HYDROGEOLOGICAL AND HYDROCLIMATIC CONTROLS ON SURFACE WATER–GROUNDWATER INTERACTIONS

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DECLARATION

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.

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Edward Wallace Banks

CO-AUTHORSHIP

Eddie Banks 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.

In addition, Dr. Andrew Love suggested investigating the importance of native vegetation in the interactions between surface water and groundwater discussed in Chapter 3. Prof. Craig Simmons suggested using a modelling approach to investigate the vegetation controls on variably saturated processes between surface water and groundwater in Chapter 4. Dr. Philip Brunner provided modelling support for the numerical model HydroGeoSphere which was used in Chapter 4.

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SUMMARY

Growing awareness about the benefits from more sustainable management and allocation of water resources has highlighted the need to manage surface water and groundwater systems as one integrated system. Whilst there has been a significant contribution to the knowledge and understanding of hydrogeological research of surface water–groundwater interactions in the past few decades, there are still specific knowledge gaps on how different types of systems (i.e. connected gaining and losing, and losing disconnected) function and interact at different spatial and temporal scales and in different hydrogeological environments.

This body of research addresses some of the complexities of surface water–groundwater interactions in fractured rock environments, at different spatial and temporal scales and investigates a number of the dominant controls (e.g. geology, topography and vegetation) that influence the exchange processes and dynamics between surface water and groundwater. Specifically, this work investigates: (1) the importance of groundwater from the fractured bedrock compared to groundwater from the saprolite zone in streamflow generation and why the bedrock interface cannot be considered a no-flow boundary. (2) surface water–groundwater interactions in a pristine catchment at a regional scale to determine the state of connection between surface water and groundwater along a river system from the catchment headwaters to the discharge point at the sea. (3) the vegetation controls on variably-saturated processes between surface water and groundwater and its impact on their state of connection.

The first part of this research was a field-based study examining surface water–groundwater interactions along a gaining river reach. The study investigated the importance of groundwater from the fractured bedrock compared to groundwater from the saprolite zone in streamflow generation and examined why the bedrock interface cannot be considered a no-flow boundary. The hypothesis was to determine whether the saprolite zone is hydraulically more active than the deeper bedrock zone. The findings of this study suggest that hydrologic conceptual models, which treat the saprolite-fractured bedrock interface as a no-flow boundary and do not consider the deeper fractured bedrock in hydrologic analyses, may be overly simplistic and inherently misleading in some surface water–groundwater interaction analyses. The results emphasise the need to understand the relative importance of subsurface flow activity in both of these shallow saprolite and

deeper bedrock compartments as a basis for developing reliable conceptual hydrologic models of these systems.

The second part of this research was also a field-based study in a pristine catchment which investigated the state of connection between surface water and groundwater along a river system from the catchment headwaters to the discharge point at the sea. The relative source and loss terms of the river and groundwater systems were assessed, as were their relative magnitude changes along the river, and how a fresh water river system in a pristine catchment covered by native vegetation exists in an otherwise saline regional groundwater system. Many surface water–groundwater interaction studies of different types of systems are either undertaken at the local or river reach scale, however, catchments encompass multiple types of systems at a regional scale. There has been very little research investigating how multiple river reaches function in the context of the entire regional river system from the headwaters to the sea or discharge point, and this study demonstrates the benefits of doing so.

The final part of this research used a fully coupled, physically based numerical model to demonstrate the vegetation controls on variably-saturated processes between a perennial river and an aquifer and its impact on their state of connection. By examining different conceptual models of catchments with different slopes and vegetation type (i.e. root depth) the research identified the conditions required for changes to vegetation to have the greatest effect on the flow regime and the presence of an unsaturated zone beneath a riverbed. The analysis also suggested that the flow regime and hydraulic response to the presence of vegetation and subsequent removal can be much greater in flatter catchments than those that are steep. Intuitively, this may appear plausible in a qualitative sense; however, it has not been demonstrated quantitatively. The results of the study therefore suggests that in addition to the well known influences of physical variables such as hydraulic conductivity or topography, the effects of vegetation need to be carefully considered when investigating surface water–groundwater interactions.

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CHAPTER 1

1. INTRODUCTION

1.1 THE RESEARCH PROBLEM

Over the past few decades there has been increasing concern about water scarcity and the impacts of water resource consumption on water dependent ecosystems (Sophocleous, 2002; Winter et al., 1998; Woessner, 2000). Growing awareness about the need for more sustainable management and allocation of water resources has highlighted the need, from both a scientific and policy perspective, to manage surface water and groundwater systems as one integrated system. Traditionally, surface water and groundwater have been managed separately which has resulted in double accounting (i.e., where one parcel of water is accounted for once as groundwater and then a second time as surface water baseflow) and over allocation of the water resources. This management regime has had serious impacts upon the environment and the long term viability of many water dependant ecosystems and industries. Successful management of surface water and groundwater as an integrated resource is greatly improved once the state of connection is determined. This requires an understanding of surface water–groundwater interactions, the state and type of connection (i.e. gaining, losing, and losing disconnection) and the role of groundwater in streamflow generation. It is inadequate to assume that pumping from a river that is considered disconnected at one location will not have an effect on the length of the river that is disconnected. The terminology that is used to describe disconnection has recently been described by Brunner et al. (2011), who identify the state of disconnection by an unsaturated zone under the stream or by showing that the infiltration rate from a stream to an underlying aquifer is independent of the watertable position.

The impacts from using surface water and groundwater from the different system types will vary depending on the connectivity state. In gaining river systems, such as in the catchment headwaters, increased groundwater extraction may impact on the state of connection between surface and groundwater systems, potentially causing a reduction in river flow and duration. Significant reductions in watertable elevation may ultimately cause groundwater levels to drop below the elevation of the surface water system such that it becomes a losing type system, eliminating baseflow and posing a threat to the sustenance of permanent pools. In a losing and disconnected surface water system, groundwater extraction is less likely to cause any further impact to streamflow conditions at the location where it is losing but will affect the state of connection along the length of the surface water system. It is therefore important that quantitative estimates of the groundwater contribution to the surface water system are understood to ensure that extraction volumes do not exceed the volume required to sustain river flow.

It is now more common to investigate and quantify surface water–groundwater interactions using a multi-disciplinary approach which includes physical hydrogeology (Hatch et al., 2006), hydrogeochemistry (Cook et al., 2003; Cook et al., 2006; Payn et al., 2009; Shand et al., 2007a; Shand et al., 2009), environmental tracers (Ellins et al., 1990; Ruehl et al., 2006; Stellato et al., 2008) and numerical modelling techniques (Bruen and Osman, 2004; Brunner et al., 2009a; Brunner et al., 2011; Brunner et al., 2010; Kalbus et al., 2009; Osman and Bruen, 2002). The combination of the different techniques helps constrain and identify contributing sources of solutes, preferential flow pathways and residence times at different spatial and temporal scales (Kalbus et al., 2006). The application of numerical modelling has been used more frequently in the last decade to examine and quantify the water flux exchange between surface water and groundwater in the different types of surface water–groundwater systems (i.e. connected gaining and losing, and losing disconnected).

While there has been an increasing focus upon integrated groundwater and surface water development, there are several areas requiring further research and investigation if sustainable management practices are to be achieved. This PhD focuses upon three specific knowledge gaps:

Firstly, there are significant complexities involved in understanding and managing fractured rock aquifer systems, which are inherently more difficult to research and conceptualise than sedimentary aquifer systems. Whilst the influence of topography on groundwater flow is important (McGuire et al., 2005; Wörman et al., 2006), the underlying geological structure can have a considerable effect on controlling the direction and contribution of groundwater to surface water systems (Fan et al., 2007). Often, to simplify the conceptualisation of fractured rock systems, the bedrock interface is considered to be a no flow boundary. However, this fails to consider the contribution from the fractured rock system to streamflow generation. In fractured rock aquifer systems, it is more likely that they will be complex systems whereby surface water features may receive water from one or more groundwater flow systems, whether they be local, intermediate, regional, shallow or deep. Understanding the functioning of fractured rock systems and their contributions to streamflow generation will help ensure that more reliable estimates of the location, volume and timing of fluxes between groundwater and surface water features can be made.

Secondly, most surface water–groundwater interaction studies are either undertaken at the local (metres to tens of metres) or river reach scale (hundreds of metres to a few kilometres) and specifically investigate one type of system or connection state. However, many catchments encompass multiple types of systems. There has been very little research investigating how individual river reaches function in the context of the entire regional river system (comprising multiple river reaches; tens of kilometres) from the headwaters to the sea or discharge point. Failing to consider the range of connection types along the entire length of a catchment can result in simplistic assessments and inappropriate management decisions resulting in poor outcomes for water quantity and quality. For example, a river reach at the top of the catchment may be found to be a gaining system; however the river system across the whole of the catchment may be a losing system overall, which would require different management approaches to that of a gaining system. Another important factor in assessing the different states of connection and the potential impacts on water quality is distinguishing between the contributing sources of groundwater to the river and the exchanges between local and regional groundwater systems.

Finally, vadose zone processes play an important role in surface water–groundwater interaction. For example, the presence of an unsaturated zone has a strong influence on biogeochemical processes of river systems (Bencala, 1993) and various ecological and hyporheic exchange processes (Brunke and Gonser, 1997; Findlay, 1995). Also, it is the presence of an unsaturated zone which controls the state of connection between surface water and groundwater. Despite recent advances in knowledge on the relationship between hydrogeological variables, the presence of an unsaturated zone and the state of connection, there is limited understanding of the role of vegetation (i.e. evapotranspiration) in forming an unsaturated zone between surface water and groundwater. The effects of evapotranspiration is significant because in regions of Australia, native vegetation clearance and land use modification (e.g. deep rooted vegetation replaced by shallow rooted crops) has had considerable impacts on the water balance and surface water and groundwater salinities as a result of increased recharge and the mobilisation of salt stored in the shallow regolith (Allison et al., 1990; Bell et al., 1990; Cartwright et al., 2004). Qualitatively, it may seem obvious that the presence of vegetation can alter the state of connection or that change to the rates of precipitation and evapotranspiration may, under certain conditions, have some effect on the state of connection. However, there is little understanding what the quantitative effects will be and the sensitivity of the state of connection (and associated exchange fluxes) to various controlling physical variables i.e. hydraulic conductivity of the aquifer and clogging layer, catchment slope and vegetation type (e.g. root extinction depth).

1.2 Research Aim

The broad aim of this PhD was to explore specific knowledge gaps in the hydrogeological research area of surface water–groundwater interactions. The PhD addresses some of the many complexities of surface water–groundwater interactions in fractured rock environments, at different spatial and temporal scales and investigates a number of the dominant controlling functions (e.g. geology, topography and vegetation) that influence the exchange processes and dynamics between surface water and groundwater using field and numerical modelling techniques. Specifically, this body of work investigates:

i. the importance of groundwater from the fractured bedrock compared to groundwater from the saprolite zone in streamflow generation and why the bedrock interface cannot be considered a no-flow boundary. It also distinguished between different contributing sources to streamflow and their relative hydraulic activity/responsiveness.

ii. surface water–groundwater interactions in a pristine catchment at a regional scale (tens of kilometres) to determine the state of connection between surface water and groundwater along a river system from the catchment headwaters to the discharge point at the sea. In addition, the research examined the relative source and loss terms of the river and groundwater system and how their relative magnitude changes along the river, and how a fresh water river system in a pristine catchment covered by native vegetation exists in an otherwise saline regional groundwater system.

iii. using a simple conceptual model based on realistic and representative parameter values, to what degree the presence of vegetation can cause an unsaturated zone to develop between a perennial river and an aquifer and therefore, its effects on the state of connection. More specifically, it investigated if evapotranspiration is a plausible mechanism to create an unsaturated zone underneath a riverbed and whether it can influence connected gaining and losing, and losing–disconnected type conditions. The physical controls of catchment slope, the hydraulic conductivity of the riverbed clogging layer and aquifer, and the vegetation root extinction depth (transpiration extinction depth) were also examined to determine how these variables influence the state of connection.

The specific research areas of surface water–groundwater interactions are addressed in three manuscripts and are contained in Chapters 2, 3 and 4 of this thesis. The three manuscripts have now been published in international hydrogeological journals. Presented and published conference proceedings as part of this PhD are shown in Appendix A.

[Chapter 2]

Banks, E. W., Simmons, C. T., Love, A. J., Cranswick R., Werner A. D., Bestland E. A., Wood, M. and Wilson, T. (2009). Fractured bedrock and saprolite hydrogeologic controls on groundwater/ surface-water interaction: a conceptual model (Australia). *Hydrogeology Journal* **17**: 1969-1989. doi: 10.1007/s10040-009-0490-7

[Chapter 3]

Banks, E. W., Simmons, C. T., Love, A. J. and Shand, P. (2011b). Assessing spatial and temporal states of connection between surface water and groundwater in a regional catchment: implications for regional scale water quality. *Journal of Hydrology* **404**(1-2): 30-49. doi: 10.1016/j.jhydrol.2011.04.017

[Chapter 4]

Banks, E. W., Brunner, P. and Simmons, C. T. (2011a). Vegetation controls on variably-saturated processes between surface Water and groundwater and its impact on their state of connection. *Water Resources Research* **47**(11): W11517. doi:10.1029/2011WR010544

1.3 CONTRIBUTION OF THIS PHD

This PhD explores the complexities of surface water–groundwater interactions in fractured rock environments, at different spatial and temporal scales using both field based and numerical modelling techniques. The research investigates several of the dominant controls (e.g. geology, topography and vegetation) that influence the exchange processes and dynamics between surface water and groundwater. It does so by examining: (i) the importance of groundwater from the fractured bedrock compared to groundwater from the saprolite zone in streamflow generation. Previous research has often over simplified this boundary condition in hydrological conceptual models, however, this research has shown that treating the bedrock interface as a no-flow boundary needs to be carefully evaluated in hydrologic analyses. The relative importance of subsurface flow activity in both of these shallow saprolite and deeper bedrock compartments is needed as a basis for developing reliable conceptual hydrologic models. (ii) regional scale surface water–groundwater systems. Most surface water–groundwater interaction studies have been undertaken at the river reach scale. Whilst many benefits have arisen from this type of investigation, a regional scale approach along a river, which was conducted as part of this research, provides greater insight into the changes to the state of connection from the catchment headwaters to the surface water discharge point (e.g. the sea) which can be of greater use to the management of the water resource. (iii) the vegetation controls on variably-saturated processes between surface water and groundwater and its impact on their state of connection. This may appear intuitively plausible in a qualitative sense; however, it has not been demonstrated quantitatively. The research therefore suggests that in addition to the well known influences of physical variables such as hydraulic conductivity or topography, the effects of vegetation (i.e. evapotranspiration) need to be carefully considered when investigating surface water–groundwater interactions. Specifically, changes in vegetation type and extent that may be associated with land use change or climate change are expected to have an impact on the state of connection and therefore on exchange fluxes, directions, water balances and water quality matters in such systems.

It is hoped that these research findings will broaden understanding of regional scale surface water–groundwater interactions. Effective management of surface water and groundwater resources requires this understanding.