Modelling unseen flow pathways of water and contaminants in the Wet Tropics: the role of alluvial palaeochannels

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SUMMARY

Nutrients from agriculture in catchments draining to the Great Barrier Reef (GBR) are a stressor of this important ecosystem. Current GBR catchment models do not mechanistically link movement of nutrients from paddocks to rivers. An understanding of these water and nutrient flow pathways is crucial in any attempt to model and manage the GBR catchments. Conduits of water transport include surface drains and subsurface features such as palaeochannels. Palaeochannels are a common feature in alluvial landscapes, representing old river or stream beds that are often filled with coarse in-fill material which make them ideal water storage zones and conduits of water movement, either by recharging surrounding ground water (GW) or exchanging water with surface drainage networks (e.g., Keen et al., 2007, Owen & Dahlin, 2010, McLachlan et al., 2017). Their presence results in heterogeneity of soil and aquifer properties, which need to be accounted for in any attempt to assess water and nutrient transport in these flat agricultural landscapes.

This project addressed this gap by looking at preferential flow pathways, via palaeochannels, of water and nutrients at the paddock to catchment scale using the Babinda Swamp Drainage Area (BSDA, 23.47 km^2) in the Wet Tropics as a study site. The BSDA is located in the Russell River catchment, which is part of the larger Russell-Mulgrave basin. Modelled dissolved inorganic nitrogen (DIN) loads for agricultural areas within the Russell River catchment range between 13.9 kg ha^{-1} yr^{-1} and 20.2 kg ha^{-1} yr^{-1} (TERRAIN NRM, cited in Cheesman et al., 2020). This, combined with a high proportion of agricultural land in the catchment leads to the Russell catchment producing the highest DIN yields per unit area across the GBR catchment at 590 kg km^{-2} (State of Queensland, Department of Environment and Science, 2017, cited in Cheesman et al., 2020). To reduce the negative water quality impacts of agricultural activities and its downstream impact on sensitive coastal ecosystems, there is a need to understand the modes of water and nutrient transport through these landscapes, including natural and artificial water flow pathways. A recent soil mapping exercise conducted by Morrison et al. (2023) using electromagnetic induction (EMI) sensors revealed the presence and extent of heterogenous soils in the BSDA and surrounding areas, highlighting the potential role of landscape features such as palaeochannels to act as regions of preferential subsurface flow (Figure 1). Yet almost nothing is known about these features and the way they transport water in agricultural landscapes.

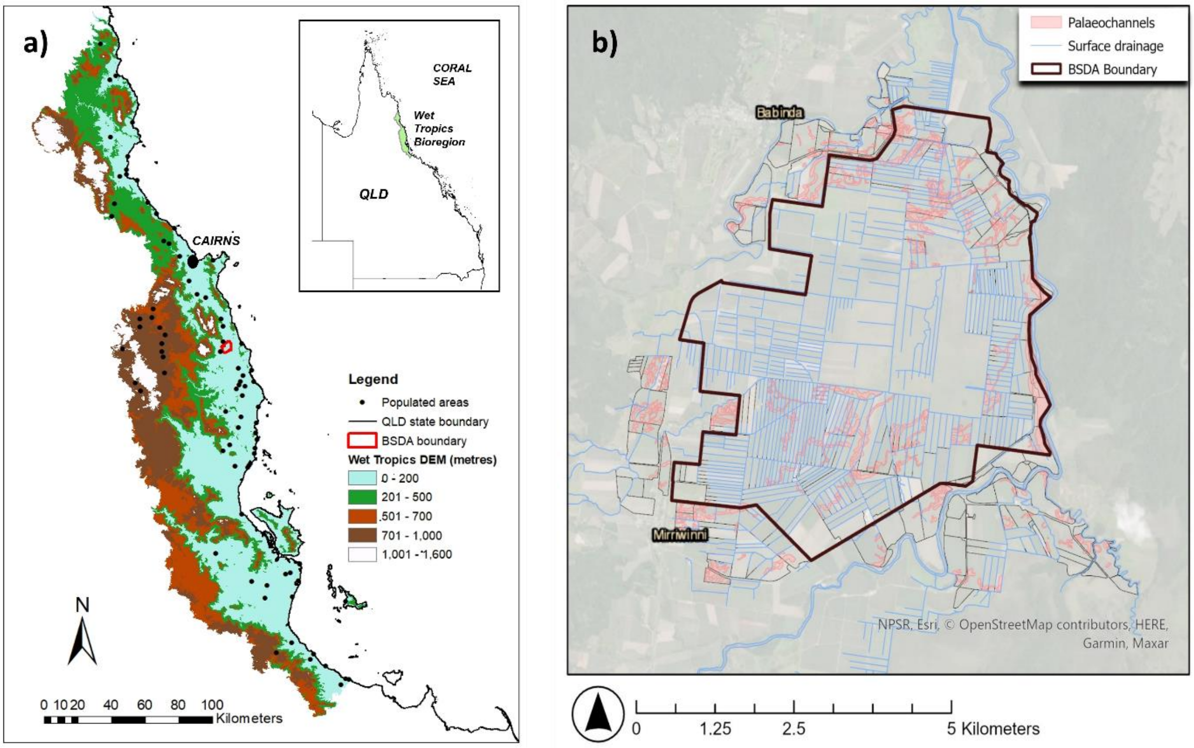

Figure 1: Location of the Babinda Swamp Drainage Area (BSDA) within the a) Wet Tropics bioregion and b) location of surface drainage and palaeochannels, the latter mapped using electromagnetic induction mapping techniques. The central part of the BSDA was not mapped because the EMI mapping project only focused on paddocks where sugar cropping was carried out (Morrison et al., 2023).

In this project, we sought to better understand the spatial extent and relationships of these subsurface features in the BSDA. A review of the modelling literature around preferential flow and palaeochannels provides the basis to conduct virtual experiments, guided by findings from the spatial analysis of these features and the landscape in the BSDA. The project aims were to:

1. examine the spatial relationships between palaeochannels and other drainage elements in an agricultural landscape in the Wet Tropics

2. provide a literature review that supports the development of a modelling framework that could be used to examine the role palaeochannels play in subsurface water movement and their interactions with surface drainage.

3. Advocate for the integration of existing models into this conceptual framework to conduct virtual experiments to guide model development and future improvements

RESULTS

A better understanding of the palaeochannel system in relation to the individual paddocks and surface drains was achieved by spatial analysis. The paddock was chosen as the smallest spatial unit of analysis as farming decisions (e.g., irrigation, nutrient application) are often made at this scale. Approximately half of the mapped paddocks had palaeochannels covering at least 14.5% of their area, with a small number of paddocks along the Russell River having over 50% of the paddock area covered by palaeochannels (Figure 2). The length of surface drains that intersected palaeochannels per paddock is, on average, 887.3 m which corresponds to approximately 74% of the total paddock boundary. For paddocks with palaeochannels, almost half (44.3%) of the paddock area was closer to the palaeochannel than to a drain (Figure 3). The shallow nature of the mapped palaeochannels, which were within 1.5 m of the surface, meant that they likely intersected with surface drains, especially the deeper trunk drains in the BSDA.

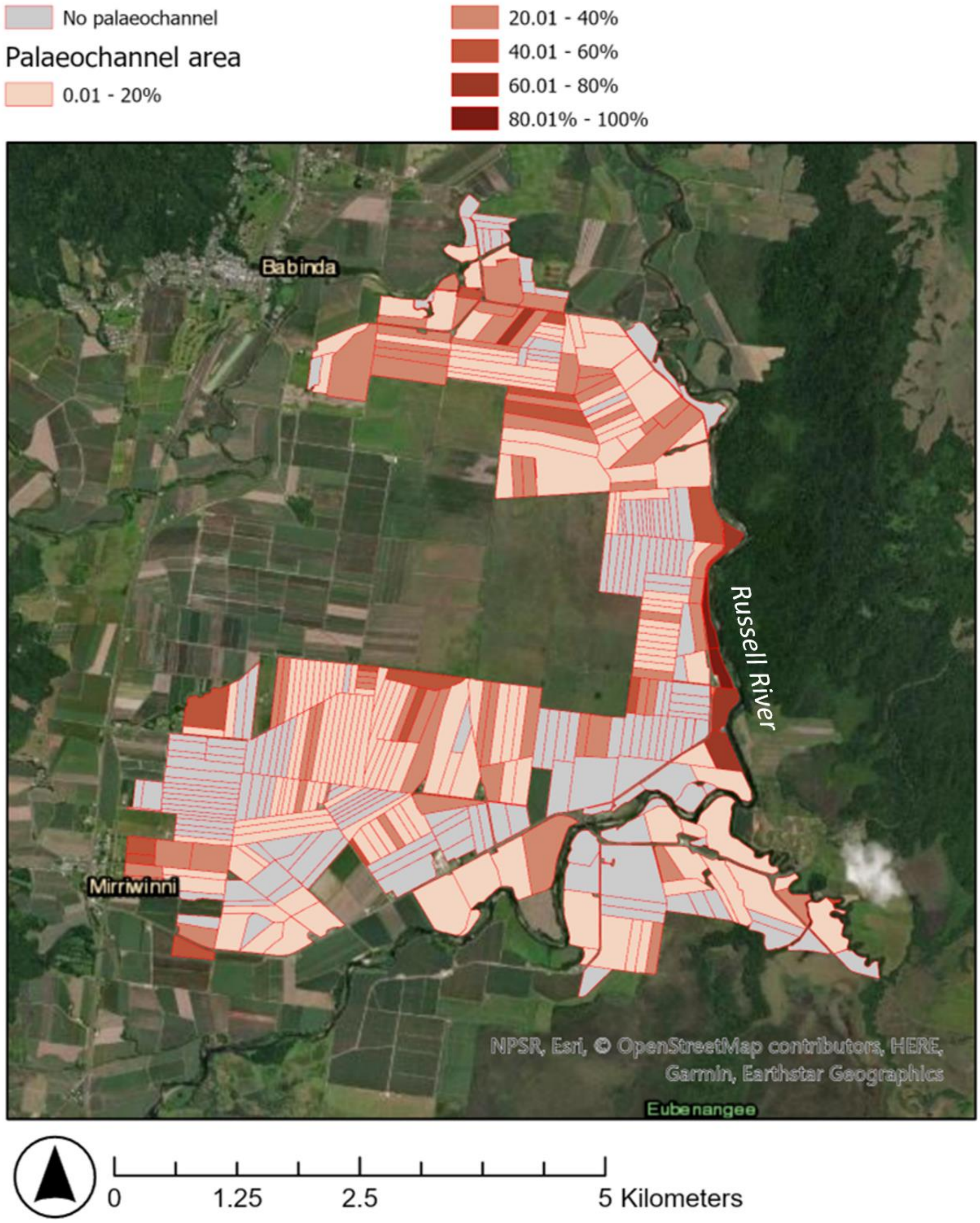

Figure 2: Proportion of each paddock consisting of paleochannels.

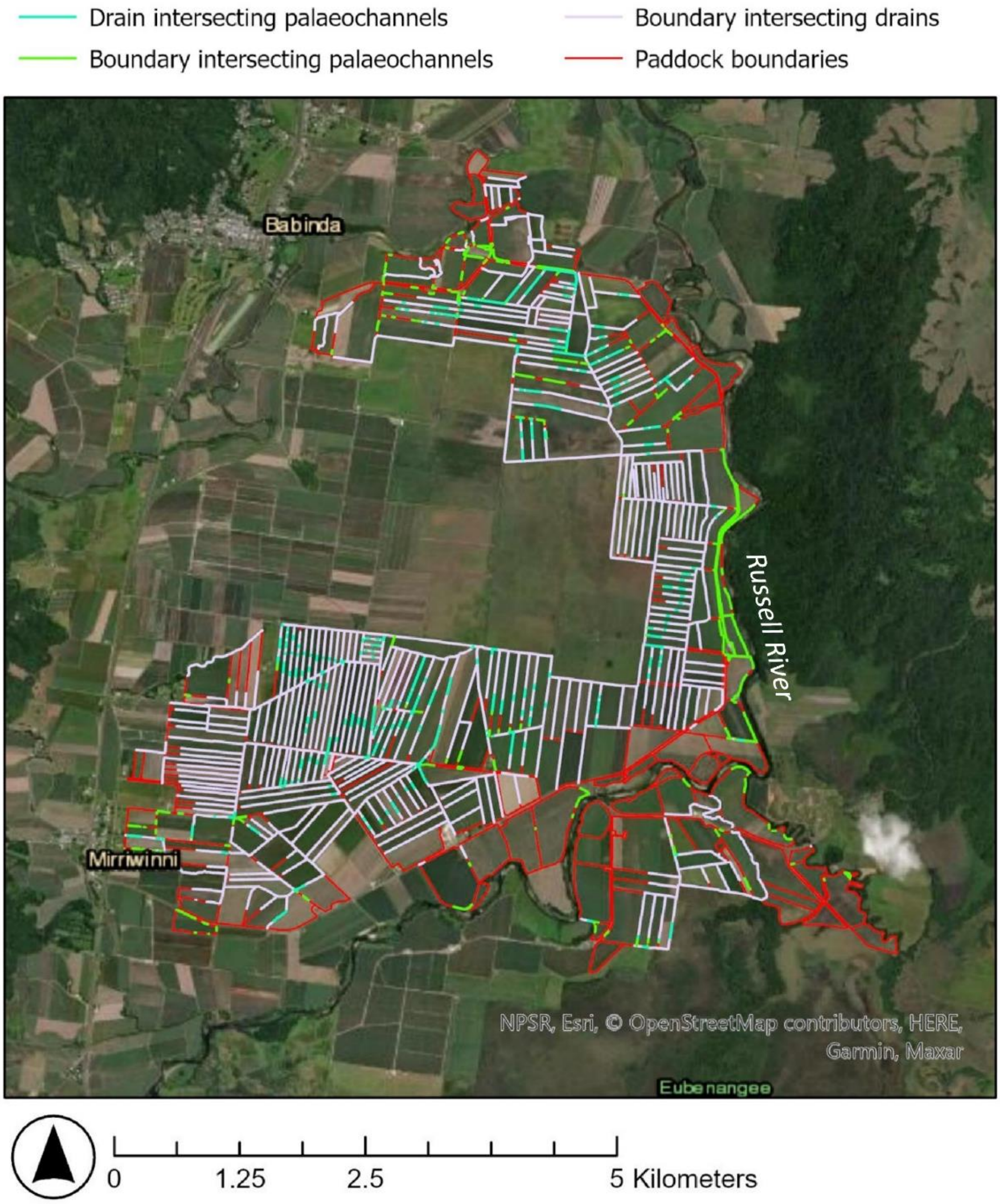

Figure 3: Map of paddock boundaries and drains, showing where they intersect with palaeochannels. The central part of the BSDA was not mapped because the area was not used for sugarcane cropping.

A literature review of existing models highlighted the need for coupled models to capture the surface-subsurface water interactions in an environment with preferential flow paths such as palaeochannels (Figure 4). To enable an assessment of the likely influence of paleochannels on water and nutrient flows to surface drains, a framework for virtual experiments was set up by coupling the crop model APSIM with the groundwater model MODFLOW. The APSIM model was chosen because it is a crop model that can model the hydrology of a crop system and is widely used in Australia. MODFLOW is also a widely used 3-D groundwater model that have the capabilities to model complex subsurface flows. The modelling framework for this coupled model is described in Figure 5.

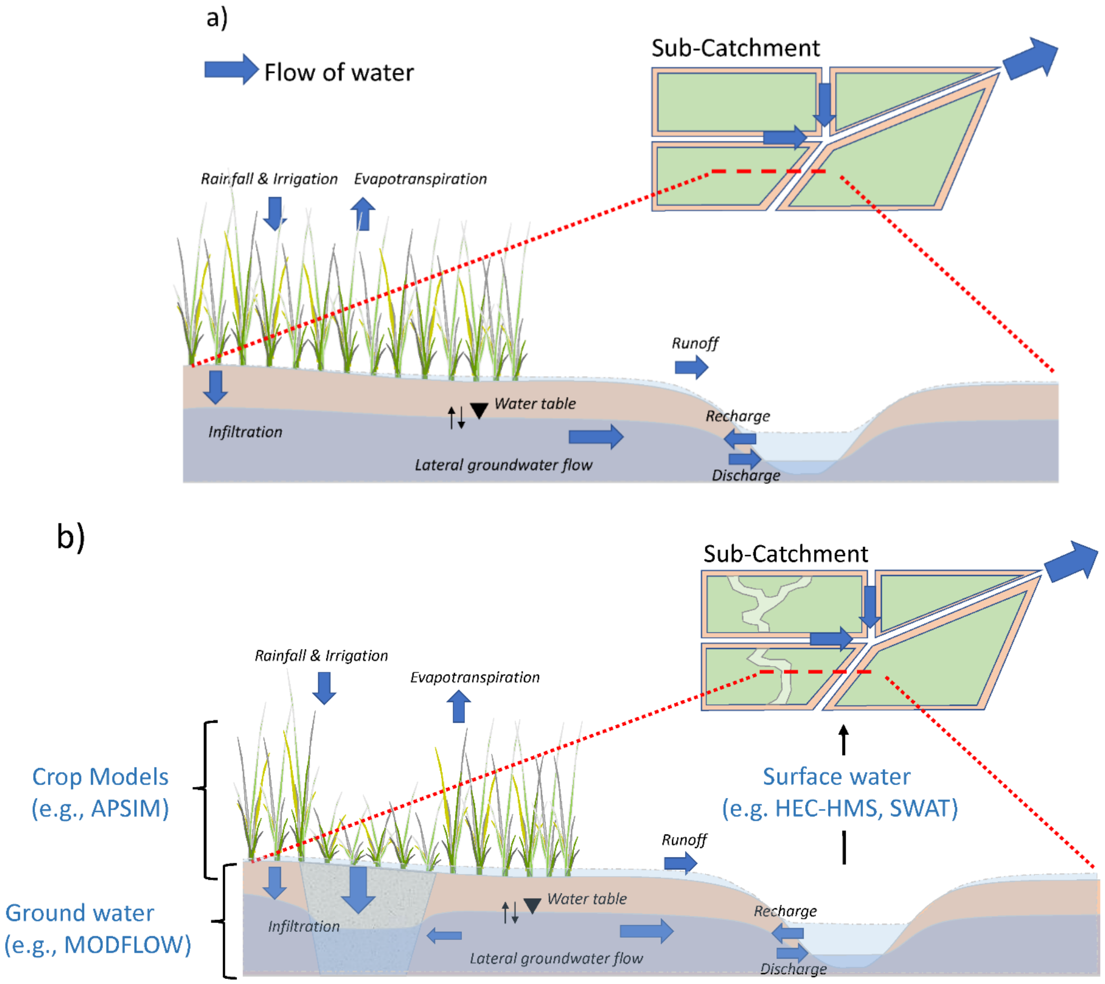

Figure 4: Conceptual model that summarises the various hydrologic processes determining the movement of water and nutrients at the paddock scale and routing of water in the agricultural landscape, for a) paddocks with no palaeochannels and b) palaeochannels in paddocks

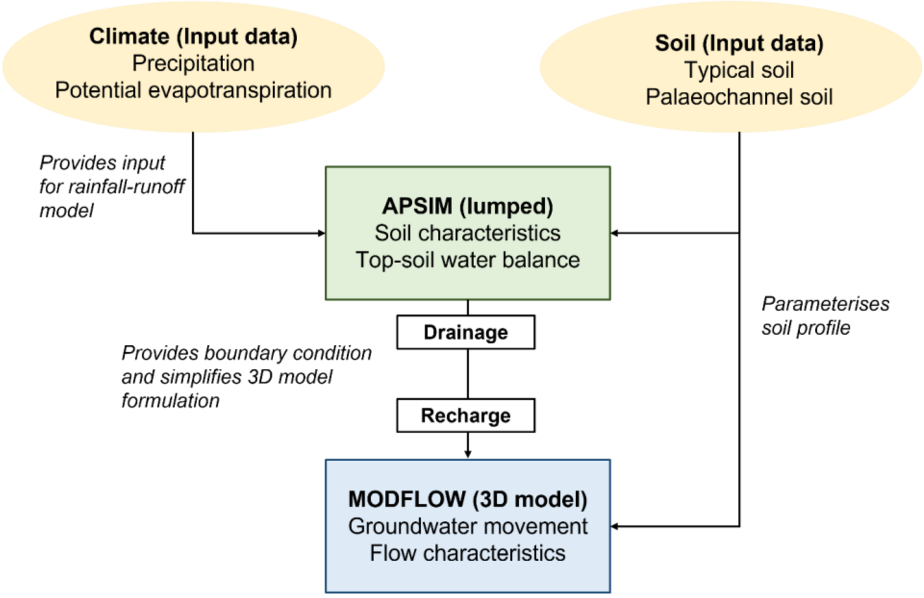

Figure 5: Conceptualisation of the overall modelling framework developed to model the influence of preferential lateral flows in palaeochannels at the paddock scale.

In a preliminary virtual experiment, three scenarios with different palaeochannel configurations were modelled to assess the impact of these preferential flow pathways on water flux from a paddock (Figure 6). The MODFLOW simulations were run with steady state conditions, palaeochannels (when present), running parallel to a hydraulic gradient, and lateral K_s of the palaeochannel being 10 times higher than non-palaeochannel soils. The experiments showed that palaeochannels altered subsurface flow patterns and water flux. A subsurface palaeochannel increased water flux by 4.4% and a surface palaeochannel increased it by 3.5%. Palaeochannels caused a slight divergence of flow towards them. With some finessing, the coupled model set-up will allow more virtual experiments to simulate the effects of different palaeochannel scenarios that are likely encountered in the BSDA landscape. Such experiments could be used to determine sensitivity of flows to palaeochannel density and characteristics and thereby enable design of efficient models to account for their effects.

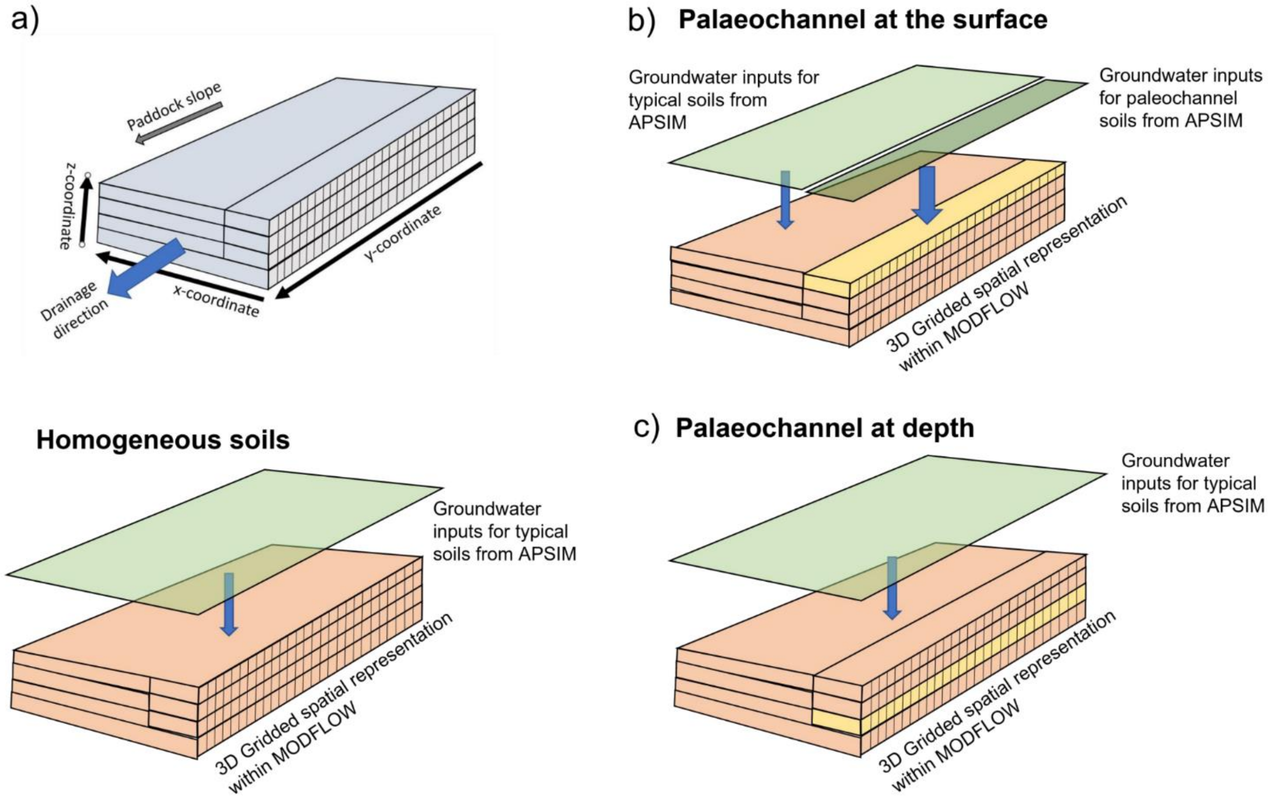

Figure 6: a) Coordinate system of the MODFLOW model and conceptualisation of the coupled APSIM and MODFLOW models for virtual experiments with, a) homogeneous soils (no palaeochannel), b) surface expressions of palaeochannels, c) subsurface palaeochannels. For the virtual experiments, the palaeochannels are assumed to be parallel to the drainage direction of the paddocks.

FUTURE WORK

Important areas of future work include the following:

1. Further virtual experiments with a coupled APSIM and MODFLOW model that considers the following:

- incorporating more realistic soil parameter values,

- changing the characteristics of palaeochannels (e.g., size, direction, depth) to assess their impact on water and nutrient transport

- model runs under non-steady state conditions to better reflect the highly dynamic water table conditions experienced in alluvial agricultural landscapes,

- sensitivity testing to see the impact of changing numerical grid size on modelled response

- assessing the impact of residence time in subsurface flows for the palaeochannel versus non-palaeochannel aquifer (i.e., use MODPATH in MODFLOW)

- conduct nutrient transport modelling (e.g., use the MODFLOW 6 solute transport package) to evaluate transport rates and the relative importance of subsurface properties (e.g., hydraulic conductivity, porosity) and dominant modes of subsurface nutrient transport. In the future, it is also important to start thinking about non-reactive nutrient transport modes and in-stream processing of nutrients in the overall framework of nutrient transport in such landscapes, both conceptually and trying to represent these nutrient transport and processing processes in the modelling efforts.

2. Development of a 'plugin' for the GBR catchment models that accounts for palaeochannel effects (if and when they are significant), based on sensitivity analyses of palaeochannel density and characteristics using the aforementioned virtual experiments. This likely requires an effort between government, universities and industry to develop a plugin that fits current GBR models in terms of computing and data requirements as well as management needs.

3. Monitoring palaeochannel water flows and nutrient levels through water sampling and tracer experiments to identify water and nutrient flow pathways and flux. Field efforts could start with monitoring water table elevation and fluctuations over time in existing bores while installing new subsurface flow monitoring sites in paddocks where palaeochannels are dominant. These paddocks become reference sites providing important information to validate the coupled modelling results.

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