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On the hydrology of the bauxite oases, Cape York Peninsula, Australia

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S U M M A R Y

One of the world's largest bauxite deposits is located in the Cape York Peninsula, North-East Australia. Little is known about the hydrology of these remote bauxite deposits. Here, we present results from a multidisciplinary study that used remote sensing, hydrochemistry, and hydrodynamics to analyse the occurrence of several large oases in connection with the bauxite plateaus. Across this vast region, otherwise dominated by savannah, these oases are sustained by permanent springs and support rich and diverse new sub-ecosystems (spring forests) of high cultural values to the local indigenous population. The spring water chemistry reveals a well-mixed system with minor inter-spring variation; TDS values of spring waters are low (27–72 mg L^{-1}), major ion compositions are homogenous (Na–Si–DIC–Cl) and $\delta^{18}O$ and $\delta^{2}H$ values are reflective of rainwater origin with little evaporation prior to recharge. Dating of spring waters with anthropogenic trace gases (CFC-12 and SF_6) indicates mean groundwater residence times ranging from <1 to 30 years. An artificial tracing experiment highlighted the existence of a flow pathway from the bauxite land surface to the sandy aquifer that feeds the springs through discontinuities in the ferricrete layer. In addition, the soil infiltrability tests showed the bauxite land surface has very high infiltrability (15 mm min^{-1}), about four times greater than other adjacent land surfaces. Across the lower part of the Wenlock Basin, satellite data indicate a total number of 57 oases consistently located on the edge of the bauxite plateaus. This super-group of permanent hillslope springs and their ecosystems adds another important attribute to the list of natural and cultural values of the Cape York Peninsula.

1. Introduction

The early twentieth century saw the first extensive attempts by scientists to document and classify springs (Bryan, 1919; Meinzer, 1923). Many modern classification systems incorporate parts of early works and have expanded on these through the quantitative knowledge of springs (Alfaro and Wallace, 1994). There is however no widely accepted spring classification system with significance attributed to particular parameters, such as geologic origin, discharge, or chemical composition, and classification therefore remains subjective. In recent times the classification and description of springs has diversified from a primary focus on physical and chemical parameters (flow regime, hydrochemistry, and geologic setting) to become increasingly interested in the microclimates and ecosystems they support (Fensham et al., 2004; DWLBC, 2009; Springer and Stevens, 2009). The increased recognition of surface water and groundwater interactions in general, and spring fed streams and groundwater dependent ecosystems in particular, as having significant ecological implications has increased markedly over the last decade with the emergence of a new field known as hydroecology or ecohydrology (e.g. Hayashi and Rosenberry, 2002; Wood et al., 2008).

Management of springs and terrestrial groundwater dependent ecosystems (GDEs) requires, as a first step, the basin-scale mapping and characterisation of permanent spring waters. The mapping of GDEs in Australia has recently advanced though the development of The National Atlas of Groundwater Dependent Ecosystems, a comprehensive inventory of the location and characteristics of groundwater dependent ecosystems for Australia. It incorporates multiple lines of scientific evidence including

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previous fieldwork, literature and mapping and products developed from analysis of remotely sensed data (SKM and CSIRO, 2012). Included in this Atlas are well-established Australian spring assemblages. For example the biodiversity and natural values associated with the springs of a large basin in central Australia, the Great Artesian Basin, are well-developed (Ponder, 1986; Fensham and Fairfax, 2003; Fensham and Price, 2004; Fensham et al., 2004, 2010). Threats from anthropogenic activities have also been identified (Ponder, 1986; Fensham, 1998; Mudd, 2000; Nevill et al., 2010). The conservation values of Great Artesian Basin springs is recognised in the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) under the 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin' listing (Department of the Environment, 2014).

However, there remain large areas in the remote northern regions of Australia where GDEs have not been identified or classified. To date, little is known about the hydrology and hydrogeology of the Cape York Peninsula; mostly due to a lack of *in-situ* observations in this remote region of northern Australia. In the Queensland Government database, only 44 springs are to date registered across the Cape York Peninsula (north of 16.5°S). For the Wenlock Basin, located in the north west of the Cape York Peninsula, two springs are registered in the upper part of the basin and none have been registered in the lower part. However, both local knowledge and the relatively high baseflow of the rivers compared with other regions of northern Australia (CSIRO, 2009), indicate that permanent springs are abundant in the landscape and play an active role in supporting surface waters and dependent ecosystems.

The Cape York Peninsula provides an ideal setting to explore hydroecological processes in their natural state. The region contains vast and relatively undisturbed landscapes, rich with Aboriginal traditions and customs, and high biological significance and diversity. For these reasons it is often considered for a nomination on the UNESCO World Heritage list (Valentine et al., 2013). Perennially flowing springs and watercourses in the Cape York Peninsula region support small assemblages of unique ecosystems within the wider savannah landscape. Unlike many areas of Australia, the freshwater-dependent ecosystems of Cape York Peninsula are relatively well-preserved and retain a high ecological integrity; possessing a diverse and unique array of aquatic, riparian and terrestrial biodiversity, near-natural flow regimes, and relatively intact riverine landscapes (Mackey et al., 2001; Kennard et al., 2010; Warfe et al., 2011; Valentine et al., 2013).

This paper investigates the permanent springs in the lower part of the Wenlock Basin, Cape York Peninsula. Due to little previous work on the hydrology of this remote region, in this study we undertake (1) a study of the spring occurrence; and (2) develop a first conceptual hydrodynamic and hydrochemical model of the springs. Firstly, the occurrence of these springs across the remote Wenlock Basin is determined using remote sensing data. The use of remote sensing techniques to map terrestrial GDEs is well-established (e.g. Boulton and Hancock, 2006; MacKay, 2006; Barquín and Scarsbrook, 2008; Howard and Merrifield, 2010). However, there has been a limited number of detailed studies worldwide focusing on the use of remote sensing to map spring waters (Saraf et al., 2000; Sener et al., 2005; Corsini et al., 2009; Oh et al., 2011). Here, we present an example of the use of remote sensing to detect the occurrence of springs in the remote Cape York Peninsula. During initial exploratory fieldwork 8 permanent spring systems were found and sampled in the lower Wenlock Basin (2 in the Ducie). These 8 surveyed springs systems served as ground truth for the satellite-based detection of additional new springs.

Secondly, chemistry and hydrodynamic data of surveyed springs are combined to determine the origins, chemical variability and flow pathways of the spring waters. This involves exploring the processes connecting the springs with the surrounding landscape, and in particular the springs' connectivity with nearby bauxite plateaus. This is achieved using a multi-disciplinary approach. To build a conceptual hydrodynamic and hydrochemical model of the springs we incorporate data from an artificial tracing experiment, soil infiltrability tests, stable isotope chemistry, major ion concentrations, and dating tracers; chlorofluorocarbons (CFC-12, CFC-11), sulphur hexafluoride (SF_6), and radiocarbon (^{14}C).

2. Study area

The study area, located in the north west of the Cape York bioregion, is formed by the lower part of the Wenlock Basin with its eastern boundary along the 142.5° longitude (Fig. 1). It is subject to a tropical savanna climate featuring high temperatures all year round, a short summer wet season, and a longer dry season between May and October, when little if any rain falls. Annual mean maximum and minimum temperatures for Weipa are 32.3 and 21.8 °C respectively. Mean annual rainfall is 2039 mm, and mean monthly rainfall for January and July is 484 and 1.6 mm respectively (Australian Bureau of Meteorology, 2014).

The bauxite land unit forms part of the broader Tertiary, Bulimba geological formation in western Cape York, which represents one of the largest areas of bauxite geology in the world (Willmott, 2009; Valentine et al., 2013). The study area includes the Steve Irwin Wildlife Reserve (SIWR) where the bauxite land unit occurs as a low, but distinctly elevated, plateau between 50 and 63 m (amsl). This bauxite plateau extends westward beyond the boundary of the SIWR. On the SIWR, the surrounding landscape to the plateau steadily grades downward to approximately 10 m (amsl) along the Wenlock River, to the south, south west, and south east and again towards the Ducie River to the north. A series of springs supporting lush oases flow from the margins of bauxite plateau at between 30 and 40 m elevation on the SIWR. These permanent springs are associated with a new sub-ecosystem type recently described by the Queensland Herbarium (Queensland Herbarium, 2014; Fig. 2): Regional Ecosystem Type 3.10.1.d: Springs and their vegetation communities (evergreen mesophyll/notophyll rainforest) associated with margins of Tertiary remnant plateaus on western Cape York. These ecosystems have been listed as "Of Concern" (QDEHP, 2014). These have been identified as having major ecological significance and performing vital ecological functions (Fell, 2009; Lyon and Franklin, 2012). Most of the plateau is vegetated by Regional Ecosystem Type 3.5.2, a tall Eucalypt woodland dominated by Darwin Stringybark *Eucalyptus tetradonta* (QDEHP, 2014). These woodlands are described as a unique Regional Ecosystem Type, being floristically distinct from the *Eucalyptus* formations in the Northern Territory (Specht et al., 1977), and representing the tallest structural development of *E. tetradonta* throughout tropical Australia (Sattler and Williams, 1999). A series of ephemeral, shallow swamps, largely vegetated by paperbark woodlands *Melaleuca* ssp. are situated towards the eastern end of the plateau, away from the areas of bauxite geology. Although not yet formally documented, the bauxite plateau and associated oases are known to be of major cultural significance to the Traditional Owners of the area, the Tephitthigghi people. Both the plateau and oases form part of tribal dreamtime stories, and it is believed the oases were birthing places for women (Arthur, 2009, pers. comm.).

3. Data and methods

In this study information from different disciplinary approaches were combined, including remote sensing data (Landsat 7 ETM+),