Journal of Hydrology 674 (2026) 135522

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review papers

Palaeochannels as hidden pathways of water flow in agricultural alluvial landscapes: A review of concepts and suggested future directions for modelling

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ARTICLE INFO

This manuscript was handled by Renato Morbidelli, Editor-in-Chief

Keywords:
Palaeochannels
Preferential flow
Hydrologic connectivity
Subsurface drainage
Water quality
Agriculture
Coupled modelling (HYDRUS-MODFLOW, SWAT-MODFLOW, MIKE-SHE, HydroGeoSphere)

ABSTRACT

Sustaining agricultural productivity while reducing off-site impacts on water quality requires a detailed understanding of water and nutrient movement through alluvial landscapes. Within these settings, palaeochannels – old river courses infilled with coarse sediments – represent major but poorly quantified subsurface flow pathways. Their influence on water and solute transport is rarely incorporated into hydrological assessments or models, despite their widespread occurrence and hydraulic connectivity with surface drains, aquifers and streams.

This paper reviews current knowledge of palaeochannel structure, distribution and hydrologic function within agricultural alluvial systems, and evaluates approaches for their identification, characterisation and representation in hydrologic models. We examine the suitability of existing coupled modelling frameworks – such as HYDRUS-MODFLOW, SWAT-MODFLOW, MIKE-SHE and HydroGeoSphere – for simulating palaeochannel-mediated flow and material transport. Conceptual similarities between palaeochannels and engineered tile-drain networks are used to illustrate how established drainage formulations can inform future model development.

We highlight virtual experimentation, combining numerical simulation with targeted field monitoring, as a practical means of exploring how palaeochannel geometry, depth and connectivity influence water and nutrient fluxes at field to catchment scales. Integration of direct and remote sensing with coupled hydrological models will enhance the capacity to parameterise and validate palaeochannel networks. Collectively, these advances provide a pathway towards more realistic representations of subsurface flow heterogeneity, improving predictions of water and solute movement and informing management strategies in intensively farmed alluvial landscapes.

1. Introduction

Poor water quality in the form of high nutrient concentrations and loads is considered a significant and pervasive impact of human activity on natural ecosystems around the globe (du Plessis, 2022). Agricultural activities in alluvial and coastal plains degrade water quality, threatening the health of downstream coastal ecosystems, with prominent examples found in both temperate (e.g. Chesapeake Bay USA) and tropical systems (e.g. Great Barrier Reef Lagoon) (Kemp et al., 2005; Pearson et al., 2021; Lewis et al., 2021). An understanding of flow pathways, water fluxes and associated biogeochemical processes in these landscapes is an important first step in tailoring landscape management to improve downstream water quality (Waltham et al., 2019). To do this effectively involves accounting for all contributing water sources and flow pathways.

In agricultural areas, human-made drains, both surface and subsurface, increase the connectivity between surface and subsurface water flow pathways, increasing the transport of water and contaminants

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https://doi.org/10.1016/j.jhydrol.2026.135522
Received 16 December 2025; Received in revised form 15 April 2026; Accepted 15 April 2026

through the landscape (French, 1859; Kirkham and Powers, 1972; De Schepper et al., 2015; De Schepper et al., 2017; Hansen et al., 2019; Hester and Fox, 2020). Webb et al. (2017) found that surface drains intersecting shallow groundwater contribute between 30 and 80% of surface water discharge. Whilst subsurface drains in a catchment in Ohio, USA contributed 45% of the total discharge at the catchment outlet (King et al., 2014). Drains also interact with natural preferential flow pathways, further enhancing water and nutrient transport (Michaud et al., 2019; Pluer et al., 2020).

Preferential flow paths occur across multiple scales, ranging from individual soil pedons to entire landscapes, driven by spatial heterogeneity in subsurface texture and structure (Lin, 2010b; Jarvis et al., 2012; Jarvis et al., 2016). They can facilitate rapid movement of subsurface water over large distances as they bypass the bulk of the soil and regolith matrix (Daughtry et al., 2001; Fuchs et al., 2009; Heeren et al., 2010; Radolinski et al., 2022; Lotts and Hester, 2023). As a result, nutrient-rich waters may bypass zones where processes occur that reduce nutrient concentrations in the water (e.g. denitrification).

Our understanding of water flow through preferential flow paths in alluvial landscapes is skewed towards fine-scale pathways, such as macropores and soil pipes (Menichino and Hester, 2015; Hester and Fox, 2020; Hester et al., 2020; Lotts and Hester, 2023). These have been found to exert significant control on surface-subsurface water interactions in riparian zones (Menichino and Hester, 2015; Orozco-López et al., 2018; Hester and Fox, 2020) and display complex temporal influences when activated during wet periods, when the water table or stream stage rises (Heeren et al., 2010; Mittelstet et al., 2011; Heeren et al., 2014; Menichino and Hester, 2015).

Palaeochannels are abandoned river courses and are found in a variety of landscapes, including floodplains (Sidorchuk et al., 2001; Young et al., 2002; Lamontagne et al., 2003), alluvial fans (Patel and Pati, 2022; Oropeza et al., 2025) and deltaic environments (Karmokar et al., 2021; Mahammad and Islam, 2025) (Fig. 1). They can be transboundary, raising geopolitical issues associated with groundwater resources (El Mahmoudi and Gabr, 2005; Elmahdy and Mohamed, 2015) and extend out to the sea linking terrestrial and coastal systems (Fielding et al., 2003; Chandra et al., 2020). Palaeochannels can function as subsurface preferential flowpaths at spatial scales of meters to tens of meters, yet their role in water movement and water quality dynamics is often overlooked in hydrological assessments. There is, however, growing evidence that palaeochannels are hydraulically connected to aquifers, streams, floodplains and marine environments (Mulligan et al., 2007; Fuchs et al., 2009; Mittelstet et al., 2011; Mastrocicco et al., 2014; Pritchard et al., 2020; Martin et al., 2023). For instance, surficial palaeochannels can be connected to other palaeochannels buried deeper in the landscape or to other groundwater bodies (Ali and Turner, 2004; Johnson and Series, 2007), making them important regional sources of groundwater (Chen et al., 1996; Zhao et al., 1999; Colombani, 2010). They may also transport water from distant sources, especially if they are linked to regional aquifers (Ali and Turner, 2004; Johnson and Series, 2007), and sustain flows during dry periods (Biehler et al., 2020). Palaeochannels also connect surface water bodies in the landscape, including wetlands, oxbows and lakes (Quenet et al., 2019; Jeelani et al., 2025). In agricultural alluvial landscapes, palaeochannels may interact with human-made drainage systems to enhance subsurface water-surface water interactions, as well as to modify flood responses in ways that may increase flood peaks and shorten flood durations (Krause et al., 2007; Webb et al., 2017). Since subsurface connections tend to persist into dry seasons (Ameli and Creed, 2017; Bishop et al., 2024), their impacts on the flow regime, material transport and ecosystem processes may be substantial (Palmer and Ruhi, 2019).

Fig. 1. High resolution RGB (Red, Green, Blue - visible spectrum) drone orthomosaic image reveals the location of palaeochannels close to ground surface. The drone image (outlined with a red line and in lighter shade) is superimposed onto satellite imagery obtained from the Global Mapper software (Source: Marcus Bulstrode, Queensland Government Department of Primary Industries).

Despite these conductive zones being prominent features in alluvial landscapes, the lack of information about their location and connectivity results from their complex formation, transformation and situational relevance within a catchment. Their cryptic character has resulted in a gap in our understanding of their role in water movement and material transport in these landscapes. Such understanding is important in any attempts to quantify nutrient, or contaminant loads for water quality management and remediation efforts. This paper provides a review and thought experiment of how we can better understand and model water flow through palaeochannels to provide support for sound decision-making around water quality improvement in agricultural landscapes. The paper reviews ways of obtaining more information about the location and connectivity of palaeochannels and evaluates the role of modelling as a tool to examine, understand and manage alluvial landscapes where palaeochannels form an important conduit for water and solutes.

2. Palaeochannel characteristics and significance

Palaeochannels are often infilled with coarse sediments, compared to the surrounding matrix (Salama et al., 1993; Lin, 2010a; Lin, 2010b; Vanags and Vervoort, 2013) and generally occur at the scale of metres or larger (Clothier et al., 2008). Their size, orientation, and physical attributes, such as texture and hydraulic conductivity, determine the nature of interactions with other drainage features in the environment.

Palaeochannels may interact with subsurface drains including tile, mole and fascine drains, (see French (1859) and Kirkham and Powers (1972)) and/or surface drains; increasing preferential lateral flow in the landscape. For example, in an agricultural area in Northern Queensland, Australia, a high density of surface drains and surface-expressed palaeochannels results in many intersections between the two (Fig. 2). Knowledge of the location and extent of palaeochannels, as well as patterns of connectivity, is important in understanding how water moves through this type of landscape. The following sections examine ways of identifying and mapping palaeochannels and characterizing the hydrologic connectivity that exists between palaeochannels and other hydrological elements in the landscape.

2.1. Identifying palaeochannels

A major challenge in understanding water flow through palaeochannels is the difficulty of mapping their location, extent, and connectivity to other flow pathways. In the past, intensive monitoring and tracing experiments conducted on soil pits, trenches and entire hillslopes have been used to understand how preferential lateral flow paths are distributed in the landscape (Dougherty et al., 2004; Fox et al., 2011; Newman and Keim, 2013; Menichino and Hester, 2015; Blume and Van Meerveld, 2015). Tracers of water movement have included stable isotopes (Mueller et al., 2014), dyes (Anderson et al., 2009), salinity (Robinson et al., 2020) or heat (Ehrhardt and Gerke, 2023). Water

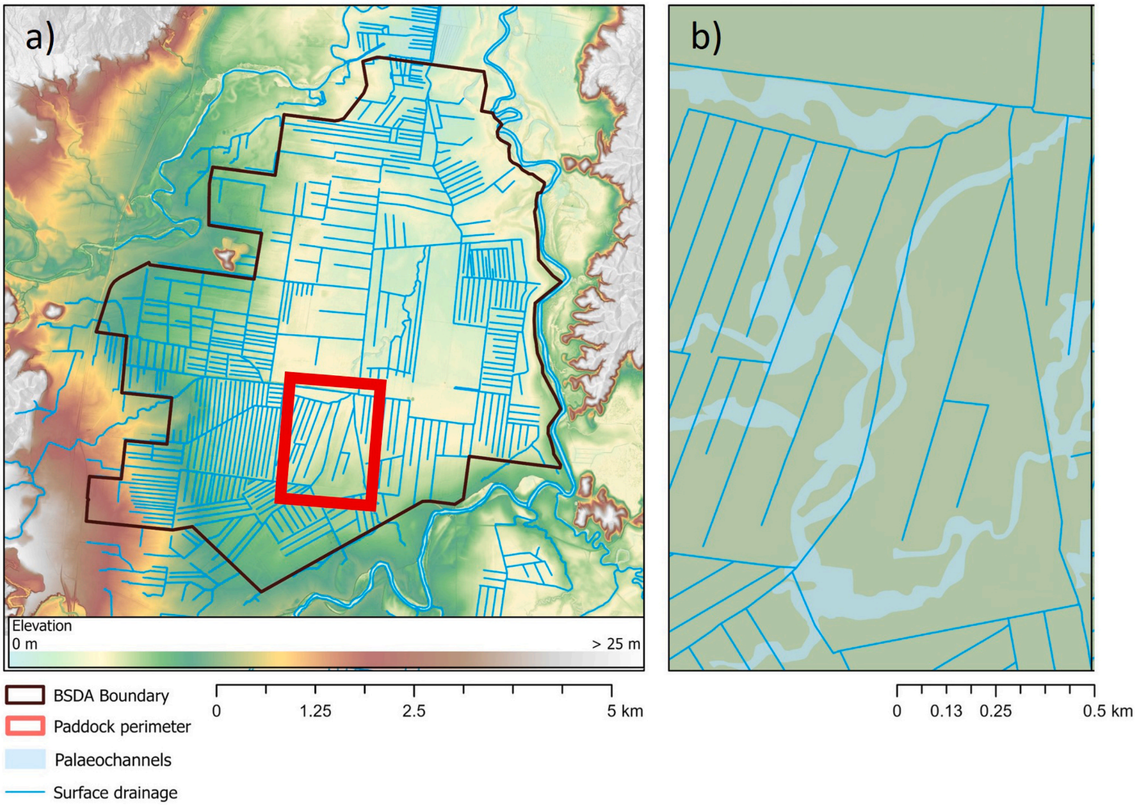

Fig. 2. An example of the prevalence of palaeochannels and intersections with surface drains in a low-lying alluvial agricultural landscape. Area outlined in black in a) represents the Babinda Swamp Drainage Area in tropical North Queensland, Australia, an area dominated by sugarcane production with a surface drain density of 8.3 km km^{-2}. Across this landscape, over half of the fields examined had palaeochannels mapped by Morrison et al. (2023) using electromagnetic induction (EMI). Image b) shows how identified palaeochannels intersect with surface drainage lines (Lim et al., 2024).

movement has also been detected directly using extensive networks of soil moisture probes or piezometers to map flow in space and time (Lin and Zhou, 2008; Mastrocicco et al., 2011; Mastrocicco et al., 2014; Demand et al., 2019) (Table 1). We also include the use of time-lapse ground penetrating radar as a 'direct' determination of paleochannels (Guo et al., 2014; Angermann et al., 2017) as it differs from other inference-based geophysical methods (Table 2) by employing repeated measures to detect the presence and movement of the water table. Direct identification of preferential lateral flow has the advantage of being definitive, but the intensity of resources required means it is feasible only at small scales, which fail to capture spatial connectivity at a larger scale where water quality impacts are felt and managed (Beven and Germann, 2013).

Inverse modelling assumes preferential lateral flow as a component of hydrologic models and uses iterative tuning to fit observations, and in the process, informs on the 'likely' presence of preferential lateral flow via features such as palaeochannels in the landscape (Table 1). This may include simple event-based hydrograph separation (Kumar et al., 1997; Gardner et al., 2017; Dusek and Vogel, 2018), examination of concentration-discharge curves (Guo et al., 2022) or the use of coupled hydrological and soil water models (Rozemeijer et al., 2010; Hansen et al., 2013; Boico et al., 2022; Valayamkunnath et al., 2022). The experiments that test different model conceptualizations of flow pathways also provide indications of the presence and relative importance of preferential lateral flow in the modelled landscape (Mencaroni et al., 2021). However, the effectiveness of inverse modelling is constrained by the availability of spatial and temporal hydrogeological data which can be extremely sparse.

Table 1
Direct methods of identifying preferential lateral flow through measurement of water movement and chemistry in the landscape, in decreasing order of spatial certainty.

Approach	Examples	Characteristics
Empirical (subsurface drain flow, groundwater)	Piezometer network, dye tracers and break-through curves	Highly localized in both space and time, require high intensity monitoring effort
Empirical (receiving waters)	Incremental stream gauging, stream chemistry, water temperature	Can identify existence of preferential lateral flow in upstream area
Inverse modelling	Using differences in discharge-concentration relationships across landscapes	Model-tuning assumes accuracy of other model components to infer preferential lateral flow

Zones with probable preferential lateral flow can also be inferred from measured soil and regolith properties associated with high hydraulic conductivity (Table 2). This indirect approach employs geophysical methods such as ground-penetrating radar (GPR), electrical resistivity tomography (ERT), and electromagnetic induction (EMI), which have been extensively reviewed by Fan et al., (2023), Guo and Lin (2018) and Mclachlan et al. (2017). These geophysical techniques detect subsurface contrasts in physical properties such as density or electrical conductivity, enabling the delineation of zones with enhanced permeability. For medium to large-scale preferential flow paths, including palaeochannels, methods such as EMI, GPR, airborne time-domain EMI (TD-EMI) have been successfully applied to map subsurface connectivity and structure (Hou and Mauger, 2005; Wray, 2009; Zani and De Fátima Rossetti, 2012; Khan and Sinha, 2019; Upadhyay et al., 2021; Sajinkumar et al., 2022).

Remote sensing of reflected, transmitted or emitted electromagnetic radiation can also be used to detect the presence of paleochannels

Table 2
Methods of mapping likely zones of preferential lateral flow in the landscape by inference from soil and regolith properties, using proximal to remote sensing.

Approach	Examples	Characteristics
Proximal geophysical	Ground penetrating radar, electromagnetic induction (EMI), seismic mapping	Identifies physicochemical soil/regolith traits at relevant spatial resolution and depths
Remote sensing	Satellite- or drone-based normalized difference vegetation index (NDVI) or hyperspectral analysis, elevation by LiDAR, determine surface features that indicate presence of palaeochannels	Identifies crop vigor or microtopography, which are correlated with relevant soil physicochemical traits

(Table 2). For example, reflectance of UV-IR frequencies related to vegetation vigor has been used to identify areas differing in water holding capacity (Wang et al., 2019). High-resolution LiDAR has also been used to identify topographic features (Zhang et al., 2020) that provide ‘signatures’ of the impact of preferential lateral flow networks on their surroundings.

Inference-based approaches may be the only viable option for mapping zones of preferential lateral flow at the broad landscape level, given the time and costs associated with direct detection methods. However, such approaches have several limitations. The proxies employed are not always reliable indicators of palaeochannels, and their spatial resolution is often insufficient for the detailed two- and three-dimensional mapping of subsurface properties such as depth, tortuosity and connectivity, needed to examine the spatial connections to surficial flow paths (Halihan et al., 2023). Furthermore, inference-based methods require careful site-specific validation in which soil and regolith properties are measured in the field or obtained using empirical relationships such as ‘pedotransfer functions’ (Upadhyay et al., 2021; von Hebel, 2021). A notable example of this is recent work by Morrison et al. (2023) in which palaeochannels and other permeable near-surface zones were mapped via inference across several thousand hectares of agricultural land in the Great Barrier Reef catchment. This was achieved by integrating EMI surveys with detailed soil-profile characterisation and remote sensing, providing a rare example of large-scale mapping supported by extensive field validation (Fig. 2).

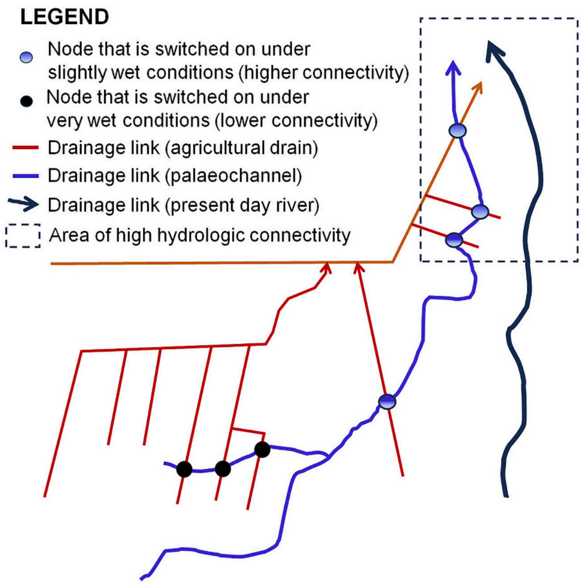

Fig. 3. Hypothetical network of water pathways in an alluvial area showing spatial patterns and frequency of hydrologic connectivity (similar to the site in Fig. 1). Nodes are switched on and off, resulting in connection or disconnection. In this figure, the nodes that are closer to the present day river are connected to the palaeochannel most of the time (high connectivity). Nodes further from the present day river are connected to the palaeochannel only for short periods of time or not at all. Scale of diagram is in metres to tens of km.

2.2. Hydrologic connectivity

Hydrological connectivity between palaeochannels and other flow pathways facilitates the transfer of water and material across the landscape. Hydrologic connectivity is broadly defined by the magnitude, duration and timing of water and water-mediated transport of materials between parts of the landscape (Jencso et al., 2009; Harvey et al., 2019). Patterns of connectivity can develop across vertical and lateral dimensions across different spatial and temporal scales. These interconnections create a mosaic of nested hydrologic connections and associated processes (Covino, 2017). In the case of palaeochannels, multi-scale hydrologic connections can occur between the palaeochannel and the surrounding matrix, small-scale preferential flow pathways (e.g. soil pipes, macropores) and subsurface drains (Noguchi et al., 1999; Sidle et al., 2000; Sidle et al., 2001; Nieber and Sidle, 2010) as well as large surface water bodies such as oxbows, lakes and streams (Quenet et al., 2019; Jeelani et al., 2025).

Network theory is often used to describe and examine flow networks in soils, and in this case, to conceptualise linkages between palaeochannels and the rest of the drainage network (Lin, 2010b). Simply put, a network is a set of discrete nodes and links connecting the nodes (Fig. 3). Nodes can be switched on (connected) or off (disconnected). The trigger for a switch is usually related to threshold moisture states associated with rainfall events that result in changing groundwater and/or stream levels (Nieber and Sidle, 2010; Mittelstet et al., 2011; Heeren et al., 2014). Links are pathways of water movement, either surface or subsurface. As antecedent wetness increases, preferential flow paths connect with other flow pathways into a complex network that is both spatially and temporally variable (Sidle et al., 2000; Sidle et al., 2001; Nieber and Sidle, 2010; Wilson et al., 2013; Gerke et al., 2015). The changing behaviour of connectivity may be modelled using percolation theory where changes in components of the network, nodes/links, are added or removed (Hunt et al., 2014; Stauffer and Aharony, 2018).

The spatial and temporal distribution of hydrologic connections determines water and material exchange fluxes in this landscape and allows for the construction of connectivity duration curves that define where and when different parts of catchments were connected for a range of hydrologic conditions, including large rainfall events and low flow periods (Jencso and McGlynn, 2011). While both Jencso et al. (2009) and Jencso and McGlynn (2011) focused on connectivity between hillslope-riparian zone-stream, the concept can be applied to understanding connectivity between palaeochannels and other drainage elements and features of alluvial landscapes. Hydrologic connectivity may be quantified using field tracer experiments, topographic analysis and modelling experiments (James and Roulet, 2007; Jencso et al., 2009; Jencso and McGlynn, 2011; Ameli et al., 2021; Schilling et al., 2022; Bishop, 2024). We focus on modelling experiments as a tool to understand the role palaeochannels play in moving water in an alluvial agricultural landscape. To do this, we first provide a conceptual model of the alluvial agricultural landscape and evaluate current models and approaches that may apply to modelling a landscape with palaeochannels.

3. Modelling water flow in alluvial landscapes with palaeochannels

3.1. System elements and linkages

The flow of water and associated materials (dissolved and particulate) in alluvial agricultural landscapes involves the complex interaction between landscape components categorized as the soil-plant-atmosphere-continuum (SPAC), groundwater and surface water (Fig. 4). The water table tends to be high and dynamic in these landscapes, fluctuating in response to rainfall, vadose zone processes (e.g. infiltration, evaporation, root uptake and transpiration, capillary rise) and groundwater processes (e.g. recharge, discharge and lateral flow). Root water uptake and transpiration vary with crop type, growth stage and management (e.g. irrigation, fertilizer applications, etc.).

Both within the soil and at the interface between ground and surface waters (Fig. 4), lateral subsurface flows can be bidirectional, depending on the relative positions of drainage lines and the local water table. These interactions can be highly dynamic in both space and time (Lamontagne et al., 2003; Karim et al., 2016; Webb et al., 2017; Biehler et al., 2020; Martin et al., 2023), as illustrated in coastal settings where the tidal influence can periodically reverse flow directions. Whilst man-made surface and subsurface drains can enhance surface water-groundwater interactions - by modifying hydraulic gradients and connectivity (Rozemeijer et al., 2010; King et al., 2014; Thomas et al., 2016) - palaeochannels can provide additional conduits that facilitate surface water-groundwater exchange. They can be activated during periods of high water table or stream stage and deactivated when the water table drops. Once the palaeochannel is connected to surface or subsurface drains, a network forms, linking them to the surrounding soil matrix, smaller preferential flow paths or larger drainage features (Fig. 3). We hypothesise that this lateral connectivity represents the dominant pathway by which water is redistributed and routed downstream in these landscapes (Sophocleous, 1991; Vanags and Vervoort, 2013).

Each major component of this environment (SPAC, groundwater, surface water) shown in Fig. 4 may be modelled individually (Sections 3.1.1 to 3.1.3) or in a coupled manner to capture system interactions and linkages more realistically (Section 3.1.4), and all can be impacted by the influence of preferential flow in palaeochannels (Section 3.2).

3.1.1. Hydrology of the soil-plant-atmosphere continuum (SPAC)

The vadose zone is the interface between plants and the groundwater zone below. Deep drainage, the downward flux between the bottom of the root zone and the top of the saturated zone, is described by Equation (1):

$$DD = P + I - R - \Delta S - ET \tag{1}$$

where DD is deep drainage, P is precipitation (rainfall), I is irrigation, R is surface runoff, ΔS is the change in soil water storage (or variably saturated zone), and ET is evapotranspiration (all in units of $[\mathrm{L}\ \mathrm{T}^{-1}]$). Inputs P and I are usually data driven whereas R, ΔS and ET are often modelled. The processes occurring in the vadose zone are complex and highly dynamic, and Richard's equation is often used to describe water flow in it, formulated as the change in volumetric soil water content (θ) with time (t):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \Psi}{\partial z} + 1\right)\right] - S \tag{2}$$

where z is distance [L]; t is time [T]; θ equals $\theta\,(z,t)$ and is the volumetric soil moisture content [V/V]; ψ is soil water potential expressed as a (negative) head [L]; $K(\theta)$ is the unsaturated hydraulic conductivity at a given water content $[\mathrm{L}\ \mathrm{T}^{-1}]$ and S is a sink term, typically root uptake.

Existing soil hydrology models capture heterogeneity due to preferential flow pathways either as dual porosity, dual permeability, or multi-region models. Dual porosity models partition the soil into macropores and a slower matrix domain, where water flow is restricted to the macropore domain and exchange between domains is governed by a first-order mass transfer term. Dual permeability models extend this by allowing water to flow simultaneously in both the macropore and matrix domains, each described by Richards' Equation, with the inter-domain mass transfer remaining a key source of parametric uncertainty. Multi-region models further generalise this framework by incorporating primary and secondary preferential flow pathways, with each region modelled using Richard's Equation. However, the application of Richards' Equation to the macropore domain remains theoretically problematic, as water flow through soils with macropores is non-equilibrium in nature, violating the local equilibrium and continuum assumptions on which Richards' Equation depends (Beven and Germann, 2013). Extensive reviews of preferential flow and approaches to modelling it more realistically are provided by Orozco-López et al.

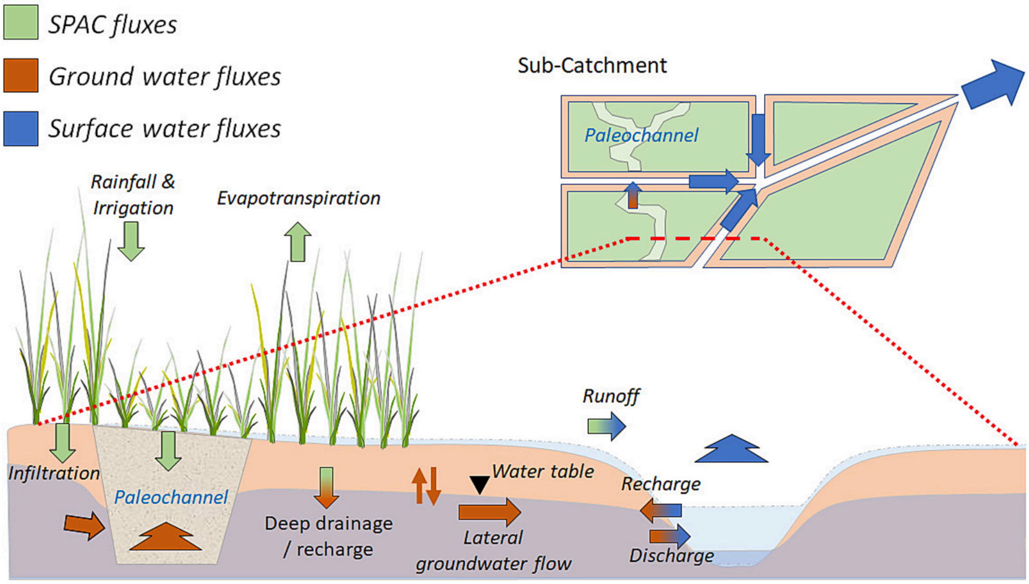

Fig. 4. Integrated hydrological fluxes within the soil plant atmosphere continuum (SPAC), groundwater and surface water elements of an alluvial agricultural landscape, such as that depicted in Fig. 2. These flux components can be modelled individually or integrated through the coupling of hydrologic models.

(2018), Germann and Beven (1981), and Kohne et al. (2009) while Glass et al. (1989) and Selker et al. (1992) demonstrate early attempts to represent preferential flow dynamics explicitly.

The HYDRUS Computer software (PC-Progress, www.pc-progress.com) and its associated packages are one of the most well-known soil water models used to model variably saturated conditions using Richard's equation for water movement due to gravity or capillary forces (Šimůnek et al., 2016). HYDRUS can model both uncompensated (water is taken up directly from the local root zone without any interaction between different root zones) and compensated root water uptake (plant can take water from other root zones) (Version 4.08, (Šimůnek and Hopmans, 2009). Root water uptake is modelled as a sink term that is added to Richard's Equation (Equation (2)) (Feddes and Raats, 2004). HYDRUS can also model drainage fluxes to drains either at the bottom of the soil profile or through a vertically distributed region in the saturated zone (Version 4.17). Model simulations can be run in one-, two- or three-dimensions (Köhne et al., 2009). The HYDRUS-2D model includes dual-region ('dual porosity' or 'mobile-immobile') models for simulating preferential flows.

Crop growth models are used to model water fluxes associated with plant growth. Widely used one-dimensional crop models including EPIC (Williams et al., 1984), DSSAT (Jones et al., 2003), DAISY (Hansen et al., 1991), CropSyst (Stöckle et al., 2003), STICS (Brisson et al., 1998) and APSIM (Holzworth et al., 2014), are often applied in a regionally specific manner. For instance, the APSIM model is widely used in modelling studies within the Great Barrier Reef catchment (Holzworth et al., 2014).

In APSIM, hydrology can be simulated either with APSIM-SoilWat (Probert et al., 1998), a 'tipping bucket' water balance model, or by the Soil and Water Integrated Model (SWIM), ecohydrological model that incorporates hydrological processes, vegetation, nutrient and erosion modelling at various scales (Verburg, 1996; Krysanova et al., 2015). The latest release in the family of SWIM models, the SWIM3 module, simulates 1D soil-water movement within soils and is incorporated in APSIM (Huth et al., 2012). The SWIM model has been used extensively for modelling deep drainage of water and N in sugarcane to evaluate the effects of management, soil type and climate scenarios on crop yield (Stewart et al., 2006; Thorburn and Wilkinson, 2013). However, there is limited validation of deep drainage fluxes because they are difficult to measure and depend largely on modelled ET, which is generally calibrated in the model (Inman-Bamber and McGlinchey, 2003). Furthermore, crop system models such as APSIM typically cannot simulate water table fluctuations as they involve processes in three dimensions.

3.1.2. Groundwater hydrology

Water movement in the saturated zone is modelled using Darcy's Law, which is a one-dimensional model that assumes laminar flow in a homogeneous porous medium and a linear relationship between specific discharge and hydraulic gradient:

$$q = -K\frac{dH}{dL} \tag{3}$$

where q is specific discharge [L T^{-1}], K is saturated hydraulic conductivity [L T^{-1}] and $\frac{dH}{dL}$ is the hydraulic gradient [L L^{-1}]. In widely used groundwater models, such as MODFLOW, Darcy's Law is combined with mass balance accounting for subsurface flows (Wang and Chen, 2021). The spatial variability in aquifer properties, especially in areas with contrasting alluvial deposits (Medici et al., 2021; Keegan-Treloar et al., 2022) is best captured with two- or three-dimensional modelling.

MODFLOW is a groundwater model that is used widely due to its ability to simulate a variety of groundwater conditions. It is a three-dimensional, mechanistic, distributed finite-difference model that captures steady and transient states and spatial variations in aquifer parameters (Wang and Chen, 2021). One challenge of groundwater flow models is the estimation of recharge, which is achieved by coupling groundwater and vadose zone models so that the output from the vadose zone model becomes the input term into the groundwater model (Zeng et al., 2019; Pawlowicz et al., 2024).

3.1.3. Surface water hydrology

Surface water hydrology is usually modelled using a catchment hydrology model that collects and routes water through the landscape. These models represent space in a variety of ways, including lumped conceptual, semi-distributed conceptual and distributed models.

Lumped models assume that inputs and parameters are homogeneous across a given catchment. This approach is limited when attempting to simulate hydrological responses in catchments having spatially variable properties (e.g. land use, slope and soil properties), limiting their application to small and medium-sized catchments (Koren et al., 1999).

Semi-distributed models discretise meteorological variables and physical parameters into several sub-catchments. The modelled runoff response from each sub-catchment is routed downstream to estimate the catchment-wide runoff. The SWAT model is widely used, especially in agricultural applications (Gassman et al., 2007; Janjić and Tadić, 2023). SWAT delineates a catchment into sub-catchments, which are further organised into hydrological response units (HRUs). HRUs are unique combinations of land use, slope, and soil properties. SWAT has had limited applications in countries such as Australia due to the scarcity of information for landuse, climate and soil properties (Saha and Zeleke, 2015). Instead eWater Source (www.ewater.org.au/ewater-solutions/tools/source/) is a widely used hydrological modelling platform in Australia (Carr and Podger, 2012).

Fully distributed models consider the spatial distribution of properties across a catchment using a grid or triangulated mesh network. While fully-distributed models may capture spatial heterogeneity better than lumped or semi-distributed models, they require more data and longer simulation times (Jajarmizadeh et al., 2012). MIKE-SHE (www.mikepoweredbydhi.com/products/mike-she) and TUFLOW-CATCH (https://www.tuflow.com/products/tuflow-catch/) are both examples of a fully distributed model, which can combine the surface and groundwater flow simulations in a three-dimensional grid, moving water between adjacent grid cells.

One of the most common routing methods is the storage-based scheme developed by Muskingum, which is based on conservation of mass and was later improved to become the Muskingum-Cunge method (Cunge, 1969). These methods are relatively simple and can be applied within models such as SWAT. More accurate representations of surface water flows involve the St Venant equations (for one- and two-dimensional surface flows), which consist of simplified representations of continuity and momentum derived from the Navier-Stokes equations (Singh, 2018; Cortés-Salazar et al., 2022). These equations are complicated to solve and are typically limited to specialised hydraulic modelling packages (e.g., MIKE-SHE). Importantly, the type of method used depends on the application, and the desired spatial resolution, level of discretization and representation of physical processes.

3.1.4. Coupling system element models

Hydrological models may be coupled to simulate the continuum of water movement through plant, soil, groundwater and surface runoff. This coupling may be implemented in diverse ways depending on the application. Examples include coupled crop-hydrological models, vadose zone-saturated zone models and coupled catchment-scale models. There are comprehensive reviews on topics related to hydrologic model coupling including reviews on coupled crop-hydrological models (Siad et al., 2019; Uniyal and Dietrich, 2021; You et al., 2024), modelling surface water-groundwater interactions (Ntona et al., 2022) and various computation aspects of model coupling (Furman, 2008; Siad et al., 2019; You et al., 2024). Several coupled surface–subsurface catchment models are outlined below as potential tools for simulating hydrological processes in alluvial agricultural landscapes containing palaeochannels.

The HYDRUS-MODFLOW coupled model is among the most widely used models for simulating vadose zone and groundwater interactions (Twarakavi et al., 2008). The HYDRUS model provides water recharge to the groundwater system, while MODFLOW (De Schepper et al., 2015; De Schepper et al., 2017) computes groundwater pressure heads, which form the lower boundary conditions for HYDRUS simulations (Peña-Haro et al., 2012). Recently, the HYDRUS-MODFLOW Synergy Engine (HMSE) provides a new approach to coupling the models, in which the user can prepare the MODFLOW and HYDRUS-1D models independently using graphic user interfaces available for both models (Pawlowicz et al., 2024).

Surface-subsurface flow dynamics at the field/catchment scale can be modelled using models such as SWAT-MODFLOW, MIKE-SHE and HydroGeoSphere models. According to recent reviews (Wang and Chen, 2021; Ntona et al., 2022), the SWAT-MODFLOW modelling system is the most widely used coupled surface water-groundwater model. This is due to its relatively simple operation, good visualisation and low data requirements compared to other coupled surface water-groundwater models. The SWAT-MODFLOW model outperformed the SWAT model in many studies due to its ability to capture unsaturated-saturated zone processes more effectively (Aliyari et al, 2019; Molina-Navarro et al., 2019; Guevara-Ochoa et al., 2020; Frederiksen and Molina-Navarro, 2021), especially for agricultural areas where subsurface drainage is dominant (Frederiksen and Molina-Navarro, 2021).

Fully coupled distributed numerical models such as HydroGeoSphere (HGS) and MIKE-SHE can also model water transport in spatially heterogeneous alluvial landscapes by representing space in a fully distributed nature and using physically-based representations of subsurface and surface flow. HGS models three-dimensional subsurface flow (Richard's Equation), two-dimensional overland flow (diffusion wave approximation) and drain flow in one dimension (Therrien et al., 2010). These models may be used to model palaeochannel flow, as they are often used to model tile drain flows in many studies (Rozemeijer et al., 2010; De Schepper et al., 2015; Thomas et al., 2016; De Schepper et al., 2017; Boico et al., 2022).

Modelling results are affected by factors such as model spatial discretisation (i.e. type and resolution), data used for model calibration (i.e. drain flow versus streamflow, and the choice of flow equations and boundary conditions (De Schepper et al., 2017)). A comparison of tile drainage modelled by HGS and MIKE-SHE showed that the HGS model reproduced drain discharge peaks more accurately. Discrepancies in flow response by these models resulted from differences in the form of the Richard's Equation used (three-dimensional in HGS, one-dimensional in MIKE-SHE) and model spatial discretisation (De Schepper et al., 2017).

3.2. *Modelling palaeochannels in hydrologic models*

3.2.1. *Palaeochannel conceptualisation*

Subsurface drainage networks are often simplified in hydrological models for two reasons. The first is the lack of information about their location, dimensions and connectivity. The second is the long simulation times required, due to dense computation meshes needed to capture spatial heterogeneity and connectivity effectively. These challenges increase with the size of the study site (De Schepper et al., 2015; De Schepper et al., 2017; Rathore et al., 2024). We look to tile drain conceptualisations in hydrological models because they have similar scale and flow direction (lateral) to palaeochannels (Rozemeijer et al., 2010; De Schepper et al., 2015; De Schepper et al., 2017; Boico et al., 2022; Han et al., 2024; Rathore et al., 2024). The three most common representations of subsurface drains in recent hydrological models can be categorised as one-dimensional linear elements, a high conductivity layer, or nodes and sinks (Table 3).

Table 3
Conceptualisations of subsurface drainage features adopted in various hydrologic models that may be applicable to the study of palaeochannels in the landscape.

	Conceptualisation	**Scale of example study**	**Reference**
One-dimension linear elements			
CATFLOW	Connected flow pathways with a hydraulic conductivity value assigned. Tile drainage is scaled by multiplying specific outflow by the width of the cross-section of the tile drain (i.e. drain width). No separation between tile drain tube and surrounding medium.	Tile-drained field	(Klaus and Zehe, 2010; Klaus and Zehe, 2011)
HYDRUS	Open cylinder with a seepage face boundary condition for the part of the drain in contact with the matrix domain.	Small-scale laboratory study of a vertical macropore connected to a subsurface drain.	(Akay et al., 2008)
HydroGeoSphere (HGS)	Drainage in tile drains modelled in one-dimension as linear elements with diameter of 0.1m using the Hazen-Williams empirical equation for pipe flow. One layer of nodes located at the depth of the drain, whose location corresponds with the network. Tile drains simulated as one-dimensional pipes following element edges.	Plot scale 125 m^2 test catchment	(De Schepper et al., 2015) (Thomas et al., 2016)
High conductivity layer (equivalent medium)			
HydroGeoSphere (HGS)	High permeability layer at 0.7-1.0m below surface. High conductivity layer 0.1m thick with properties of typical sand to gravel material, determined through manual calibration. Nodes of this layer along the downstream boundary were given a head equal to their elevation. High permeability layer. 0.1m thick, at 1.0m below surface. Nodes of this layer along the downstream boundary were given a head equal to their elevation.	Field scale Plot scale 125 m^2 test catchment	(Rozemeijer et al., 2010) (De Schepper et al., 2015) (Thomas et al., 2016)
Nodes and sinks			
MIKE-SHE	Drainage is generated when the water table is above the subsurface drain elevation. Drainage is routed either downhill or to nearest stream. Same as above. Routing	Plot scale 4.7 km^2 catchment	(De Schepper et al., 2015) (Hansen et al., 2013)

(continued on next page)

Subsurface drains are conceptualised as one-dimensional linear

Table 3 (*continued*)

	Conceptualisation	Scale of example study	Reference
	of subsurface drainage discharge based on drain codes, to either the model boundary or nearest river node in the area.		
FEFLOW	Nodal sink. Water is removed from the model when water table rises into the drain. Becomes inactive when water table drops below. Seepage face boundary conditions where only outflow from the model is allowed.	0.92 km^2 area	(Hansen et al., 2019)
Advanced Terrestrial Simulator (ATS)	Catchment-based sink made up of multiple cells in subsurface drain layer. Tile drainage is routed from each catchment-based sink to nearby stream or ditch.	1024 km^2 catchment	(Rathore et al., 2024)

elements in situations where there is information about the drainage network. This conceptualisation requires long simulation times, so it is applied mainly to small study sites and short time periods (e.g., hours, days) (De Schepper et al., 2015; Thomas et al., 2016; De Schepper et al., 2017).

The subsurface drainage network may be modelled as a homogeneous, high conductivity layer (also known as equivalent medium) for the entire model domain (Rozemeijer et al., 2010; De Schepper et al., 2015; Thomas et al., 2016; De Schepper et al., 2017; Boico et al., 2022). This approach overcomes the problem of precisely locating the subsurface drainage network. Flow in this layer is often modelled using Richard's Equation (Carlier et al., 2007; Wilson et al., 2013). In a rare modelling study of palaeochannels, they were modelled as a single layer with conductivity values obtained from field information (Mulligan et al., 2007). The parameters of this medium may be calibrated against observed data or calculated. Carlier et al. (2007) averaged vertical saturated hydraulic conductivities to obtain a value for the equivalent medium. The disadvantage of this approach is that tile flow is mixed with non-tile flow. This inability to separate flow pathways is a disadvantage in modelling solute transport, where partitioning of flow pathways is required (Boico et al., 2022; Rathore et al., 2024).

Subsurface drainage can also be simulated using nodes or as sinks (Gärdenäs et al., 2006; De Schepper et al., 2017; Boico et al., 2022; Rathore et al., 2024). Tile drains are usually represented as a layer of its own in hydrological models, where drainage is modelled at the location of the nodes. The position of the nodes can either correspond to a predefined elevation (Thomas et al., 2016), the location of a surface ditch/drain (De Schepper et al., 2015; De Schepper et al., 2017) or at the mouth of a small catchment (Rathore et al., 2024). Tile drainage is generated in several ways. A common approach is to generate subsurface drainage in these networks when the groundwater level rises above the tile drain elevation and to stop it when the groundwater level drops below the prescribed elevation (e.g., Hansen et al., (2019)). This approach is adopted by the MIKE-SHE model. Other ways of generating tile drainage include setting soil moisture thresholds, where tile drainage occurs when soil moisture rises above a level between field capacity and saturation (Lam et al., 2016). If the tile drain is simulated as an internal sink, then water flowing into the tile drain from the soil is not allowed to flow back into the surrounding soil and can leave the simulation domain as soon as it reaches the surface drains (Kirkham, 1949; Barcelo, 1981; Barcelo and Nieber, 1982; De Schepper et al., 2017). A full seepage face boundary condition implemented in a model ensures full contact between the drain and the surrounding soil (e.g., FEFLOW-3D model (Hansen et al., 2019)) and in De Schepper et al., (2017)'s case, specified to allow water flow in both directions.

To understand the effect of subsurface drainage conceptualisation on modelling results, Boico et al. (2022) compared four conceptualisations of tile drainage: a) modelling only the main collector drains, b) distributing tile drains all over the catchment with no consideration of their locations, c) representing the tile drains where they are located, as seepage nodes and d) as a high permeability layer. All four conceptualisations performed equally well when the HGS model was applied to a small catchment (6 km^2) in Denmark. In other studies, errors in modelled subsurface drainage were greater when the drainage network was under-represented (De Schepper et al., 2015; De Schepper et al., 2017). This problem is greater for larger-scale studies, which require more information about the spatio-temporal distribution of palaeochannel flow, which may not always be available. However, for small-scale studies with limited information on the subsurface drainage network, an option is to simplify the subsurface network by modelling only main drains (De Schepper et al., 2015; Boico et al., 2022).

3.2.2. *Connecting palaeochannels to other landscape components*

The interactions between palaeochannels and surface/subsurface drains are ideally captured using a coupled, fully distributed model that includes a crop model and a hydrological model that models tile drainage in one dimension, surface flows in two dimensions, and subsurface flows in three dimensions. For alluvial agricultural landscapes, a key connection node will be to capture the flows of water between subsurface and surface drainage elements.

For distributed hydrological models, the connections between surface and subsurface flows through artificial drainage structures have been achieved in two main ways. In studies where tile drainage is modelled as one-dimensional pipeflow following the edges of a model element, they are then connected to a stream centreline to ensure connectivity (Thomas et al., 2016). If tile drainage is modelled as seepage nodes or sinks, then tile drainage is either summed or routed to surface drains or a pre-set model boundary condition (Hansen et al., 2013; Thomas et al., 2016; Hansen et al., 2019). Instead of using regular grids or triangulated irregular network meshes, mixed meshes that involve finer mesh resolution nearer to streams and coarser resolution for cells further away from streams often improve simulations of surface water-groundwater interactions (Thomas et al., 2016; Rathore et al., 2024; Han et al., 2024). Despite these improvements in capturing spatial heterogeneity, model runs are still computationally intensive, limiting their application to small-scale studies, either at the field or small catchment scale (Rozemeijer et al., 2010; De Schepper et al., 2015; De Schepper et al., 2017). Rathore et al., (2024), however, modelled a large catchment ($>$1000 km^2) by aggregating tile drainage for the entire catchment, rather than modelling drainage from individual tile drains. This was achieved by representing tile drainage as a uniformly distributed subsurface source of water, which was injected into stream/ditch elements.

Instead of a fully distributed model, the modelled landscape can also be divided into similarly functional hydrologic units (Winter, 2001). An example is the hydrologic response units (HRUs) adopted by the SWAT model. HRUs are lumped units with similar soil, topography, and landuse that are found within a sub-catchment (Arnold et al., 2010). In a similar vein, Sidle et al., (2001) suggested delineating a catchment into hydro-geomorphic response units (e.g., hillslopes, riparian/channel areas) and lumping the hydrologic response from each unit. For a landscape with palaeochannels, one functional unit represents the palaeochannel, and another unit represents non-palaeochannel soils. Connecting these functional units over a larger scale ensures continuity in flow routing.

Recent developments in the SWAT modelling platform, SWAT+, allow landscape elements (e.g., HRUs, channels, reservoirs, ponds, point sources, etc.) to be treated as separate spatial objects (Bieger et al., 2019; Bailey et al., 2022; Wagner et al., 2022). The modeller determines the hydrologic interactions between these spatial objects in the model. SWAT+ uses routing units to lump hydrographs and route them to another spatial object (Bailey et al., 2020). In the SWAT+(MODFLOW) model, water fluxes are passed between HRUs, grid cells and stream channels. MODFLOW river cells are spatial objects that can exchange water with SWAT+ stream channels (Bailey et al., 2020). When this model was compared to SWAT+, the greatest improvement was observed for groundwater fluxes, showcasing its potential to model surface water–groundwater interactions more accurately in areas where these processes are dominant. SWAT+(MODFLOW) has also been used to model catchments where there is extensive tile drainage and near-surface water tables (Wagner et al., 2022; Bailey et al., 2022), suggesting its potential application to environments with palaeochannels.

Although mixed-meshes for fully distributed models or functional units with grid cells in coupled models are useful ways of dealing with landscape heterogeneity, they involve challenges. They entail a heavy computational burden, and there is often insufficient field data to run and calibrate them. Furthermore, hydraulic parameters are often scale-dependent, with values depending on grid resolution (Refsgaard, 1997). Parameters may also need to change in time to reflect the dynamic nature of the subsurface drainage network, such as clogging. Another challenge arises in modelling reverse flow in areas experiencing bi-directional flows. Despite using a fully coupled distributed model, (Rathore et al., 2024) failed to model reverse flow. This presents a significant problem in modelling alluvial landscapes, given that reverse flow may occur on a seasonal basis (Lamontagne et al., 2003).

3.3. *Understanding palaeochannel hydrology through virtual experimentation*

Apart from traditional laboratory experiments and field monitoring, virtual experiments using models can enhance the understanding of landscape hydrology (Thyer, 2024). We use the term virtual experiments here after Weiler and McDonnell (2004) who envisioned numerical experiments or simulations with a model that is driven by collective field intelligence, highlighting the benefits of understanding gained through collaboration between the experimentalist and modeller. The advantages of virtual experiments are that they can a) point to processes and potential interactions that are not directly observed in the field, b) reveal data requirements that help constrain model parameterisation and, in the process, highlight required model modifications, and c) aid field data collection (Thyer, 2024; Bishop, 2024).

There has been little use of virtual experiments to examine palaeochannel flows, but they have been used to study small-scale preferential flow paths (e.g. macropores, soil pipes) at the hillslope and catchment scale (Weiler and McDonnell, 2004; Nieber and Sidle, 2010). Lim et al. (2024) examined the impact of the presence and depth of palaeochannels on drainage fluxes from a hypothetical agricultural field. Palaeochannels parameterised to match field observations increased discharge from the field slightly, 3.6% and 4.4% when a surface and subsurface palaeochannel were present, respectively. The subsurface palaeochannels induced more lateral flow in the palaeochannel compared to the surface palaeochannel. From a nutrient transport perspective, the increased drainage from a field with palaeochannels could decrease the water and nutrients available for plants and increase the nutrient discharge to downstream system via a subsurface route. Mulligan et al. (2007) explored groundwater and seawater exchange and found that palaeochannels are potentially important conduits for saltwater intrusion into confined aquifers when over pumping of groundwater occurs on land.

There is considerable scope to carry out virtual experiments to examine the effects of palaeochannel characteristics (i.e. size, depth, position, orientation) on water fluxes at the scale of agricultural fields, similar to experiments conducted with artificial subsurface drains, for example, with and without drains (Carluer and De Marsily, 2004; Carlier et al., 2007). Other virtual experiments could explore the mechanisms surrounding water propagation through palaeochannels. Sophocleous (1991) found that water moved from a stream to the aquifer along palaeochannels via the propagation of pressure waves. The extent of this pulse propagation and the speed of water movement were determined by hydraulic diffusivity. Further experimentation in this area may reveal new ways of representing water movement at this scale, rather than adopting classical small-scale physics to describe water movement through soils and larger preferential flow paths (Germann and Beven, 1981; Beven and Germann, 2013). Other experiments could examine the spatial-temporal patterns of connectivity and their impacts on water and material fluxes.

4. Future directions in modelling

This paper identifies a need for better approaches to examine the impacts of water and material transport via palaeochannels, moving beyond their identification and characterisation. This is particularly important in alluvial landscapes, where palaeochannels are common and where agricultural production and environmental concerns require improved management approaches. Fig. 5 provides a framework to achieve better understanding and use of various approaches to achieve better management and monitoring decisions in heterogenous environments where paleochannels are found. Important directions for future work are outlined below.

4.1. *Capturing real-world processes*

An important issue that requires further work is to capture the dynamics of fluctuating water tables more effectively in coupled vadose zone-groundwater models, which tend to be computationally intensive. Preferential flow models also need to better account for important processes around the fluctuations in the shallow water table (Orozco-López et al., 2018) by adopting approaches that account for non-uniform groundwater motion due to varying hydraulic gradient and thickness along the flow path - due to the presence of a palaeochannels (Pavlovskii, 1930; Pavlovskii, 1932). Modelling reverse flow in environments, where bi-directional flow is common, remains a challenge, especially for agricultural alluvial landscapes where reverse flow from rivers and other hydrological features can feed water into palaeochannels (Rathore et al., 2024).

Furthermore, researchers still need to address a fundamental issue around the use of classical small-scale physics which does not reflect real world spatial heterogeneity, temporal dynamics associated with the soil, crops, meteorological conditions, and boundary conditions that occur at the larger scale where palaeochannels are found (Germann and Beven,

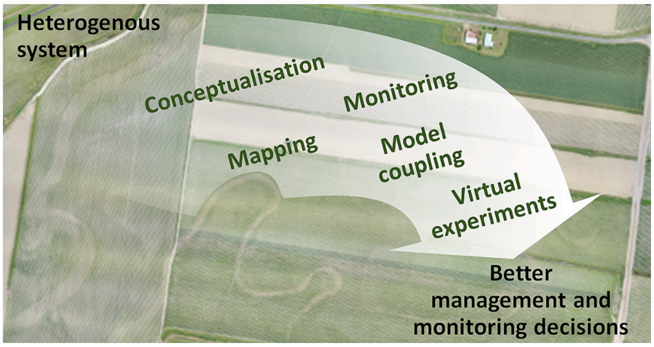

Fig. 5. A framework for modelling hydrology of alluvial landscapes with paleochannels (Source of image: Marcus Bulstrode, Queensland Government Department of Primary Industries).

1981; Köhne et al., 2009; Beven and Germann, 2013; Jarvis et al., 2016). An alternative approach may be the Hooghoudt Equation, which is used to calculate tile drainage in several models, such as the more recent version of the SWAT model and in MODFLOW's Drain package (Moriasi et al., 2013; Golmohammadi et al., 2016; Yang et al., 2022). The Hooghoudt drainage model accounts for tile drain (e.g., spacing, depth, radius, etc.) and matrix properties (e.g., permeability, conductivity, soil depth, water table elevation) (Rathore et al., 2024). This reduces the need for model calibration, includes important features that control subsurface flows in tile drains, and is less computationally intensive. For these reasons, Rathore et al., (2024) modelled subsurface tile drainage over a large area (>1000 km^2). The development of scale-appropriate equations for palaeochannel flows will benefit from increased understanding of how these features behave with information gained through field measurements and virtual experimentation.

4.2. Addressing heterogeneity at larger scales

Modelling preferential flow at a larger scale (metres or more) requires that models upscale these processes either in the form of the equations used and/or the way model parameters and heterogeneity are represented in the modelling framework. Examples include the use of aggregated model parameters or using distribution functions to address spatial variability. Linking scales in hydrologic modelling remains a challenge for landscapes where palaeochannels are found, as the modelling not only needs to account for water flow in these larger-scale preferential flow paths, but also the interactions with other flow pathways of different scales (Blöschl and Sivapalan, 1995), both fine (e.g., soil pipes) and large-scale (e.g., drains, rivers), in a dynamic environment where the shallow water table fluctuates frequently. To model larger areas, some options include simplifying the drainage network, i.e. model only the main drainage network, with good results achievable when the model is well calibrated (De Schepper et al., 2015). Interestingly, the impact of drainage conceptualisation on modelling results is scale dependent. At small scales, soil heterogeneity exerts a greater impact than the drainage conceptualisations adopted in models. This is opposite at the sub-catchment scale, where both soil heterogeneity and drainage conceptualisation have comparable impacts on modelling results (Boico et al., 2022). Improvements in our ability to map and measure subsurface drainage properties will aid model conceptualisation of subsurface drainage networks to test the scale-dependency of drain conceptualisations in hydrological models.

An important aspect in modelling water fluxes through palaeochannels more effectively may be achieved through innovative ways of representing spatial heterogeneity, either through mixed meshes or functional units coupled with grid cells and, importantly, user autonomy in connecting spatial units together (Bailey et al., 2020). Despite these improvements, the challenge of high computational requirements remains as model complexity increases, particularly when it comes to modelling the landscape or regional scales (Chen et al., 2023). One approach to reducing computational burden is to replace computationally intensive models that represent mechanistic, physical processes (e.g., MODFLOW) with machine learning models that provide comparable results with lower computational requirements (Chen et al., 2023). These developments reflect a move towards combining physics-informed model integration with machine learning algorithms (Karpatne et al., 2017; Karniadakis et al., 2021). Using 'digital twin' models further allows virtual experimentation for extended periods or different climate scenarios (Bartos and Kerkez, 2021; Morlot et al., 2024).

4.3. Integration of field mapping and monitoring to support modelling efforts

Accompanying virtual experiments is a holistic approach in field data collection that involves multi-scale mapping of palaeochannels to identify their network patterns and connectivity, as well as monitoring water movement through them. Developments in technology present new ways to sense subsurface flow pathways at various scales using drones (small scale, cm resolution) to large scale (satellites, kms and beyond). For example, a towed transient electromagnetics (tTEM) sensing system could provide three-dimensional imaging of the subsurface profile down to a depth of 70 m (Auken et al., 2019), which, if applied to palaeochannel mapping, can provide useful information about the depth range of palaeochannels and patterns of subsurface connectivity at field to small catchment scales. This technology was used successfully for subsurface mapping of hydrogeological settings, sometimes in areas with difficult access (Maurya et al., 2020; Grombacher et al., 2022). Remote sensing images may be used with machine learning algorithms to map palaeochannels, given successful applications to mapping subsurface drainage, especially at the catchment scale (Redoloza et al., 2023; Wan et al., 2024). New ways of sensing may also provide soil moisture and evapotranspiration data over different spatial and temporal scales, which are useful for parameterising crop models, which are often not well parameterised (Lubczynski et al., 2024) and can yield additional information about palaeochannel physics as a proxy.

Additional field data supports a multitude of future work, such as improving calibration of hydrological models or absence of calibration (Rathore et al., 2024), theoretical developments to support modelling water fluxes through larger preferential flow paths and importantly, a better understanding of how palaeochannels interact in the environments they are found in. This can be achieved by combining virtual experimentation with field observations across a range of spatial and temporal scales.

5. Conclusions

This paper provides a review and thought experiment of how we can better understand and model water flow through palaeochannels found in agricultural alluvial landscapes. The review has shown the multitude of ways palaeochannels can be detected and mapped at various scales, from the ground level to remote sensing from outer space. To model water and material transport through palaeochannels, we found that these features are conceptually similar to agricultural tile drains. Coupled hydrological models, HYDRUS-MODFLOW, SWAT-MODFLOW, MIKE-SHE and HydroGeoSphere, offer the best option to simulate palaeochannel-mediated flow and material transport because they have the capability to capture interactions between the unsaturated-saturated zone as well as between surface water and groundwater. However, this review has also shown that despite advances in model development, modelling water flow through palaeochannels is constrained by data availability and high computational demands that restricts modelling to plot- or field-scale studies. These challenges may be overcome by developments in the way models represent drainage flow (e.g. Hooghoudt equation) and spatial discretization (e.g. mixed mesh or HRUs). Further improvements in modelling may be achieved by replacing computationally intensive models with machine learning algorithms. However, the way we model water movement through heterogeneous environments remains a challenge. Continuous efforts to overcome this challenge require the integration of field mapping and monitoring activities with modelling efforts to provide insights that guide the development of more scale-appropriate flow equations for hydrologic models andimprove model parameterization to guide further model development. The outcome of this collaborative field data collection and modelling approach will be improved predictions of water and solute movement and management strategies that better capture water movement and material transport in heterogeneous agricultural alluvial landscapes.

Funding sources

Funding: This work was supported by the Queensland Water Modelling Network (QWMN), Department of Environment and Science (DES121436-2022 Research, Development and Innovation Priorities grant 2022), Queensland Government, Australia.

CRediT authorship contribution statement

Han She Lim: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alexander W. Cheesman:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paul N. Nelson:** Conceptualization, Visualization, Writing – original draft. **Rohan Eccles:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Felix Egger:** Writing – review & editing, Methodology, Formal analysis. **Marcus Bulstrode:** Writing – review & editing, Visualization, Conceptualization. **Tony Weber:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Han She Lim reports financial support was provided by Queensland Water Modelling Network (QWMN), Department of Environment and Science, Queensland Government Australia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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