Understanding the evolution of floodplain channels by avulsion: An investigation on the floodplain of Murray River

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Key Points
Avulsion
Floodplain-levee channel
Levee hole

Abstract

The evolutionary sequences of avulsion induced floodplain channel include a successful entering of floodplain flow into river channel as a major development step. Understanding of the evolutionary sequences of such floodplain channel has significant implication on paleo-environment reconstruction, floodplain stratigraphy and overall stream management issue. There are well recognized models available describing the evolutionary sequences of floodplain channel. According to those models, floodplain channels develop via downvalley progradation of crevasse-splays and subsequent entering of floodplain flow into a channel nearby or via up-valley migration of head-cut following an entering of floodplain flow into a channel. However, the detailed hydraulic and erosion processes that ensure a successful entering of floodplain flow into river are not quite clear. We hypothesize that a successful flow entry depends upon a direct connection between floodplain-levee channel and the river nearby. This study aims to explore the processes by which the floodplain-levee channels located on the Murray floodplain can connect to the river nearby. There are abundant floodplain-levee channels of different development stages, makes this place ideal for this investigation. Geomorphic mapping of these channels and related features along with simulating hydraulic processes and investigating field evidence have identified that the connection between floodplain-levee channel and river has certain stages involved: levee hole, levee channel, and then reversing slope of the levee channel. Overall, the levee channels connect to the river when the channels will have slope towards the river, thus resulting a successful entry of floodplain flows.

Keywords

Avulsion, Floodplain-levee channel, Levee hole, floodplain flow return

Introduction

Avulsion is a fluvial morphodynamic process that creates a new floodplain-levee channel due to the abandonment of an active channel. The to date references suggest that the development processes of such floodplain-levee channel are complex involving a wide variety of distinctive evolutionary sequences, some of them are still unknown. Until now the sequences demarcate the development boundary from a tiny channel to an elongated and mature one so that it can defeat the main channel from hydrologic perspective (Erskine et al., 1993, Field, 2001, Schumm et al., 1996, Smith et al., 1989, Stouthamer and Berendsen, 2000, Miller, 1991, Makaske et al., 2002). But the Murray investigation has made the development boundary more widen and explanatory.

There are two alternative doctrines available in the relevant research community regarding how floodplain-levee channel evolves via avulsion. One doctrine, Smith et al. (1989) can be considered as pioneer of the doctrine, proposes at the beginning, an intricated network of crevasse-splays is developed on a floodplain, from which one of the splay channels becomes dominant in the network and re-connects a main stream at downvalley. Later, with further development, this splay channel gradually captures most of the main channel flow and becomes dominant course in the system. Another doctrine, Schumm et al. (1996) can be considered as pioneer of the doctrine, denotes that a floodplain flow moving downvalley can drain into a river, forms a knickpoint at the draining point, which propagates towards up-valley creating a channel through the floodplain. The channel can connect with another floodplain channel at up-valley, thus forming a continues channel section over the floodplain. This newly developed floodplain channel section may dominant in the system capturing the river's flow and bed-load.

The review of existing studies describing avulsion mechanisms in the formation of floodplain channel indicates that there is something yet to be elucidated. As per classical avulsion mechanism models and studies (e.g., Donselaar et al. (2013) and Li et al. (2015)), the floodplain flow is found to drain back into the main stream downvalley either through channelized or non-channelized forms. This draining back of floodplain flow into the main stream has made the avulsion inherently more complex than any other flow diversion mechanisms (e.g. cut-off) due to the main stream having levees along its length and the timing of drainage having recession period. To date, no consensus has been found that explains the detail processes of how floodplain flows would connect and drain back into the main stream.

The relevant research community however highlight an alternative approach of avulsion, where entering of floodplain flow is not must. But this thought does not put forward the creation of a floodplain-levee channel by avulsion, instead it refers to the rejuvenation of an abandoned floodplain channel (Goswami et al., 1999, McCarthy et al., 1992, Perez-Arlucea and Smith, 1999, Smith et al., 1998, Bernal et al., 2011, Stouthamer et al., 2011).

So far, the approaches for investigating how floodplain channels evolve overtime have included analysis of facies geometries sometimes with image interpretation (e.g. Smith et al. (1989), Donselaar et al. (2013), Li et al. (2015)), long and cross-sectional elevation profile analysis (e.g. Schumm et al. (1996), dating techniques (e.g. Stouthamer and Berendsen (2001), Tooth et al. (2007)), Törnqvist (1994)), mathematical derivation adopting a conceptual model (e.g. Slingerland and Smith (1998), Nanson and Huang (1999) or a physical model (e.g. Mackey and Bridge (1995). Each of the approaches has particular scope of analysis. For example, facies and stratigraphic interpretation describe the sedimentary product but not the process in detail. Mathematical derivation and physical model experiments, as they need to simplify the complex response behavior of the natural system, they often could not analyze many vital underlying processes.

To investigate the key process based on the research problem identified, I have investigated the detail succession of selected floodplain-levee channels aiming to avulsions. The investigation area is on the Murray floodplain in Kanyapella paleo-lake. This investigation allows us to not just draw an explicitly definite association of floodplain channel from geomorphic interpretation but explore hydraulic forces and processes associated. This study thereby makes the existing avulsion models more specific and precise as well.

Aim and objective

The aim of this study is to make the existing avulsion models in the formation of floodplain channel more explanatory and understandable than before. This aim comes up when the avulsion models are reviewed and a mystery centering the draining back of floodplain flow into the main stream is found out.

General description of the study area

The study area has been selected within the Murray's middle alluvial reach, the Lake Kanyapella, a large paleolake (Figure 1). However, the history denotes that the Murray did not flow within this lake, it comes there after six major avulsions took place at further up-valley around Tocumwal, Green Gully creek, Edward River, Bullatale Creek and Picnic Point over the last 60,000 years (Bowler, 1978). Rutherfurd (1994) finds the reaches of Murray in the Kanyapella are highly variable in channel form. The river frequently shows abrupt change in planform and cross section, and often associated with anabranching reaches and paleo-channels. Within the study area, width-depth ratio of the Murray river typically be 11 where the width stays typically 90 m through the reaches. The river bank and floodplain materials are mostly light brownish grey medium silt with some molted Manganese (Stone, 2006). The floodplain is enriched with river red gum forest (Eucalyptus camaldulensis).The geomorphic origin of Lake Kanyapella is about 25 ka. Bowler (1978) says when the Cadell Fault defeated the Goulburn River, the river continued in the fault-angle depression, thus the lake formed in the depression. The climate of the study area is cold and temperate. The precipitation in the river catchment is 1,400 mm in the headwaters, which becomes 600 mm at Albury a downstream area of the river from headwater (Walker et al., 1986).

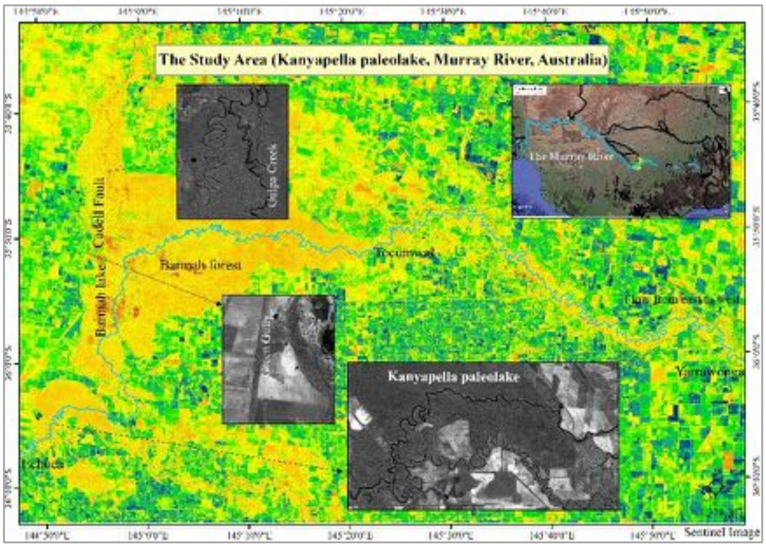

Figure 1. The study area map (Kanyapella paleolake). The map at upper right shows the whole Murray River and the location of where the study area is.

Overview of the methodology

Geomorphological mapping

Table 1 is the list of geomorphic features and their respective measurements identified for the geomorphological mapping exercise. For this mapping exercise the Digital Elevation Model- Light Detection and ranging (LiDAR)-1m resolution datasets of two different periods (1999 and 2011) have been utilized. The GIS interface- ArcGIS 10.5 has been used in this mapping exercise. The software has model building facility, can incorporate various GIS operations, applying them one can perform different kinds of spatial analysis. I have built such an ArcGIS model, which allows me to perform this geomorphological mapping ahead of the study aim.

Table 1.List of geomorphic features identified in the geomorphological mapping

Geomorphic features	Natural levee	Hole on natural levee	Floodplain channel	Floodplain
Measurements	Back slope	Volume	Distribution	Mean direction
	Levee width	Distribution	Type of origin	Geometry (width-depth)
		Geometry (width-depth)	Direction of development	
		Direction of development	Geometry (width-depth)	

Hydraulic simulation

A linked two-dimensional, non-uniform hydraulic model of different channel sections of the Murray River in Kanyapella has been assembled using the software model Hydraulic Engineering System- River Analysis System (HEC-RAS), version 5.0.3. The software is developed by the US Department of Defense, Army Corps of Engineers. The software is capable of modelling the hydraulics of water flow in a given river-floodplain system. In this study, the hydraulic properties investigated using the HEC-RAS include- flow direction that determines the stages of floodplain-levee channel, and shear stress That indicates the erosion-deposition potentiality of the geomorphic features modelled. For some specific cases, this erosion potentiality indicates at which stage a certain geomorphic feature is now.

Results and discussions

There are many channels of different development stages available on the Murray floodplain-levee in the study area. Hydro-geomorphic investigation of those channels and associated geomorphic features leads process exploration of how the floodplain-levee channels connect to the Murray. There are certain stages of geomorphic events involve in the whole processes of this connection as obtained. Those are described below.

Stage-IA: Origin of levee hole

In the study area, there are numerous holes available on the river levee. The holes are found specifically from few meters back of levee top (Figure 2 left). The origin of those holes is due presumably by less overbank deposition rather than scouring of the levee materials. Field investigation on several holes developed on the Murray levee did not get any evidence of erosion. Rather, it got some signs of deposition (Figure 2 left). It is most likely that during flood events, the generated bed shear stresses on the hole corresponding levee points are neither enough to erode the levee materials nor so less to deposit sediments at same amount as surroundings. The generated shear stress into overbank flows occur less amount of deposition that surroundings. The levee in the studied portion is only ~0.5 m thick deposited over the last ~460 years (Stone, 2006). The levee materials are mostly medium silt. Figure 2 (right) shows the typical face of the river bank in the study area.

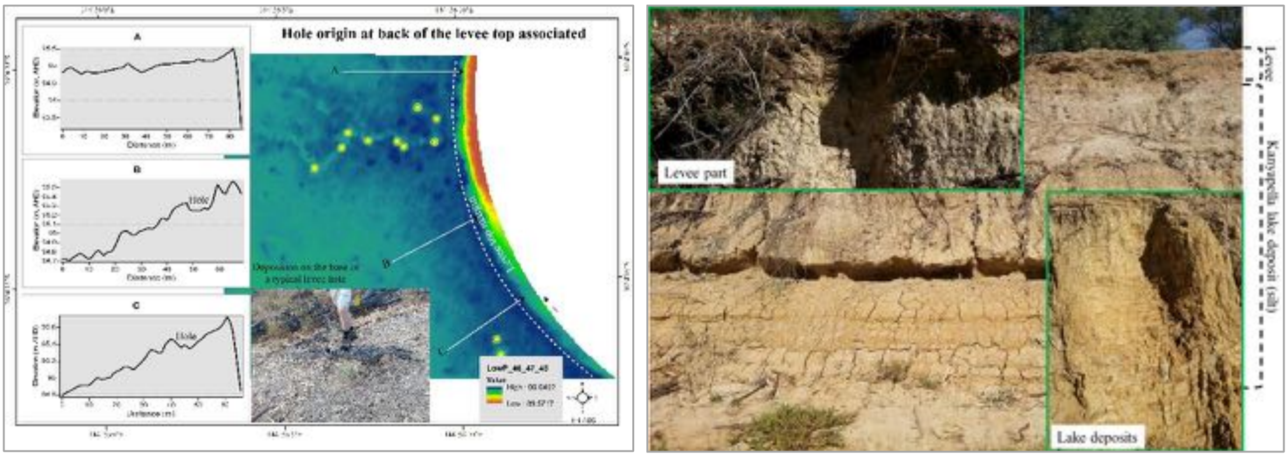

Figure 2 The map (left) in the figure shows that the holes (yellow circle) origin at back of the levee top. The graphical representation of long profiles: A,B,C denotes where the levee top and hole are (dotted white line in the map shows the margin of levee top). The inset image in the map shows deposition on the base of a typical levee hole investigated. The image (right) shows the river bank face near to a typical levee hole.

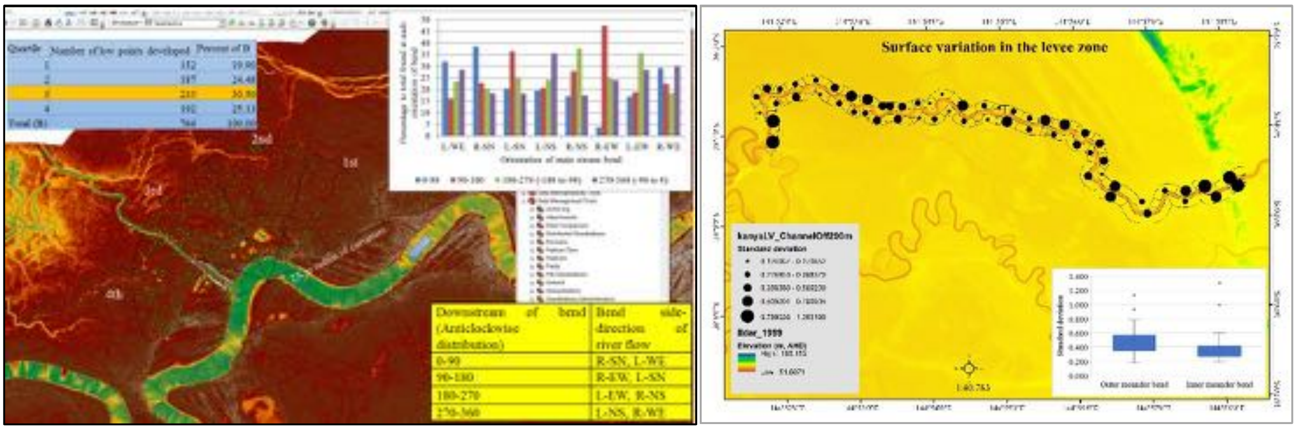

Figure 3 The image shows the distribution of the Murray levee holes in a typical study section. The 3rd quartile of the river bend has the highest percentage of holes. The graph inserted in the map showing the spatial distribution (in %) of levee holes in the whole study area. The table inserted shows how can we identify the downstream of bend for each type of bend orientation. For example, in the table 0-90 as bend zone indicates this is the downstream of bend for the case of R-SN and L-WE. The map in the figure shows the topographic variation (standard deviation of elevation) in the levee zone of the Murray River in Kanyapella section. The graph in the map shows the distributional range of standard deviation of surface elevation (Z) at outer and inner meander bends.

The distribution of levee holes is another critical to understand for the origin and development of levee-floodplain channel. Figure 3 (left map) shows a typical section of the Murray floodplain, downstream of Tocumwal and North of Bearii, Victoria, where the third (3rd) quartile of the bend outside (downstream of bend) has the highest number of levee holes. As a whole, it is a common scenario as shown in the inset graph in the map, and similar observations to Smith and Pearce (2002) and Beltaos et al. (2011). The origin of these levee holes preferentially in downstream of meander bends apex can be explained by interface vortexes and their generated bed shear stress available in the zone during shallow floods. A very recent numerical study by Moncho-Esteve et al. (2018) has shown that during shallow floods, several zones of concentrated higher bed shear stress are appeared in the downstream of meander bend apex not in other areas of the floodplain modelled. As a result, a levee hole originating topographic variation can be come out in the downstream of meander bend apex unless the meander planform is unstable. The Murray's meander activity is very slow (Dixon et al., 2018). So, we can expect such zones of concentrated higher bed shear stress in the downstream of the meander bends apex along with significant topographic variation, from where the levee holes are generated presumably by less overbank deposition. Figure 3 (right map) shows the outer meander bends of Murray have significant topographic variation than inner meander bends.

Stage-IB: Development of levee holes

The development of levee holes after having a certain volume is then run by erosion. In general, erosion in the levee holes take place when those holes expose with bigger floods, ensuring more shear stress to scour. Figure 4 shows the shear stress layers over the levee holes generated at different return periods of flood.

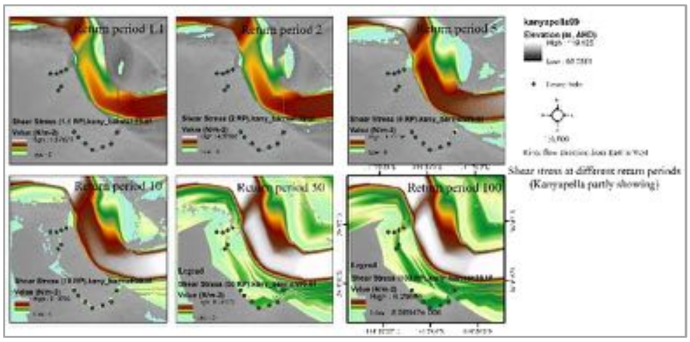

Figure 4. Shear stress layers at different return periods generated from HEC-RAS hydraulic simulation.

Further, in the study site, erosion in the levee holes has been found due when their respective nearest river bank comes close to them. One of such sites, which has now evidence only has been shown in the Figure 5 (left map). The HEC-RAS simulation shows that for majority of the cases (62%) site shear stress increase into holes as their respective nearest river bank migrates towards them and decreases when the bank migrates away (Figure 5 right map).

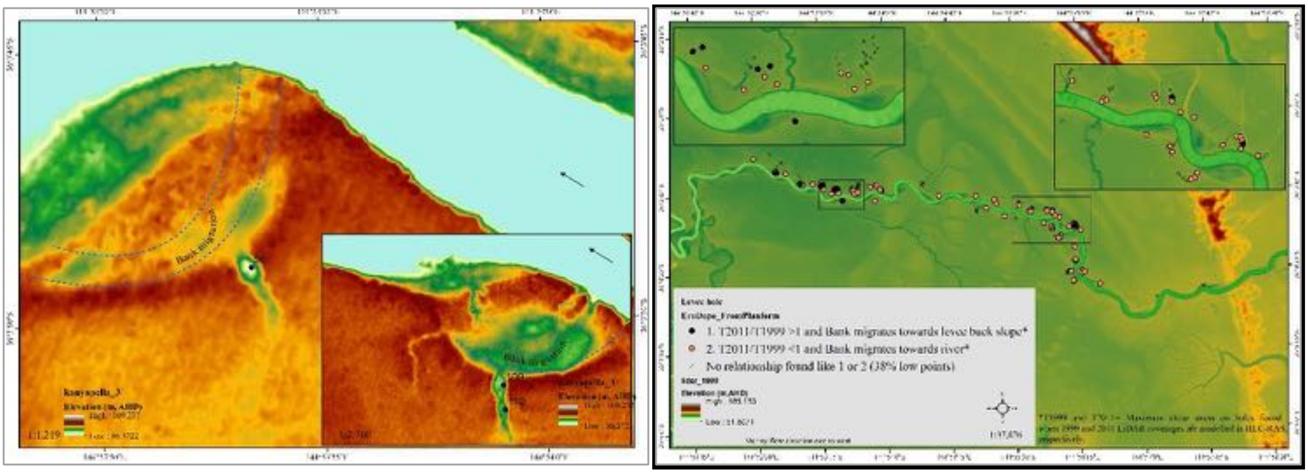

Figure 5. The map (left) shows the locations of the levee holes-56 and 109 are at such position where the nearest river bank used to locate touching the holes' edges. Presumably, those holes experienced more erosion when their respective river bend was close to them. The map (right) shows the levee holes having change in shear stress depending on the direction of nearest bank migration (LiDAR 1999 to LiDAR 2011).

Stage-IIA: Origin of levee channel

On the Murray levee when the multiple holes originate they mostly follow a linear distributional pattern to locate (Figure 6). We suggest this pattern is due by line of interface vortices formed when overbank flow invades floodplain from river (Sellin, 1964). The center of these vortices could induces less overbank deposition at corresponding levee, thus forming a linear distributional pattern of holes' position (Zawada and Smith, 1991). When these holes get bigger, coalescence among themselves can form levee channel. Zawada and Smith (1991) suggest the levee holes when coalescence, become connected by head-cutting and or by downstream erosion.

We have observed that the direction of slope of the levee channels is towards the floodplain following the levee back slope. Also, we have observed the connection between the levee channels and the river is uncertain at this stage. The connection in fact depends on the closest hole from river. If that hole has already been touched the river bank migrating towards the holes, then a direct connection between the levee channels and the river is possible.

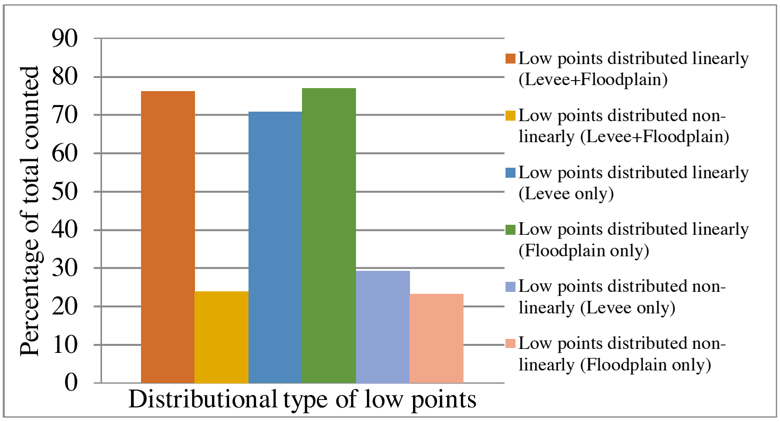

Figure 6. Distributional type of the Murray levee holes.

Stage-IIB: Development of levee channel and connection with river

Over the period of time, the Stage- IIA levee channel gets wider and deeper due to in-channel erosion. Zawada and Smith (1991) suggest this in-channel erosion during flood maintains the channel cross-section. We agree with this statement and suggest further that this in-channel erosion (deepening) reverses the direction of slope of Stage-IIA levee channel, thus bringing the slope towards river. This is the Stage-IIB levee channel. Figure 7 shows the levee channels of different development stages (*Stage-IIA and Stage- IIB*) in Kanyapella. Their development stages are based on their respective direction of slope. In terms of connectivity with the Murray, the Stage-IIB levee channel's connection is very much likely than prior stage. Because to attain this stage- IIB (slope towards the river) the levee channels must need exposing with erosion for long time, and meanwhile the river bank gets chance to come close to the channels' mouth and establish a physical connection.

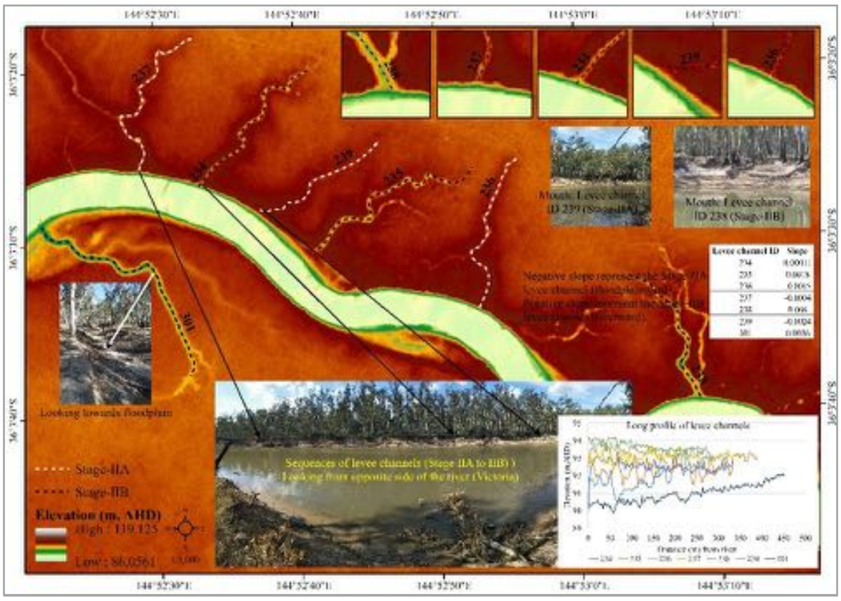

Figure 7. The map shows several levee channels of different development stages (*Stage-IIA and Stage- IIB*) in the study area. The elevation long profiles of those channels have been presented in the graph inserted. The table inserted in the map shows the slope of those channels. Stage-IIA levee channels have negative slope (towards floodplain) and Stage-IIB have positive slope (towards river). The image of two levee channels' (ID 238 and 239) mouth shows the status of connection with the river.

Conclusion

A successful physical connection between floodplain-levee channel and the river nearby is the pre-condition of draining back of floodplain flow into its nearby river. This study has shown that, establishing such a connection is subjected to certain processes involved. The processes start with originating multiple levee holes at back of the levee crest, where their origin is associated with less overbank deposition instead of erosion. Over the period of time, those holes get bigger, and on the other hand their nearby river bank migrates towards them, thus resulting coalescence of those holes themselves and connection between these holes and the river, respectively (Figure 8). However, these two processes: hole development and river bank migration, are not competitive, any of them could happen first. The coalescence of holes initiates levee channel developed (Stage-IIA) having the slope away from the river primarily. Connection with river of Stage-IIA levee channel initially may not be possible depending on the rate of river bank migration and how far the closest levee hole forming the levee channel is from the river. But over the period of time, Stage-IIA levee channel experiences with erosion, and own a slope towards the river as well as most possibly own a connection with the river (Figure 8). This is the Stage-IIB levee channel (Figure 8), can be called as floodplain-levee channel with further floodplainward development. Whenever this connection is established floodplain flows can enter to river through this floodplain-levee channel. Thus, the study concludes that the evolution of avulsion induced floodplain channels is from the origin of multiple levee holes to the development of levee channel should be connected with the river nearby.

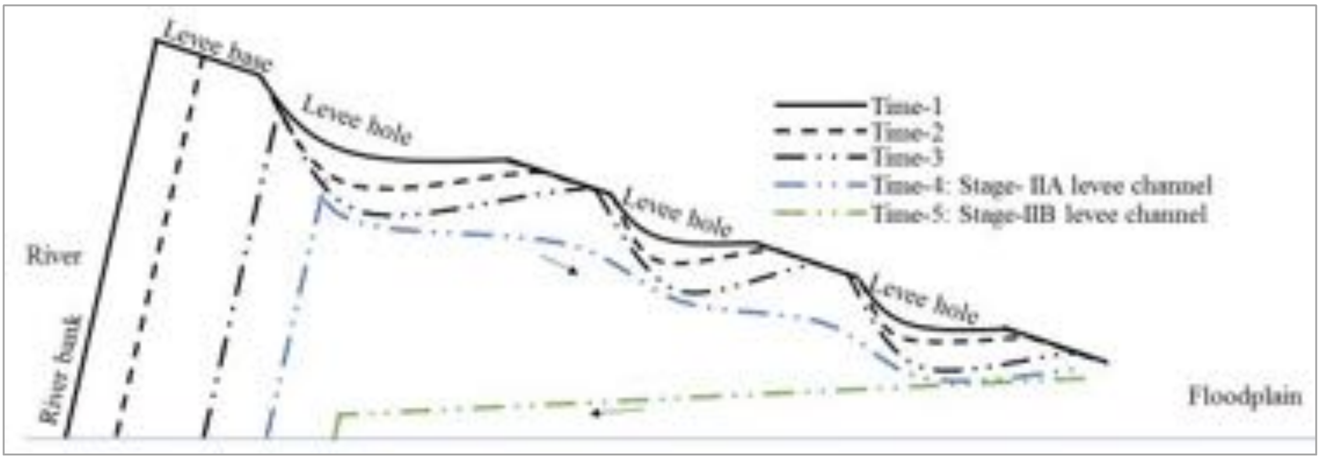

Figure 8. The schematized diagram (Cross sectional view) shows the development sequences of levee holes, gradual river bank migration and development of a levee channel over the Time-1 to Time-5. The holes get bigger and coalescence themselves, develops a levee channel (Time-4 and 5) and meanwhile the river bank migrates towards the levee channel, establishing a connection between the levee channel and the river. Now, the floodplain can enter to the river.

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