Delineating multiple flow paths in anastomosing river systems with wetlands using DEMs

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Key Points
- Flow path and channel delineation from Digital Elevation Models (DEMs) was undertaken for low-gradient anastomosing rivers with wetlands.
- GRASS GIS offered a suitable flow accumulation tool that was computationally efficient and accurate.
- Realistic channel networks were derived through a combination of semi-automatic and manual mapping.
- Flow path and channel delineation supports water, river and wetland management.

Abstract

Anastomosing rivers with wetlands are difficult systems to measure and model using conventional geographic, hydrodynamic and morphodynamic tools. Successful environmental assessment, monitoring and modelling of these systems relies on realistic and accurate delineation of flow paths and channels. High-resolution Digital Elevation Models (DEMs) allow for improved flow path and channel delineation in low-gradient anastomosing rivers with wetlands. Several flow accumulation tools commonly used to derive drainage networks from DEMs in GIS software packages were reviewed, and the GRASS flow accumulation model was applied to a 1 m DEM of the Gwydir Wetlands, NSW. Flow convergence settings in GRASS yielded few variations, and all had limitations where channels became very small and entered wetlands. Zones of flow dispersal and channel breakdown were not easily identified. Manual adjustment of polylines derived from the model outputs were required to achieve the most accurate representation of major and minor flow paths. Identification and mapping of channel networks in anastomosing rivers with wetlands provides an improved understanding of the channel hierarchy and flow routing patterns. Ultimately, advances in channel delineation techniques can guide further research including hydrodynamic, morphodynamic and landscape evolution modelling to support environmental management.

Keywords
Flow accumulation, channel pattern, geomorphology, modelling

Introduction
Realistic and accurate delineation of flow paths and channels underpins appropriate environmental assessment, monitoring and management of complex river and wetland systems. The increasing availability of high-resolution Digital Elevation Models (DEMs) allows for improved delineation of flow paths and channels in low-gradient anastomosing rivers and their wetlands, that were previously only able to be mapped at large spatial scales from aerial photographs and lower-resolution satellite remote sensing data. For example, DEMs derived from Light Detection and Ranging (LiDAR) methods have been used previously to assess channel

change (Yousefi et al., 2018) and to identify earthworks in the Macquarie Marshes (Steinfeld et al., 2013). Water and wetland managers seeking to understand and support ecological communities in rivers and wetlands rely on understanding the water regime and biotic water requirements at key sites, as well as the flow paths and channels that influence the routing and dispersal of water, sediment, carbon and nutrients on the floodplain (Ralph et al., 2020). To support such conservation and management initiatives, we compared GIS techniques and developed a semi-automated method to delineate major and minor flow paths and palaeochannels from a high-resolution DEM for the Gwydir Wetlands State Conservation Area (SCA), NSW.

Study area

The Gwydir River drains a catchment area of ~26,600 km^2, rising to ~1450 m a.s.l. in its headwater catchments on the western slopes of the Great Dividing Range in northern NSW (Figure 1). Downstream of Pallamallawa, the Gwydir River emerges onto a large (~7,500 km^2), low-gradient floodplain-fan (or distributive fluvial system, DFS; Pietsch, 2006). Across the Gwydir floodplain-fan is a complex array of abandoned palaeo-channels and their associated alluvial deposits (e.g. ridges, levees and depressions), modern distributary and anastomosing channels and unchannelised wetlands. Owing to dramatic and persistent downstream declines in discharge and stream power, many distributary and anabranching channels terminate in ephemeral, intermittent or semi-permanent floodplain wetlands (Pietsch and Nanson, 2011). Consequently, the Gwydir system only establishes a hydrological connection with its regional baselevel, the Barwon River, during the largest floods (Pietsch, 2006; Pietsch and Nanson, 2011). Land use change and the regulation and abstraction of flows have led to a significant decline in the area of wetlands on the Gwydir floodplain-fan to ~15 % of their previous ~200,000 Ha extent (Kingsford, 2000).

The Gwydir Wetlands SCA lies in the heart of the Gwydir Wetlands, spanning the two main watercourses, the Lower Gwydir River (also known as the Big Leather Watercourse) in the southern part of the reserve, and the Gingham Channel in the northern part of the reserve (Figure 2). Between these two main watercourses the landscape is characterised by floodplain wetlands with woodland and grassland communities which contain numerous intersecting ephemeral flow paths that convey water during high flow events. Within the core wetlands adjacent to the Gwydir River and along the Gingham Channel an array of smaller surface channels spread water through wetlands dominated by plant species such as marsh club-rush (*Bolboschoenus fluviatilis*), cumbungi (*Typha spp.)* and water couch (*Paspalum distichum*).
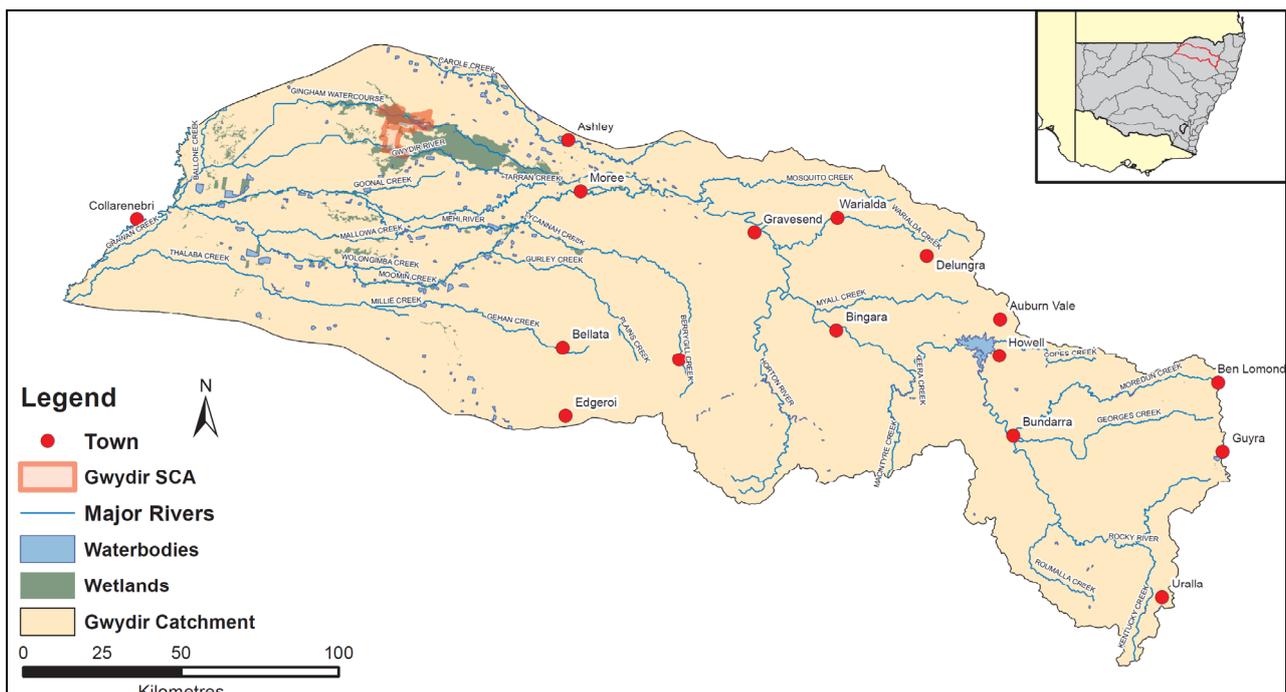

Figure 1. Location of the Gwydir Wetlands and SCA in the Gwydir River catchment, New South Wales.
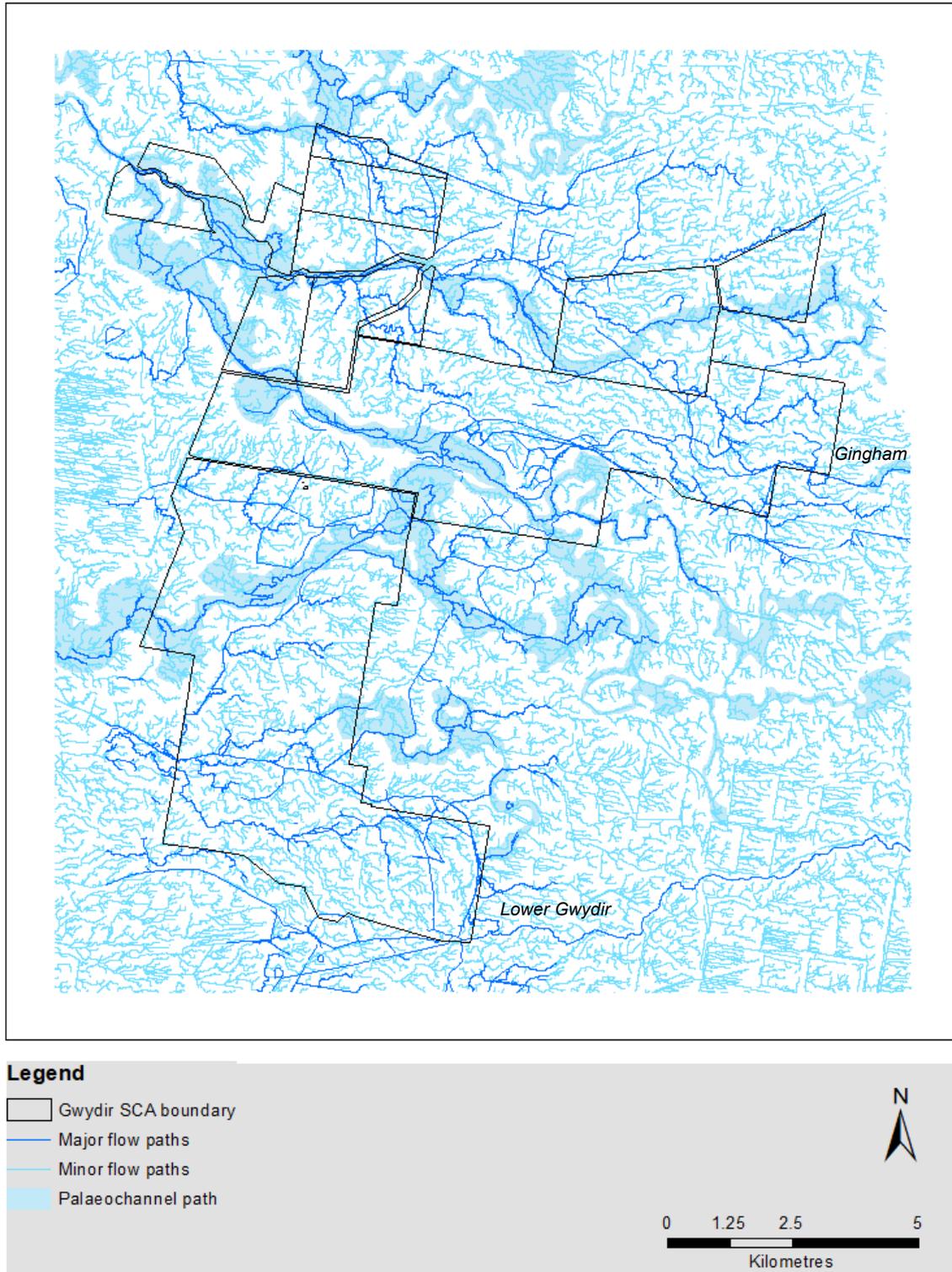
Figure 2. Study area of the Gwydir Wetlands, with major flow paths (dark lines generated using a local >=1 km² catchment area supplemented by manual digitising), minor flow paths (light lines generated using a local >= 1 ha (0.01 km²) catchment area, no manual digitising) and key palaeochannel paths (all manually digitised). Flow direction is generally from right to left. Modified from Ralph et al. (2020).

Methods

The strengths and weaknesses of several common Geographic Information System (GIS) tools were reviewed before open-source software GRASS (Geographic Resources Analysis Support System; GRASS Development Team, 2019) was chosen for this study (Table 1). Major and minor flow paths were derived semi-

automatically using the GRASS GIS flow accumulation model (r.watershed) run on the 2008 Gwydir 1 m LiDAR-derived DEM (Geoscience Australia, 2008). The GRASS GIS r.watershed model was chosen as it does not require a DEM to be 'filled' unlike many of the other available models (such as those found within the ArcMap and SAGA GIS software packages; Table 1). This makes it computationally more efficient and limits issues including loss of detail in the low-relief environment, inaccurate identification of small flow paths and channel segments, over-straightening of flow paths, and oversimplification of flow path networks due to the filling of smaller flow paths. The r.watershed model in GRASS GIS uses a least-cost path methodology to model flow accumulation (i.e. cell-based catchment area; Ehlschlaeger et al., 2018). The r.watershed model can also take into account multiple flow directions unlike other more simplistic models (such as those found in ArcGIS- pre 10.6), which helps to model flow networks that experience divergent flow, as the modelled flow can be partitioned into multiple downslope cells (instead of just the single most downslope cell).

Table 1. Strengths and weaknesses of selected GIS-based flow accumulation tools used to derive automated flow paths from DEMs. Modified from Farebrother and Ralph (2017).

Model / Tool	Software package	Strengths	Weaknesses
r.watershed	GRASS GIS	• Does not require 'filled DEM' (A^T least-cost search algorithm) • Methods based on peer-reviewed literature • Can utilise SFD or MFD methods including modelling various proportions of divergent flow • Scales well with large datasets (can utilise RAM in addition to disk swap space)	• Requires user input (flow accumulation threshold for channel generation) • Requires simple coding to run tools
Flow Accumulation Tool	ArcMap GIS	• Computationally efficient • Since ArcGIS 10.6 can model MFD	• Struggles with complex drainage patterns (non-dendritic) • Relies upon using a 'filled DEM' • Struggles with large datasets (e.g. LiDAR) • Requires user input (flow accumulation threshold for channel generation)
Flow Accumulation (Flow tracing, Mass-flux, Recursive, Top-down)	SAGA GIS	• Can utilise complex flow models (including MFD, KRA, DEMON, Deterministic Infinity etc.) • Methods largely supported by peer-reviewed literature	• Requires large amount of RAM to run (all analyses are run in RAM instead of hard disk) • Most methods require 'filled DEM'. • Requires user input (flow accumulation threshold for channel generation)
Notes: MFD = Multiple Flow Direction, KRA = Kinematic Routing Algorithm, SFD = Single Flow Direction, DEMON = Digital Elevation Model Networks.			

The r.watershed tool includes a convergence parameter that enables it to model different flow types (where CONV1 = most divergent flow, CONV10 = most convergent flow). For this study, multiple iterations of the flow accumulation model were run in GRASS GIS using different degrees of divergence/convergence from CONV1 to CONV10, and ultimately the default setting of CONV5 was used to determine the final flow paths.

Flow path segments were extracted from the flow accumulation rasters using two flow accumulation area cutoff values (i.e. local cell catchment areas required to form a flow path), those representing 1 ha (0.01 km^2) and 1 km^2 cell catchment areas within the DEM extent (using the CON tool in ArcMap 10.6). This yielded output flow path rasters representing minor (smaller) and major (larger) flow paths within the DEM, respectively. Raster layers representing flow paths with local cell catchment areas of 1 ha and 1 km^2 were converted to polylines using ESRI's ArcScan module. This process enables the vectorized output to take into account artefacts (e.g. holes and dangles) in the raster to create a more accurate and smoothed output that is suitable for analysis (Ralph et al., 2020). Palaeochannel features were manually digitised at a 1:10000 scale through the visual analysis of the LiDAR-derived DEM, and ground-truthing was undertaken to support interpretation of the minor and major flow paths making up the anastomosing channel network (Ralph et al., 2020).

Results and Discussion

Flow divergence/convergence patterns

Comparison of outputs from different flow divergence/convergence settings in the GRASS r.watershed tool shows that flow accumulation raster pixels derived from all CONV1 to CONV10 models for flow paths with both 1 ha and 1 km^2 local cell catchment areas had some deviation from CONV5 in terms of the total pixel count, but that none had a deviation of more than ~8 % (Figure 3A). None of the CONV1 to CONV10 settings found new or different flow paths that CONV5 did not already identify, but some models included slightly different patterns of cells in parallel or in series along the identified flow paths. Comparison of CONV1 to CONV10 raster outputs with the final smoothed flow path polylines derived from CONV5 shows that almost all had >90 % overlap within a 2 m buffer of the polylines (Figure 3B). These analyses consider millions of raster cells, but, spatially, the deviation in pixels across the CONV settings translates into very few differences in flow accumulation cell and polyline patterns (Figure 4). As such, the default model of CONV5 (the midpoint of divergent/convergent flow) was suitable for determination of the final flow paths and there was negligible difference between CONV5 and the outputs of the other divergence/convergence parameter values.
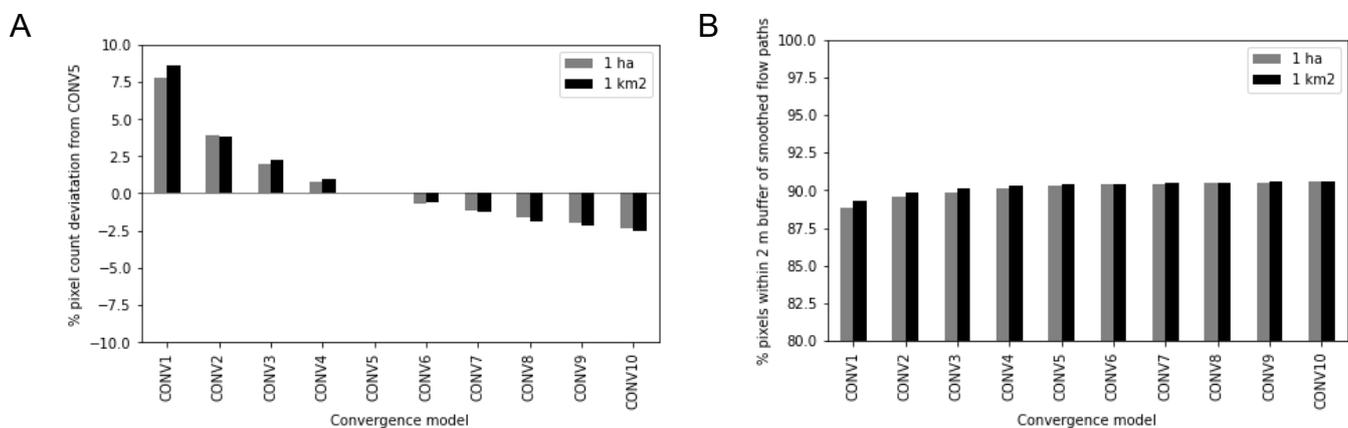
A

B

Figure 3. (A) Raster pixel count deviation from CONV5 for flow convergence settings using the GRASS r.watershed tool (CONV1 = most divergent flow, CONV10 = most convergent flow); (B) Proportion of raster pixels from all flow divergence/convergence models occurring within a 2 m buffer of the final smoothed flow path polylines derived from CONV5.

Flow paths and palaeochannels

Overall, there were ~213 km of major flow paths and ~910 km of minor flow paths delineated and mapped in the Gwydir SCA (Figure 2). Flow paths occurred where surface water was both channelised and unchannelised, for example, where water typically moves overland in shallow depressions or through wetlands and where there are no channel beds and/or banks present. Unchannelised flow paths are common in the Gwydir Wetlands SCA, and the Gwydir floodplain more broadly. Channel beds and banks were not specifically identified and mapped, so the layers derived include all the flow paths that met the flow accumulation model criteria, some of which were channels with bed and banks, while many others were not.

The presence of anthropogenic structures, vegetation and inundation artefacts, and inherent variability within the DEM (the latter either a result of LiDAR 'noise', inadequate validation, and/or vegetation removal, and/or the effects of inundation), resulted in inaccurate discontinuities along some flow path segments, thereby requiring manual digitisation. All of the GRASS r.watershed divergence/convergence factor scenarios had limitations for the detection of distributary channels and where they entered wetlands. Zones of flow dispersal and channel breakdown (i.e. places where flow paths were supposed to be discontinuous) were not easily identified, but these limitations were overcome with manual digitisation. This step was important for cross-validation of the dataset and allowed small errors to be identified and corrected. Ground-truthing of the flow path mapping also indicated that the semi-automated method used was accurate and was able to detect shallow flow paths that were barely noticeable on the ground (see Ralph et al., 2020).
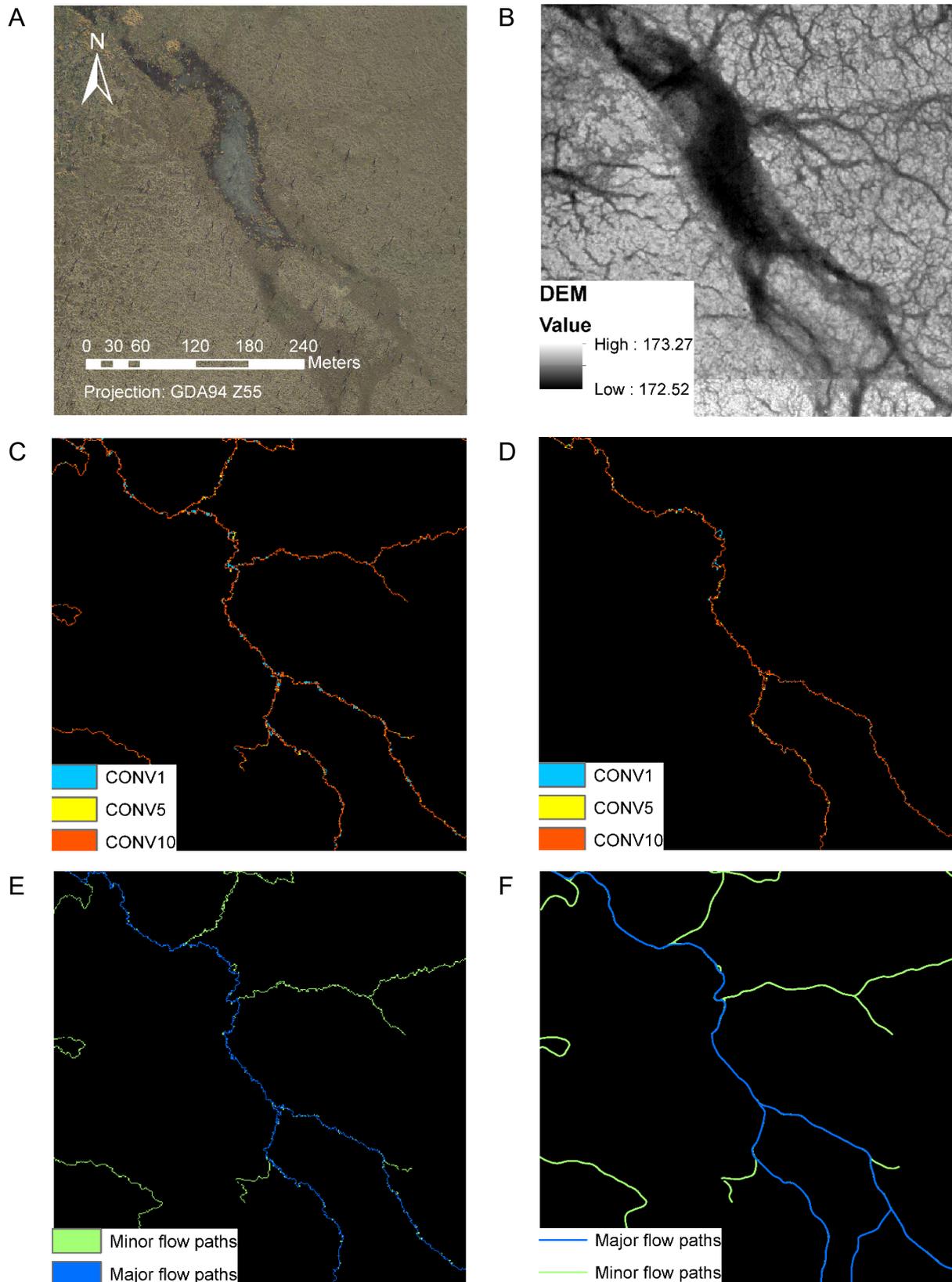
Figure 4. (A) True-colour aerial image of a section of the Gwydir Wetlands; (B) LiDAR-derived DEM of the section; (C) CONV1, CONV5 and CONV10 raster outputs for minor flow paths with 1 ha cell catchment area in the section; (D) CONV1, CONV5 and CONV10 raster outputs for major flow paths with 1 km² cell catchment area in the section; (E) Raw model output of major and minor flow paths derived using CONV5; (F) Smoothed final major and minor flow path polylines derived using CONV5.

Palaeochannel traces accounted for ~15 % of the area of the Gwydir SCA, which is a significant spatial area. Almost all the palaeochannels were discontinuous owing to partial burial by sediment and/or reworking which obscures the surface expression of these old channels. In such a low-gradient environment, however, the topographic expression of the palaeochannels (i.e. partly-filled depressions, low alluvial ridges and levees) plays an important role in determining the location and extent of modern flow paths and inundation patterns.

Importance of accurate flow path delineation for river and wetland management

The Lower Gwydir River and Gingham Channel experience downstream declines in discharge and stream power (Pietsch and Nanson, 2011), have multiple channels with discontinuous segments, and many smaller unchannelised flow paths in wetlands in the Gwydir SCA. Reticulate channel patterns dominate the wetland areas where surface flows circulate and backflooding occurs. At the downstream ends of some unchannelised wetlands, coalescing flows contribute to the formation of small knickpoints and waterholes. Therefore, small, but important, variations in topography play a critical role in determining the direction of flow paths, the associated patterns of in-channel flow and overland inundation, and at a larger scale the accommodation space for wetlands to occupy and to form aquatic ecosystems (Kelleway et al., 2010). The most important factors affecting channel and flow path connectivity in the Gwydir Wetlands are the antecedent palaeochannel topography, earthworks, and inherent downstream declines in discharge and stream power.

Other than through flow accumulation modelling and flow path delineation using a high-resolution DEM, the controls on and patterns of small, complex flow paths such as those in the Gwydir Wetlands are difficult to quantify. In similar floodplain wetlands, such as the Macquarie Marshes, channels can be quite dynamic over time, with processes of sedimentation and erosion driving channel adjustment and new channel formation through avulsion (Ralph et al., 2011; Ralph et al., 2016). Rapid erosion due to knickpoint retreat (i.e. head-cutting gullies) can cause major changes in the water-holding capacity of the channels (Oyston et al., 2014), while bed incision and/or bank erosion and slumping can contribute significant amounts of sediment to the downstream system. Excessive channel erosion and enlargement may also pose a significant threat to wetland inundation and aquatic ecosystem processes (e.g. Kobayashi et al., 2011; 2015). Therefore, high-resolution DEMs and flow path delineation methods using semi-automatic and supplemented by manual digitisation not only offer better representation of flow paths, corridors and channels, but also the potential to assess and monitor fine-scale changes across wide areas of wetlands. Maps derived from these techniques also provide a physical baseline to be combined with inundation and vegetation mapping to support water and wetland management in anastomosing rivers with wetlands. Applications may include identification of barriers to flow that with intervention may improve inundation, and identification of flow paths or corridors likely to be important under future environmental watering or hydro-climatic regimes.

Conclusions

Flow paths were delineated for the anastomosing section of the Gwydir River, its secondary channels and wetlands in the Gwydir SCA using a robust semi-automatic method based on a high-resolution DEM. This baseline flow path data requires complementary manual digitisation and ground-truthing, but is suitable to support water and wetland management, conservation planning and decision-making. Further research is required to fully quantify and understand the patterns and processes of channel formation and maintenance in this and similar systems, as well as the risks associated with erosion and sedimentation inherent in low-gradient fluvial systems which are sensitive to topographic variations and channel change.

Acknowledgments

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