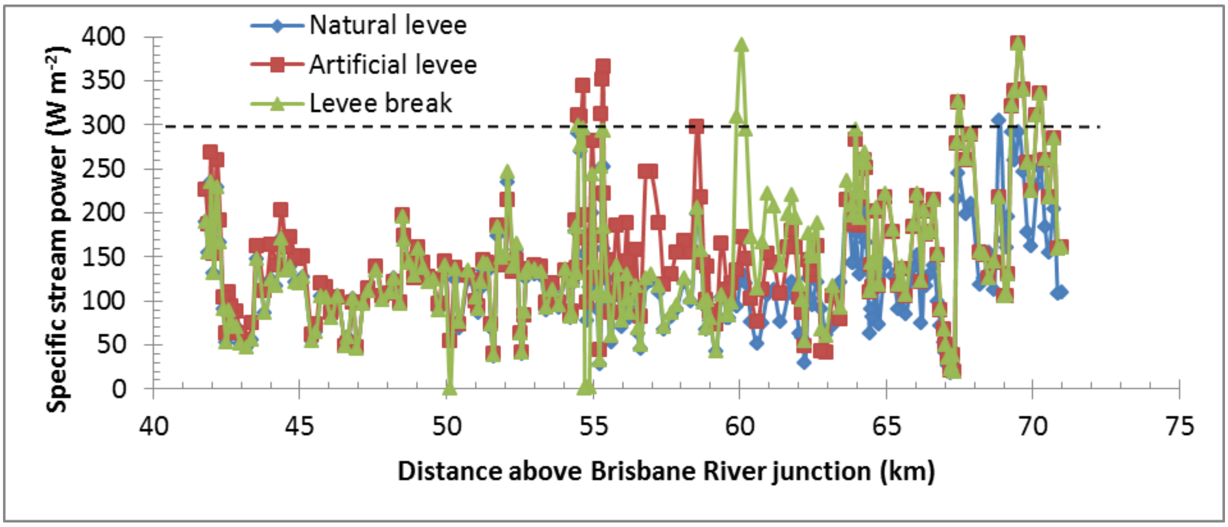

Figure 1. Specific stream power along the modelled reach. Dashed line marks the geomorphic change threshold of Magilligan (1992).

Discussion

Hydrology, hydraulics and the fate of sediment

Hydraulic modelling of the lower Lockyer reach showed that the addition of a 1m high artificial levee bank, which is a self-assessable Category 1 development, can increase bankfull ω by 24% thereby resulting in flood peak specific stream power exceeding the threshold of 300 Wm^{-2} for major geomorphic change (Magilligan, 1992) at river distances 55 km, 68 km and 70 km (1.5 km total length). Exceedance of this threshold was shown to correlate with high fluvial entrainment and erosion in the upper Lockyer during the 2011 flood event (Thompson and Croke, 2013).

A flow-on effect of the artificial levee increasing channel capacity is the proportional decrease in overbank discharge. Croke et al. (2013a) using a sediment budgeting approach with LiDAR data showed that significant sediment deposition occurred over the lower Lockyer floodplain reach during the 2011 floods. Therefore, any reduction in channel-floodplain connectivity would result in increased sediment delivery along the main channel (Remo et al., 2012). Two-D hydraulic modeling is required to quantify overbank discharge losses and partition lateral sediment storage from main channel sediment delivery which is beyond the scope of this study.

Levees and channel evolution

The presence of natural levees is indicative of an aggrading floodplain (Hudson, 2005). However, evolution of natural levees in laterally stable channels, such as the Lockyer, also means their continued buildup requires ever larger or rarer floods which increase the risk of channel avulsion (Hudson, 2005). The average recurrence interval of Q_{bf} for the lower Lockyer is between 25-30 years (Croke et al., 2013a) which represents a relatively rare event. This fact may indicate that the lower Lockyer natural levees have evolved towards some maximum elevation self-limiting overbank flooding. This represents one of the key setup conditions for channel avulsion (Slingerland and Smith, 2004; Aslan et al., 2005). Other conditions include the thresholds of floodplain (across to downstream) slope ratio (3 – 5, Tornqvist and Bridge, 2002) and normalized super elevation (0.5, Mohrig et al., 2000). The lower Lockyer reach equals or exceeds these values in a number of locations indicating a high probability of channel avulsion. It is noted however, that while slope advantages and super elevation are required factors for avulsion, they do not guarantee an avulsion or avulsion success (Aslan et al., 2005; Phillips, 2009). Phillips (2012) describes, in addition to set up factors, triggers which are conditions or events required to divert flow away from the main channel and initiate avulsion. Triggers include flood magnitude, flow obstructions and factors leading to lowering of banks or levees (Phillips, 2012). For example, the avulsion of the perched Thomson River in Victoria was triggered by flood magnitude once the set up conditions were established (Brizga and Finlayson, 1990). Log jams caused flow obstructions leading to a number of avulsions on the San Antonio Delta rivers (Phillips, 2012). Recent floods in the Lockyer catchment stripped much of the riparian vegetation from along the headwater channels and log jams were described as contributing to the cutting of a flood chute (Thompson and Croke, 2013) but there was no reported log jams in the lower Lockyer. An alternative trigger condition did present in the lower Lockyer in the form of bank mass wasting (Grove et al., 2013). These wet flow mass failures propogated back into the bank and levee system forming a low point. The mass wasting occurred on flood recession such that they have potentially set up a low point for flow diversion for subsequent high magnitude floods.

The enhancement of levees along the lower Lockyer Creek through the construction of artificial levees has the potential to hasten the system towards avulsion by firstly increasing the slope ratio and normalized super elevation which is already within the setup condition. Secondly, the increased channel capacity allows larger flows to be conveyed. Any discontinuity of the levee system or failing of the earthworks provides a flow diversion point with serious overbank flooding and erosion consequences (e.g. Changnon, 1998). Thirdly, if flow is diverted onto the floodplain, enhanced levee banks may prevent the return flow to channel thereby exacerbating the length of channel avulsion. These are hypothetical scenarios, but the Lockyer appears to be a system with many of the conditions conducive to avulsion. Management for flood mitigation needs to recognize the systems potential for avulsion and manage the high risk reaches accordingly which includes building resilience into adjacent floodplains.

Conclusions

Specific questions asked in this paper were: (1) what are the characteristics of natural levees in the Lockyer, (2) could a 1m high artificial levee construction (on top of natural levees) cause significant increases in specific stream power leading to geomorphic channel change ?, and (3) what are the likely consequences of artificial levee construction on sediment delivery? Based on analysis of high resolution terrain data we described the occurrence of 48 km of natural levee along the lower Lockyer which have now evolved to be close to a threshold for channel avulsion. Lockyer Creek is also susceptible to the various trigger conditions described in the literature. Hydraulic modeling showed the construction of Category 3 levees along the lower Lockyer (on top of natural levees) will increase ω by 24%. The increased ω results in the geomorphic change threshold being exceeded in a number of locations and is likely to result in increased channel erosion and sediment delivery to the catchment outlet during bankfull events. To further exacerbate sediment delivery is the increasing channel-floodplain disconnectivity by increasing channel capacity. Hydraulic modelling also showed that breaks or gaps in levee extent will also lead to ω exceeding geomorphic change thresholds. Additional study into avulsion factors such as floodplain aggradation rates, mapping of paleochannels, and 2D modelling of overbank flooding is required. The potential of channel avulsion is a risk and management actions affecting any of the setup and trigger conditions need due consideration.

Acknowledgments

ARC Linkage project (LP120200093) with partner organizations' DSITIA, SEQ Water and Lockyer Valley Regional Council. Thanks to Ian Rutherfurd and DSITIA for reviews which have improved the paper.

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