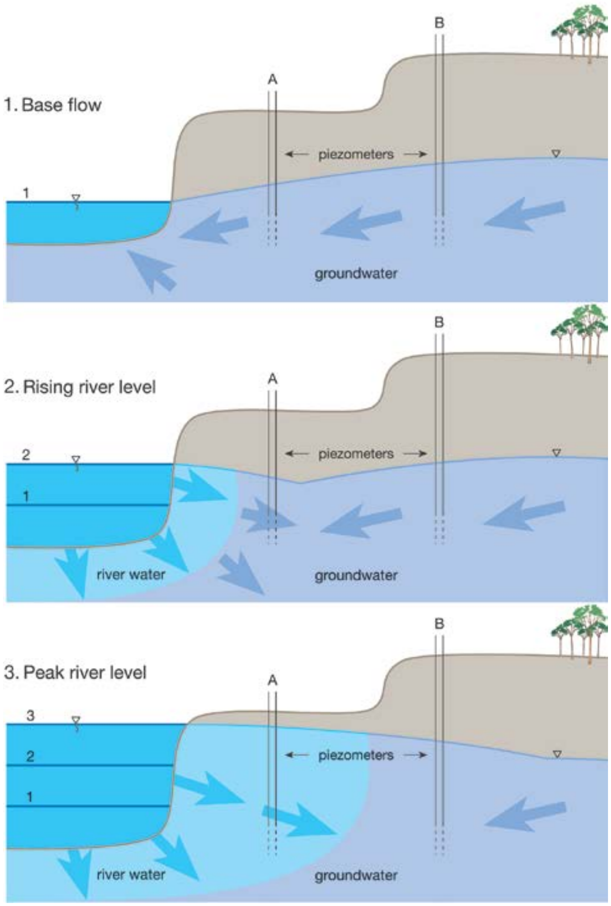
Evaluation of Bank Storage Using Pressure and Solute Propagation



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Summary

Bank storage is the process of river water mixing with near-river groundwater as a result of an increase in river stage due to a flow event. Such mixing causes temporal and spatial variation in near – river groundwater chemistry. However, the extent of the interaction is poorly defined. The extent of the interaction has important ramifications for biogeochemical cycling, contaminant mixing and degradation, and resource assessment techniques that differentiate between surface water and groundwater reservoirs. Previous assessments of bank storage have primarily relied on hydraulic methods, particularly pressure propagation, and chemistry measurements with limited temporal resolution. This work aimed to evaluate the relative rates of solute and pressure propagation and develop new assessment techniques for bank storage in a variety of hydrogeological environments.

In contrast to pressure propagation into homogeneous aquifers in response to river stage rise, the relationships between water propagation and aquifer properties were not well understood prior to this study. Practically, water movement is most readily measured using a conservative solute or tracer. Numerical assessment of a new analytical relationship between solute and pressure travel times and distances and aquifer and flow event characteristics determined that the solution may be used in variably saturated aquifers with errors generally less than 30%. In homogeneous aquifers the ratio of solute to pressure travel time is independent of hydraulic conductivity. Consequently, under certain hydrological conditions time series measurement of pressure and a solute (or proxy) and computation of pressure and solute travel times enables a first-order estimate of aquifer properties and the lateral extent of river water penetration into an aquifer.

In homogeneous systems river stage rise causes pressure to propagate faster and further into an aquifer than water (or solutes). Numerical testing of two conceptual models of alluvial heterogeneity indicated that pressure and solute propagation are unequally affected by aquifer heterogeneity. Hence, under certain conditions, substantial solute

change can be recorded in an aquifer before substantial pressure change. This may be identified by computing a solute travel time less than a pressure travel time. Flux estimates obtained from solute travel times using homogeneous solutions were determined to be more accurate than estimates obtained from pressure data. The error in estimates derived from pressure data was proportional to the contrast in hydraulic conductivity in a system.

Theoretical investigations of bank storage have not systematically quantified the influence of the hydraulic gradient between aquifer and river. In this work analytical and numerical techniques demonstrated that variation in the hydraulic gradient influences bank storage exchange, penetration distance and residence time, at a scale similar to substantial variation in hydraulic conductivity, wave height and period, dispersivity, and river partial penetration. Consideration of the hydraulic gradient is therefore integral to quantitative assessments of exchange.

Simultaneous measurement of pressure and solutes at high temporal resolution within rivers and adjacent aquifers is a useful technique for improving understanding of the spatial and temporal extent of river – aquifer exchange during flow events. The utility of the theory relies on contrasting river and aquifer chemistries. Future work should consider the use of alternative tracers to test residence time distribution theories, and geostatistics, spatial imaging, and uncertainty techniques to further understand the influence of heterogeneity.

Declaration of Originality

I certify that this thesis does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any other university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Chani Welch

Co-authorship

Chani Welch is the primary author on this thesis and all the enclosed documents. Chapters 2 to 4 were written as independent manuscripts in which the co-authors provided intellectual supervision and editorial comment. Neville I. Robinson completed the analytical derivation presented in Appendix A.

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1 Introduction

1.1 The research problem

Quantifying the exchange of water and solutes between rivers and aquifers has become crucial in many water-limited environments as climatic conditions and human consumption stress surface water and groundwater systems simultaneously (Baillie et al., 2007). This situation has highlighted the interconnection between the two resources, and historical over-allocation of water in some areas (Nevill, 2009; Sophocleous, 2002). A variety of methods are available to quantify water fluxes between aquifers and rivers, but many are limited by the localised nature of the measurements, and spatial heterogeneity in hydrogeological properties (Kalbus et al., 2006). This can result in highly variable and uncertain volume estimates, and, where such values are subsequently used for management purposes, potential sub-optimal allocation of resources. In addition, estimates made using hydraulic and chemistry based methods often produce conflicting results (Kirchner, 2003).

Characterising the river-aquifer exchange processes occurring in a system is the first step to appropriately quantifying groundwater discharge or recharge. Exchange processes occur over a continuum of timescales and include hyporheic exchange (minutes to weeks), parafluvial flow (hours to months) and bank storage (hours to years). Hydrological, geological, and geomorphological controls on the significance of these processes vary throughout time and space, as do the drivers for the exchange (Winter, 1998). These short to medium term mixing processes occur, and therefore need to be considered, in the context of regional processes that occur over decades to millennia as a result of aquifer-wide recharge/discharge dynamics.

Chemical mass balance flux quantification methods are considered most appropriate on a scale potentially useful to water resource managers due to their ability to integrate processes over larger scales (Kalbus et al., 2006). However, interpretation of chemistry data using simple models requires that processes are lumped, and hence, results can be highly dependent on the conceptual model and parameterisation. Lack of consideration of hyporheic exchange, for example, can significantly affect estimates of groundwater discharge to rivers (Cook et al., 2006). Furthermore, river aquifer exchange processes mix river water with groundwater. In many cases this creates a temporally and spatially variable zone of water around a river with a chemistry that is distinct from the wider aquifer. Lack of consideration of this temporal variability has rarely been considered but can lead to significant errors in estimates of groundwater discharge to rivers (McCallum et al., 2010). Techniques that exploit temporal chemistry changes to determine, for example, travel times from rivers to aquifers, are increasing as measurement technologies improve, but existing analysis methods such as deconvolution (e.g., Cirpka et al., 2007; Vogt et al., 2010) and principal component analysis (Lewandowski et al., 2009; Page et al., 2012) cannot explicitly identify the influences of individual aquifer properties or processes.

Temporal changes in groundwater chemistry have many drivers. In aquifers connected to rivers, flow events are considered to be one of the main drivers. As the river level rises above that of the adjacent groundwater, river water moves into the aquifer, and mixes with the existing groundwater. As the flood wave passes, this mixture of water returns to the river. This process is termed bank storage (Todd, 1956). Bank storage occurs regardless of whether a river is gaining or losing water from the adjacent aquifer, as long as the river and aquifer are hydraulically connected.

Analytical solutions that relate pressure propagation as a function of river stage rise to aquifer properties, and from that estimate flux, have long been available for homogeneous systems (Cooper and Rorabaugh, 1963) and for rivers with clogging layers (Hall and Moench, 1972; Hantush, 1965). However, pressure change alone cannot be directly correlated to the extent of water movement into an aquifer. Conventional theory indicates that pressure propagates further and faster than water or any solutes it contains. However, explicit relationships between solute propagation, river stage rise, and aquifer properties have not been described in analytical solutions. Consequently, solute data has been under-utilised. Similarly, numerical investigation of the process of bank storage has been predominantly hydraulic, and in homogenous systems, as pressure data is more readily available for model calibration and simulating solute transport is more numerically intensive. Field assessment of bank storage has also predominantly used hydraulic methods, or measurements of river chemistry obtained at low temporal resolution. Systematic assessment of the movement of water and solutes during bank storage was required to facilitate exploitation of increasingly available high temporal resolution solute data for the purposes of improved management of surface water and groundwater resources.

1.2 Research aim

The aim of this research was to increase bank storage process understanding in general, evaluate the relative rates of pressure and solute propagation during bank storage, and develop new techniques for assessment of river – aquifer exchange during flow events. The research was based on two hypotheses:

i. River stage rise and fall induces a predictable variation in near-river groundwater chemistry, the spatial and temporal extent of which is dependent on key aquifer properties and the degree of stage change; and
ii. Continuous measurement of a solute (or proxy) in addition to pressure in near-river groundwater will assist with the determination of additional aquifer properties (compared to solely measuring pressure) and the conceptual model of the river-aquifer interface.

In order to address these hypotheses this work aimed to:

- use analytical and numerical methods to explore relationships between water (which can be represented by a generic conservative solute) and pressure travel time and distance and aquifer and wave characteristics in variably saturated aquifers with a wide range of characteristics and conceptual models;

- provide a preliminary assessment of the influence of heterogeneity structures on the relative rates of solute and pressure propagation identified for homogenous aquifers using transient numerical flow and transport simulations;
- examine the relationships of bank storage exchange, penetration distance and return time to aquifer properties, river – aquifer conceptual models, and hydraulic gradients; and
- verify the practical application of theoretical findings using data collected in distinct hydrogeological environments. Field sites were instrumented in semi-arid northern New South Wales on the Cockburn River and tropical north Queensland on the Mitchell River.

1.3 Structure of this thesis

This thesis consists of a broad overview (Chapter 1), three pieces of work published in or submitted to international peer-reviewed journals (Chapters 2 – 4) and overarching conclusions of the research, including the research contribution and recommendations for further work (Chapter 5). The three manuscripts included are:

(1) **Welch, C.**, P. G. Cook, G. A. Harrington, and N. I. Robinson (2013), Propagation of solutes and pressure into aquifers following river stage rise, *Water Resources Research*, 49, 5246–5259, doi:10.1002/wrcr.20408 [Chapter 2];

(2) **Welch, C.**, G. A. Harrington, M. Leblanc, J. Batlle-Aguilar, and P. G. Cook (2014), Relative rates of solute and pressure propagation into heterogeneous alluvial aquifers following river flow events, *Journal of Hydrology*, 511, 891-903, doi: 10.1016/j.jhydrol.2014.02.032 [Chapter 3]; and

(3) **Welch, C.**, G. A. Harrington, and P. G. Cook (under review), Influence of hydraulic gradient on bank storage exchange, penetration distance and return time, submitted to *Groundwater* [Chapter 4].

Supplementary information for Chapters 2-4 is contained in appendices, as are conference papers which resulted directly from this research.