Elucidating the nature of surface water - groundwater interactions beneath a large unregulated river system with the aid of AEM data

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SUMMARY

The Fitzroy River with its associated alluvial aquifer in northern Western Australia has been considered in planning for Perth's future water supply and for agricultural development but its potential needs to be informed by detailed understanding of groundwater-surface water interactions occurring along its extent, and in particular must consider and account for the consequences that might arise when extracting groundwater from shallow and deep aquifers linked to this river system. Results from the interpretation of a regional scale longitudinal transect (~274 line kms) of SkyTEM helicopter EM data are presented which elucidate river-bed processes occurring along its extent. The AEM indicate a variable groundwater quality and related aquifer characteristics associated with different parts of the river. A 1D laterally constrained inversion (LCI), was examined against hydrochemical, environmental tracer (including 222Rn and Cl-), and hydrogeological data sampled longitudinally. Combined, they indicate a link between the Fitzroy's alluvial aquifer system and with underlying Canning Basin sediments. The results demonstrate the value of regional, reconnaissance scale AEM surveys to better define groundwater processes beneath large unregulated river systems.

Key words: surface water, groundwater process, AEM, unregulated river, Kimberley Australia.

INTRODUCTION

The Fitzroy River in the Kimberley of Western Australia discharges into King Sound, about midway between Broome and Derby (Figure 1). It drains a catchment of approximately 93,000 square kilometres. Available hydrogeological data for the Fitzroy are limited (Lindsay and Commander 2005), with only general and very limited local knowledge concerning groundwater quality, interactions between the alluvial aquifer and sedimentary aquifers that lie beneath, processes of groundwater recharge and discharge, and variability associated with the alluvial aquifer itself. The Fitzroy River and its associated alluvial aquifer have been considered in planning for Perth's future water supply and for agricultural development. However, their potential needs to be informed by a more detailed understanding of the aquifer geometry and extent, groundwater characteristics and links to deeper aquifer systems, groundwater-surface water interactions occurring throughout the basin, and the extent and significance of groundwater dependent ecosystems and cultural flows. Determining the origins of the water that sustains dry season flows and the associated riparian ecosystems, vital for traditional owners, biodiversity and tourism, is a key part of this process. It is not known whether the water that sustains dry season flows along the river is from groundwater systems or from the return flow of water stored in the river bank from annual flood events (Doble et al. 2010).

Arguably, longitudinal sampling of the river system and the underlying aquifers can therefore aid conceptual understanding of stream–aquifer connections through the use of natural tracers (Doble et al. 2010, Harrington et al. 2010), and the employment of non-invasive hydrogeophysical techniques such as airborne electromagnetics (fFitzpatrick et al 2011). This paper considers results from the analysis and interpretation of a regional scale longitudinal transect of SkyTEM helicopter EM data to help elucidate river-bed processes occurring along its extent, and to provide an indication of groundwater quality and related aquifer characteristics associated with different parts of the river. They were interpreted against hydrochemical and environmental tracer results, acquired in separate studies to help understand surface water – groundwater interactions. An integrated analysis of hydrogeophysical data, which provides information on aquifer geometry/inter-relationships, and groundwater character, with hydrochemical and environmental tracer results, which tells us about the residence time of groundwater and flow paths, provides a unique opportunity to assess how these methods complement one another in an understanding of surface water – groundwater interactions in this region. Similar studies, addressing the interpretation of airborne EM data, linked with hydrochemical data acquired along the stream axis have been reported by Paine et al. (2006 and 2009), and Hatch et al. (2010). However, none of these have explored the more complete integration of the geology, geophysics, geochemical and environmental tracer data as was trialled here.

METHOD

AEM system, data acquisition and inversion

The Fitzroy River survey was undertaken with the SkyTEM Time Domain helicopter EM (TDHEM) system (Fitzpatrick et al 2011). This system has been successfully applied to the mapping of alluvial aquifers in northern Australia (see, for example, Lawrie et al. 2010) and has a demonstrated ability to define both a near surface and deep conductivity structure in these environments. Of particular value to this survey was that the system is calibrated (Sorensen and Auken 2004), calibrated in the laboratory, and verified at the Danish

National Reference Site. Therefore the data set acquired by the system in the Fitzroy Valley did not necessarily require the acquisition of additional ground calibration data or the use of external calibration procedures to ensure accurate models of ground conductivity were generated.

The SkyTEM time domain EM system is carried as a sling load towed beneath the helicopter. A full technical description of the SkyTEM is given by Sorensen and Auken (2004). The nominal survey altitude of the transmitter in the Fitzroy survey was ~30m, but this varied depending on the presence of trees or cultural features. The transmitter, mounted on a lightweight wooden lattice frame, is six-sided loop with an area of 314m2 (Reid and Peters 2010). It is divided into segments for transmitting a low moment in one turn and a high moment in all four turns. SkyTEM is capable of operating in a dual transmitter mode (Sorensen and Auken, 2004), and for the Fitzroy survey all data was acquired using interleaved low and high-moment transmitter modes with a 25hz base frequency. Data were pre-processed by filtering and then stacked data output every 0.5secs (~ 11m on the ground) (Reid and Peters 2010). Just over 274 line kilometres of data were acquired as a single long line down the axis of the Fitzroy River, and in four other transects running roughly perpendicular to the river (Figure 1).

The SkyTEM data were inverted using a Laterally Constrained Inversion (LCI) (Auken et al. 2005). This procedure allows prior information (e.g., the expected geological variability of the area) to migrate along the line of acquired data and the output models balance the information present locally within the individual TEM soundings with the ones carried by the constraints, in this case from adjacent soundings. The LCI has a demonstrated applicability in semi-layered environments such as would be expected for the Fitzroy area.

The SkyTEM data were fitted within noise levels which were ranging from ~3% at early times (nominal) to roughly 20% at late times, based on the stacked data. Data were inverted with a smooth model having 19 layers. The SkyTEM data had both Low and High moment converging locally to the same models. This approach yields the maximum possible resolution of model parameters, as the Low moment contains information from the near surface, and the High moment information relating to the deeper part of the models. Results were presented as conductivity–depth sections (e.g. Figure 2) or as depth intervals calculated for 19 layers, thereby providing a spatial picture of changes in ground conductivity along the main channel and, where the lateral traverses are present, an indication of the lateral conductivity structure associated with Fitzroy alluvial and underlying sedimentary aquifer systems.

Hydrochemistry and environmental tracers

A helicopter was used for sampling the Fitzroy River on two occasions in May 2008 and 2010, as the river was inaccessible for most of its length, and the depth too shallow for boat operations (Doble et al. 2010). Timing was important with the sampling undertaken at the end of the wet season, while the river was still flowing but where the major component of the water was believed to be from groundwater, either as return flow from the alluvial aquifer or from deeper aquifer systems, rather than surface flows. Sampling was undertaken for a number of locations along the river for electrical conductivity (EC), major ion chemistry, for the dissolved gas radon (222Rn), and terrigenic 4He.

Radon (222Rn), which is produced naturally in all rocks and soils in various concentrations, accumulates in groundwater as the water flows through the aquifer. When groundwater is discharged to surface water bodies, radon activity decreases due to radioactive decay and gaseous exchange with the atmosphere. Locations of high groundwater discharge along a stream or river can be identified in a longitudinal sampling program by identifying zones where there are sharp increases in radon activity (Doble et al 2010). Terrigenic 4He which is a new tracer technique that has been developed and trialed along the Fitzroy River to identify and quantify groundwater discharge of very old age in a large catchment (Gardner et al. 2011). 4He is an inert, rare, stable noble gas. Gardner et al. (2011) report that radiogenic 4He is produced in aquifer materials as a result of the decay in the 238U, 235U and 232Th decay chains and continually increases in groundwater along the regional flow path. Given the slow production rate of 4He in most settings, elevated quantities are the result of protracted residence times (in the order of 1000's of years). Locally derived groundwater (bank storage, hyporheic exchange, etc.) will not contain significantly elevated radiogenic 4He, hence the presence of elevated 4He in river water can then be used to identify regional (old) groundwater discharge.

RESULTS

The May 2010 longitudinal river sampling program offered the opportunity to examine the relationships between the observed conductivity structure, the interpreted subsurface geology and the environmental and chemical tracers in more detail. A summary of the results are presented in Figure 2. Only Cl- is plotted, along with 222Rn, and terrigenic 4He, Figure 2 shows a satellite image (top) with the track of the SkyTEM survey and the sample points used to collect water samples by helicopter along the river in May 2010. Superimposed on the satellite image is the regional basement geology defined in collaboration with Arthur Moray (GSWA). A conductivity-depth section from the inverted SkyTEM data is plotted at the base of the figure with the interpreted litho-structural relationships superimposed. Inferred groundwater flow lines are also overlain on the section. For the convenience of presentation, the conductivity-depth section is projected onto a single northing and the section has been titled to remove the regional topographic gradient.

Figure 2 shows defined F(4He) and 222Rn along the reach. Two distinct peaks in helium with F(4He) well above atmospheric values, can be observed, one beginning at ~ 730000mE and another at about ~710000mE. Both peaks indicate focused discharge of regional groundwater in these areas (Gardner et al 2011, and Harrington et al. 2011). Dissolved 222Rn is present above the detection limit along the entire reach with 222Rn concentrations range from 0.1 to 0.4 Bq/l. One large peak in 222Rn beginning about ~ 730000mE is present with a smaller one at ~ 691000mE. The peak for both tracers beginning at ~ 730000mE, is interpreted as relating to a large volume of groundwater discharging into the river with high 222Rn to F(4He) ratios. This could be either from discharge of a single groundwater with elevated but not extremely high F(4He), or from a mixture of locally derived groundwater (from the alluvium?) and a small amount of deep regional water with very high F(4He) values (Gardner et al. 2011).

Coincident with the peaks in 222Rn and 4He at the eastern end of the traverse is a marked rise in chloride from around 736000mE. As for the May 2008 data (not shown) this is interpreted as indicative of a significant input of brackish groundwater over a short reach, consistent with the AEM data which shows a conductive alluvial aquifer and deeper sedimentary aquifer (Figure 2). The deeper aquifer has been interpreted as comprising sediments of the Liveringa Group, and more specifically the Middle to Upper Lightjack Formation. The elevated conductivity structure appears to be relatively well confined and distinct from the more resistive Lower Lightjack Formation which sub-crops further to the west. The steady decrease in chloride downstream from the Cunnigham – Fitzroy confluence indicates a change, and improvement in the quality of groundwater inflows further downstream from this point. It points to the dilution of river water downstream by other groundwater inflows or flood derived bank storage.

Downstream of the first peak in F(4He), is a second peak at around 700000mE. However this second peak is not associated with a corresponding increase in 222Rn. This adds significant constraints to source of the groundwater influx at this point, and Gardner et al (2011) suggest that the only way to achieve this signal is to have a relatively small volume of old groundwater with very high F(4He) discharging to the river. A hydrogeophysical analysis of the AEM data suggests that this peak is coincident with a resistive zone and may represent the upward flux of fresh old groundwater along faults from the (upfaulted?) Poole Sandstone which is interpreted to subcrop near the river at this point. A third, albeit subdued, peak in both F(4He) and 222Rn is observed at around 692000mE. We interpret this to represent a small amount of groundwater discharging to the river, this time from a combination of sources that include local, shallow, and deep, old groundwater. It is apparent that along the Fitzroy River, regional groundwater discharge comprises a small but significant portion of total groundwater discharge. This is evidenced by the chemical and environmental tracer data. However, the AEM data supports the interpretation of these data sets confirming observed patterns in river EC (or chloride), and provides an explanation for sources of deeper and older groundwater.

CONCLUSIONS

For the Superficial (alluvial) Aquifer
The AEM data suggest that salinity in the alluvial aquifer is well developed and extensive, particularly away from main channels and anabranches.

For the Deep Sedimentary Aquifers
Available environmental tracer and chemistry data support the interpretation that regional structures influence groundwater discharge from deep systems to the surficial aquifer and to the river. Discharge via these structures may contribute to the maintenance of river, pools and billabongs having environmental and cultural significance in the late dry (September – November). The AEM data define litho-structural boundaries not apparent in other data sets and they define groundwater quality in the deeper sedimentary aquifers beneath the alluvial aquifer. Further, targeted drilling would confirm this. The AEM data suggest a strong connectivity between the deeper aquifers and the overlying alluvial system, and that high salinities in the surficial aquifer are, in part, a result of discharge from the regional flow systems.

For an integrated approach
The combined hydrogeological, hydrogeophysical and environmental tracer and hydrochemical approach to understanding surface water - groundwater interactions represents a first for an unregulated river system in northern Australia. The integrated interpretation of these various data sets, linked to a sound geological understanding, albeit limited by available bore data, provides additional confidence and in the interpretation and should be encouraged for future studies of this nature. The spatial juxtaposition between observed trends in the tracer and hydrochemical data sets and the conductivity structure provide confidence that these data can be combined to better define processes linking surface water and groundwater quality. The connectivity between the alluvial and deeper aquifers indicated in the hydrochemistry, the environmental tracer and hydrogeophysical data sets, suggests that base flow from both aquifer systems supports dry season flows and permanent pools.

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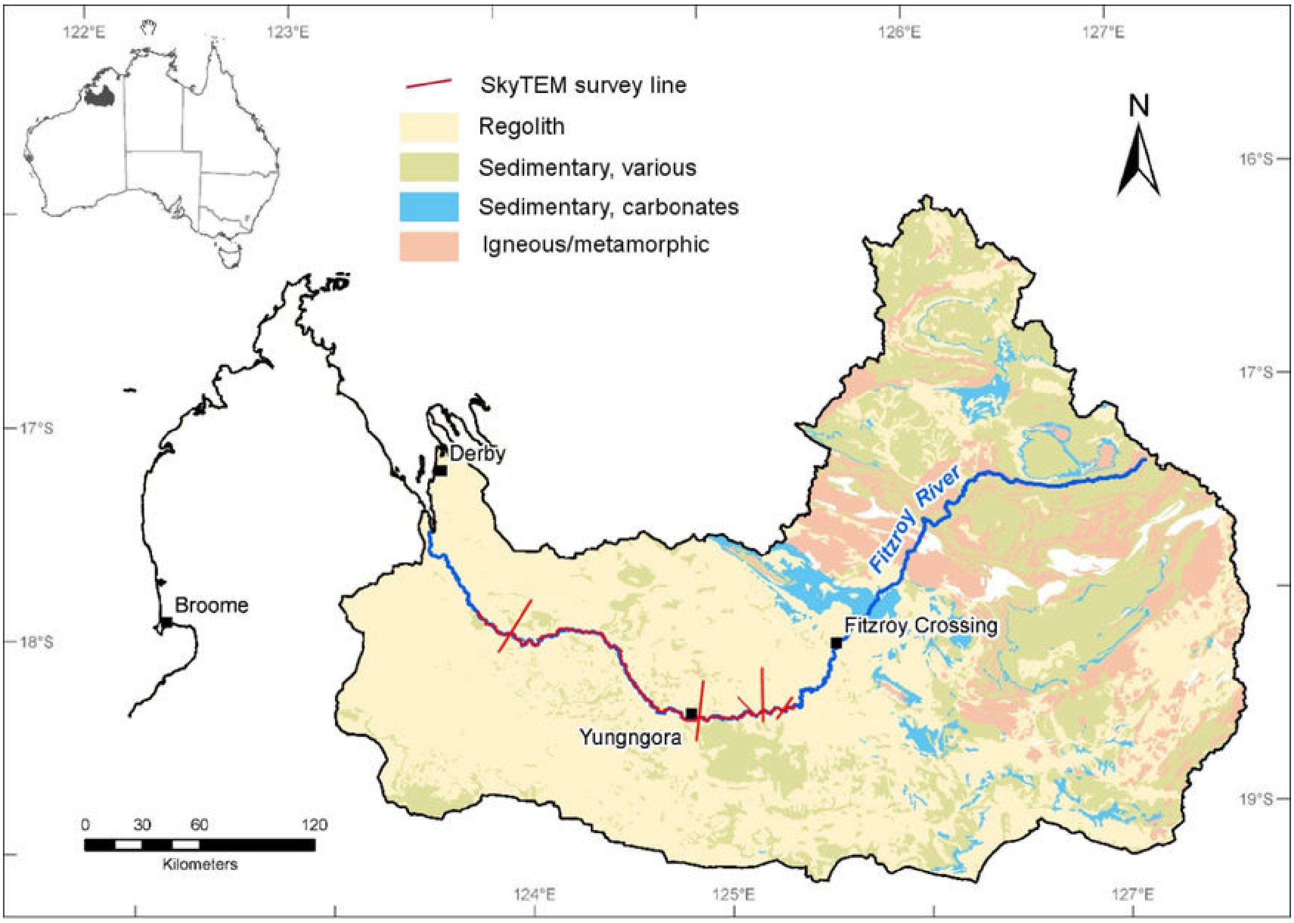

Figure 1: Location of the Fitzroy River and catchment area in Western Australia, showing principal outcropping geological units and the extent of the SkyTEM survey lines flown (in red).

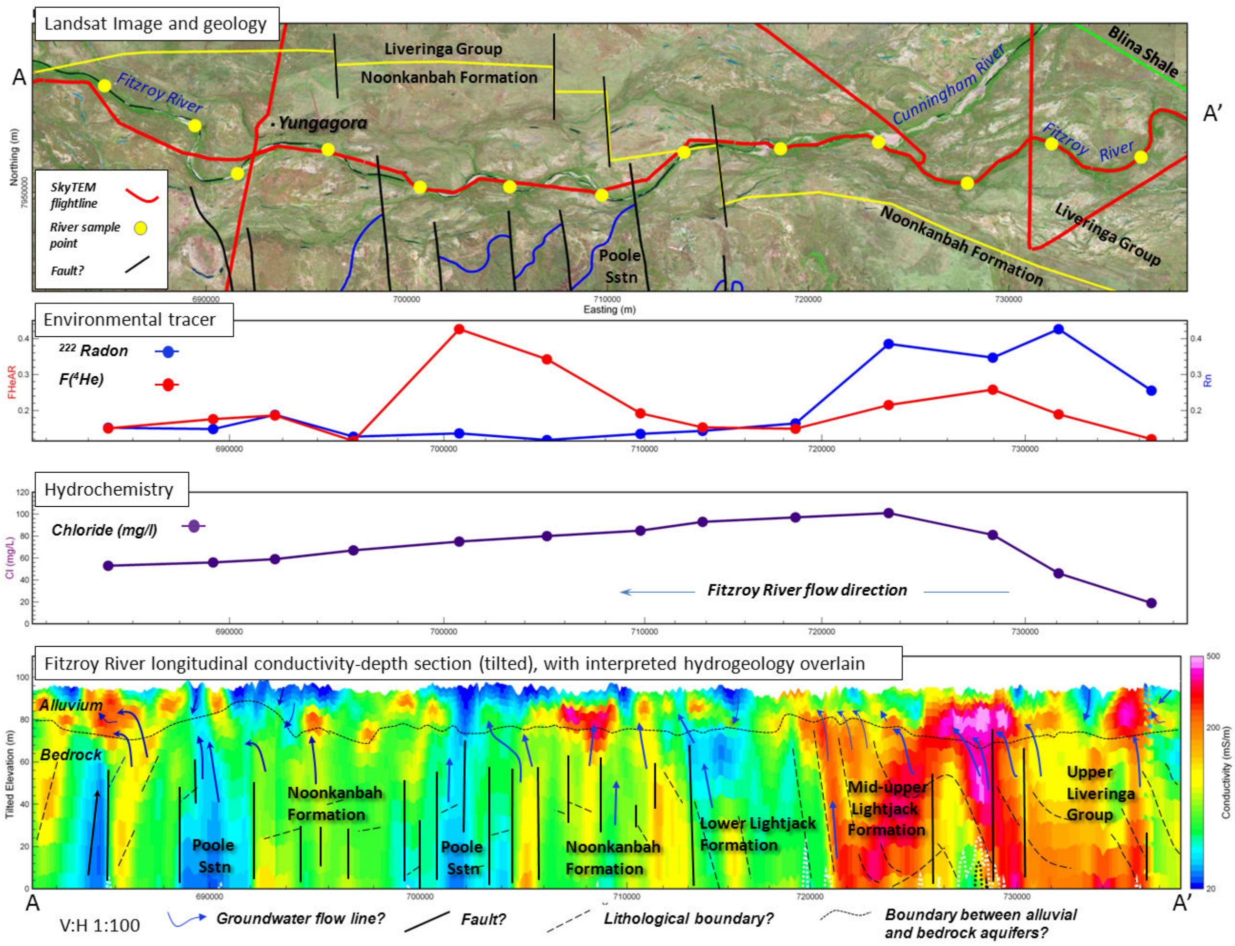

Figure 2: Hydrogeological interpretation of the Fitzroy River longitudinal axis conductivity-depth section for the eastern end of the survey area with associated environmental tracer and hydrochemical data acquired in 2010. Sample point location and flight line orientation are plotted on a Landsat true colour composite (top).