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Constraining models of lake water balance and groundwater–surface water interaction by stable isotope tracers

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Abstract The groundwater release zone of flow-through lakes can be delineated by mapping the distribution of enriched stable isotope compositions of former lake water in the surrounding aquifer. The rate of release of lake water to groundwater can be estimated from a coupled lake water, solute and stable isotope mass balance for the lake. Estimations of groundwater interaction with the lake from groundwater flow modelling can then be compared to the lake water balance estimates and the known geometry of the lake's release zone. Such an analysis is applied to a coastal freshwater lake (Lake Jasper) in the southwest of Western Australia. The results indicate that Lake Jasper is a flow-through lake and provide validation that the estimated groundwater outflow from the lake is consistent with the geometry and hydraulic characteristics of the release zone in the aquifer.

INTRODUCTION

Lake Jasper is a coastal freshwater lake located within the boundaries of the D'Entrecasteaux National Park in the southwest of Western Australia. Numerous small lakes within coastal plain regions of Western Australia are shallow (2–3 m deep) and many are flow-through systems with respect to their interaction with groundwater. Several different approaches have been used to investigate surface water–groundwater interactions at Lake Jasper:

(a) regional-scale groundwater modelling,
(b) modelling of the lake's water, solute and stable isotope balances, and
(c) mapping of the lake's release zone geometry from the distribution of stable isotope enrichments in groundwater.

The purpose of this paper is to demonstrate the integration of these results through coupling of the water, solute and stable isotope balances in both surface water and groundwater. By demonstrating that the mass balance constraints are satisfied in the Lake Jasper study, an improved and validated understanding of the surface water–groundwater interaction is achieved.

Figure 1 summarizes the relationship between the numerical groundwater modelling and field observations of chloride and stable isotope distributions in the lake and groundwater. Natural enrichment of environmental tracers in Lake Jasper enabled the geometry of the lake release zone to be mapped by delineating a "plume" of former lake water in the contiguous aquifer. The regional groundwater flow model was then

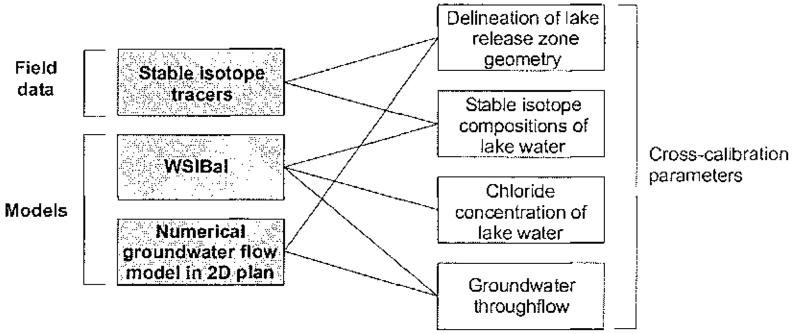

Fig. 1 Schematic relationship between groundwater flow modelling, field measurement of environmental isotopes and lake balance modelling.

calibrated with the constraint that the predicted release zone geometry must be consistent with the mapped release zone. At the same time, the rates of groundwater flow into and out of the lake in the groundwater model had to be consistent with the groundwater through-flow component used in the lake balance modelling. Finally, the chloride and environmental isotope compositions predicted from the lake water balance model were calibrated against the original field observations. This procedure imposed new constraints that are in addition to the "normal" constraints that apply to the calibration of the individual models.

LAKE JASPER STUDY AREA

A location plan of Lake Jasper and surrounding area is presented in Fig. 2. The study area generally lies at or below 40 m AHD (Australian Height Datum) with the exception of the high coastal dunes that reach a maximum height of 195 m AHD between Lake Jasper and the coast and a sub-cropping basalt ridge to the northwest of Lake Jasper, which reaches an elevation of 72 m AHD. Details of the region's geology, sedimentary stratigraphy, hydrogeology and geomorphology are presented in Turner *et al.* (1996).

Field observation

Lake Jasper is a fresh water body with an open-water surface area of approximately 4.5 km^2 and an average depth of 3 m (maximum depth 10 m). Extensive data collection on groundwater levels from Lake Jasper and multilevel piezometers (Fig. 2) were used to establish the regional groundwater gradients (Turner *et al.*, 1996). Groundwater flows from the northwest of the study area toward and through Lake Jasper, which is identified as a flow-through lake. The lake's groundwater release zone occurs through a comparatively narrow zone along the southeast margin—beneath a zone of aeolian dune encroachment—and extends to a depth of approximately 20–25 m below ground level.

There is a close coupling between Lake Jasper and the shallow groundwater system (Superficial Formation), such that the seasonally varying lake level responds

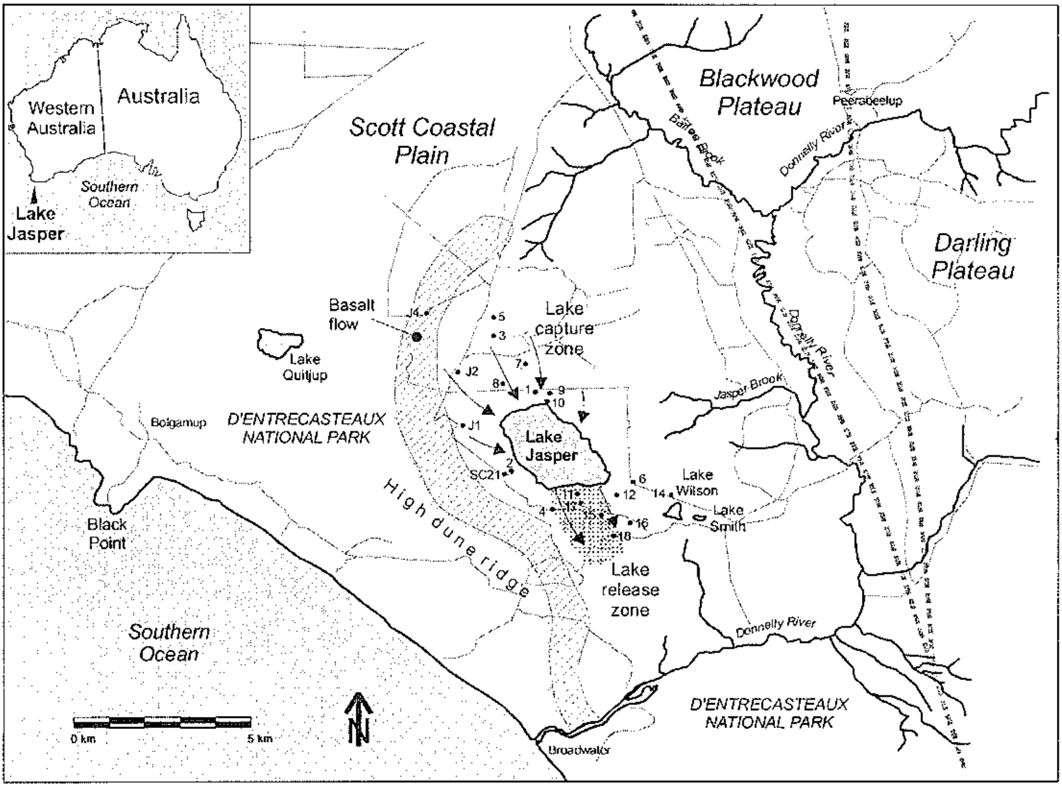

Fig. 2 Location map depicting the groundwater release zone of Lake Jasper.

to, and closely tracks, the shallow groundwater level. Hydraulic connection between the deeper confined aquifer (Yarragadee Formation) and Lake Jasper is less significant. The upper sections of the Yarragadee Formation are characterized by high clay contents and act as confining layers that restrict vertical flows between the lake and deeper groundwater. Downward head differences of several metres exist between the shallow and deep aquifers.

HYDROLOGICAL STUDIES OF LAKE JASPER

Mapping the release zone geometry using stable isotope tracers

The heavy isotopes of hydrogen and oxygen (deuterium and oxygen–18) are significantly enriched within Lake Jasper, with the lake water going through a seasonal range of isotopic composition (Fig. 3). This has enabled the lake release zone to be mapped by comparison of groundwater isotopic compositions with the seasonal range of lake water compositions. Comparison of Figs 2 and 3 indicates that the release zone forms a relatively narrow plume extending approximately 2 km downgradient of the lake from its southeastern margin. The lake appears to capture groundwater from the north, west and east, such that the capture zone is much larger than the release zone.

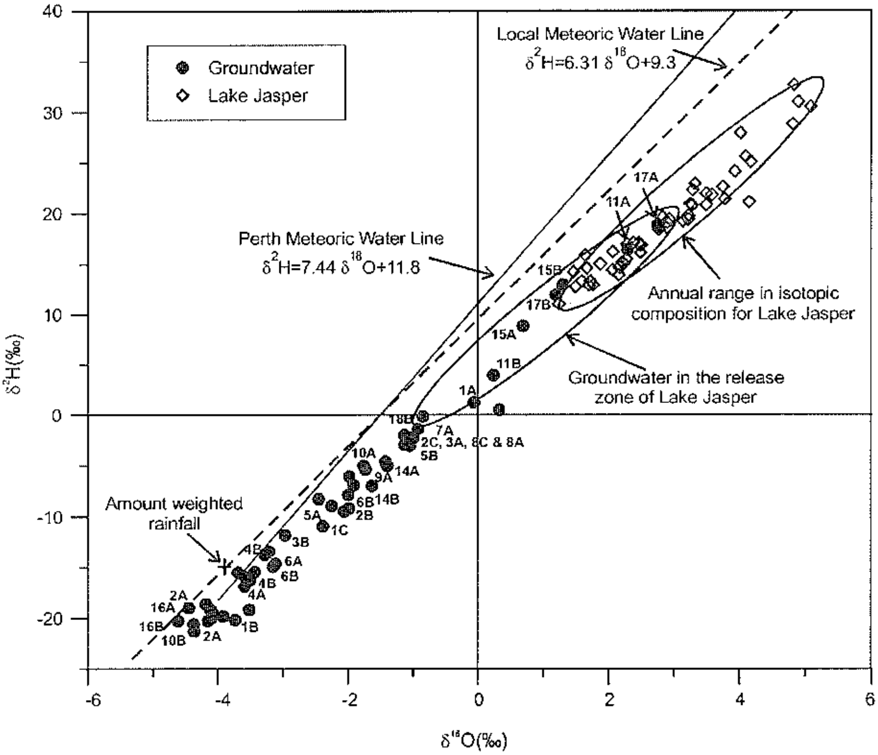

Fig. 3 Stable isotope plot of Lake Jasper water and regional groundwater.

The direction of flow in the release zone, which is southeast toward the Donnelly River, also appears to be influenced by the basalt acting as a hydraulic barrier. Were the barrier not present, the lake's release zone would be expected to occupy a more southerly location, with outflow from the lake toward the Southern Ocean.

Regional groundwater flow model

Numerical modelling in two-dimensional plan confirms the general characteristics of the regional groundwater flow and predicts a release zone geometry that is consistent with the mapped distribution of former lake water. The modelling also demonstrates that the observed downward hydraulic head gradient between the shallow and deep groundwater systems can be sustained by incorporating shallow, low-permeability layers into the Upper Superficial Formation.

Significantly, the groundwater modelling confirms that there is an apparent barrier to regional groundwater flow beneath the high coastal dunes to the south of Lake Jasper; this is further supported by other geophysical, drilling and outcrop evidence of a basalt flow. In outcrop areas and where the subcrop elevation is above the shallow groundwater level, the basalt acts as an impervious barrier to flow. Where the subcrop elevation is below the shallow groundwater level there is reduced aquifer thickness above the basalt, resulting in reduced transmissivity and flow.

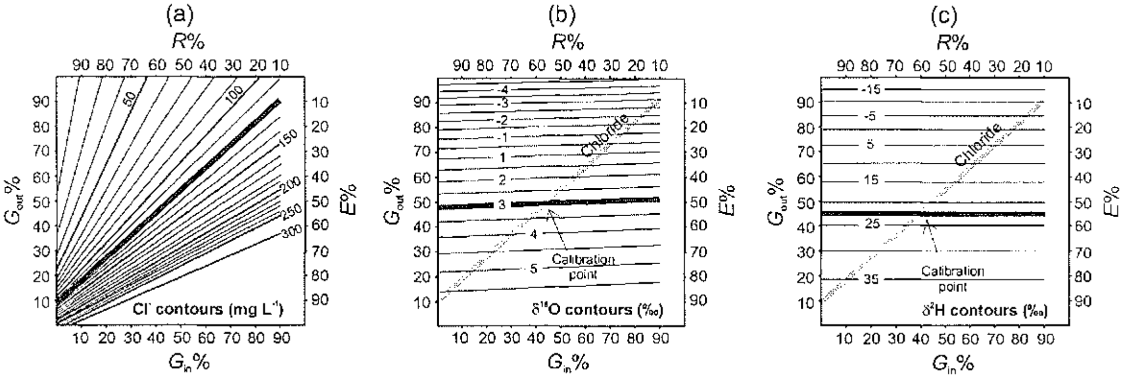

Fig. 4 Water, solute and isotope mass balance plots from the WSIBal model of Lake Jasper.

Coupled water, solute and stable isotope balance (WSIBal)

WSIBal (Barr *et al.*, 2000, this volume) is a quantitative mass balance model that uses a paradigm of a fully mixed water body to compute water, conservative solute and stable isotope mass balances of a lake. The inflows to the water body have specified concentrations of the solutes and environmental isotopes, whilst the outputs, except for the evaporation, consist of lake water.

A summary of results for the WSIBal model of Lake Jasper is presented in Fig. 4; depicted are water balance contours of chloride (Fig. 4(a)), oxygen-18 (Fig. 4(b)) and deuterium (Fig. 4(c)). The plot axes are the lake's four main water balance components, which are direct rainfall recharge to the surface of the lake (R), evaporation from the lake surface (E), groundwater inflow to the lake through the lake's capture zone (G_{in}) and lake water outflow to the aquifer through the release zone (G_{out}). Each component is expressed as a percentage of the total throughflow (Q) in the lake, where:

$$Q = R + G_{in} = E + G_{out}$$

The contours in Fig. 4 are generated by running the WSIBal model for many combinations of R, E, G_{in} and G_{out} to obtain coupled predictions of the chloride, oxygen-18 and deuterium compositions in the lake for each of the water balance combinations. The bold contours represent the observed mean values determined from field measurement, such that their intersection indicates a unique calibration point for the model; it is only for this combination of R, E, G_{in} and G_{out} that the modelled and observed values agree for both chloride concentration and stable isotope compositions in lake water. The result indicates that the inflow to Lake Jasper is approximately 40–45% groundwater flow and 55–60% rainwater recharge, while the outflow is approximately 45–50% groundwater flow and 50–55% evaporation. This is an important result and suggests that groundwater is a significant component of Lake Jasper's hydrology.

CROSS CALIBRATION OF STUDY RESULTS

While the WSIBal model of Lake Jasper has a relatively well-defined calibration point, the regional groundwater flow model is calibrated against independent parameters (i.e.

the regional hydraulic heads) and there is a range of possible calibrations that correspond to different, though realistic, estimates of the aquifer hydraulic properties and groundwater recharge rate. Figure 5 depicts the region of the water balance domain where an acceptable calibration of the groundwater flow model is obtained. There are two constraints that limit the extent of this region. The first is a climatic constraint in which evaporation (*E*) is estimated to be between 80 and 100% of rainfall recharge (*R*). The second is a hydrogeological constraint that requires realistic estimates of the aquifer transmissivity and groundwater recharge. The lower left-hand limit of the shaded region corresponds to a low groundwater recharge rate (10% of rainfall) and small regional transmissivity (300 m^2 day^{-1}). The upper right-hand limit corresponds to a high recharge rate (40% of rainfall) and large transmissivity (1200 m^2 day^{-1}).

The strength of integrated approach is seen from Fig. 5 where the calibration point for the WSIBal model is shown to fall within the calibration region for the groundwater flow model. At this location the groundwater recharge rate is between

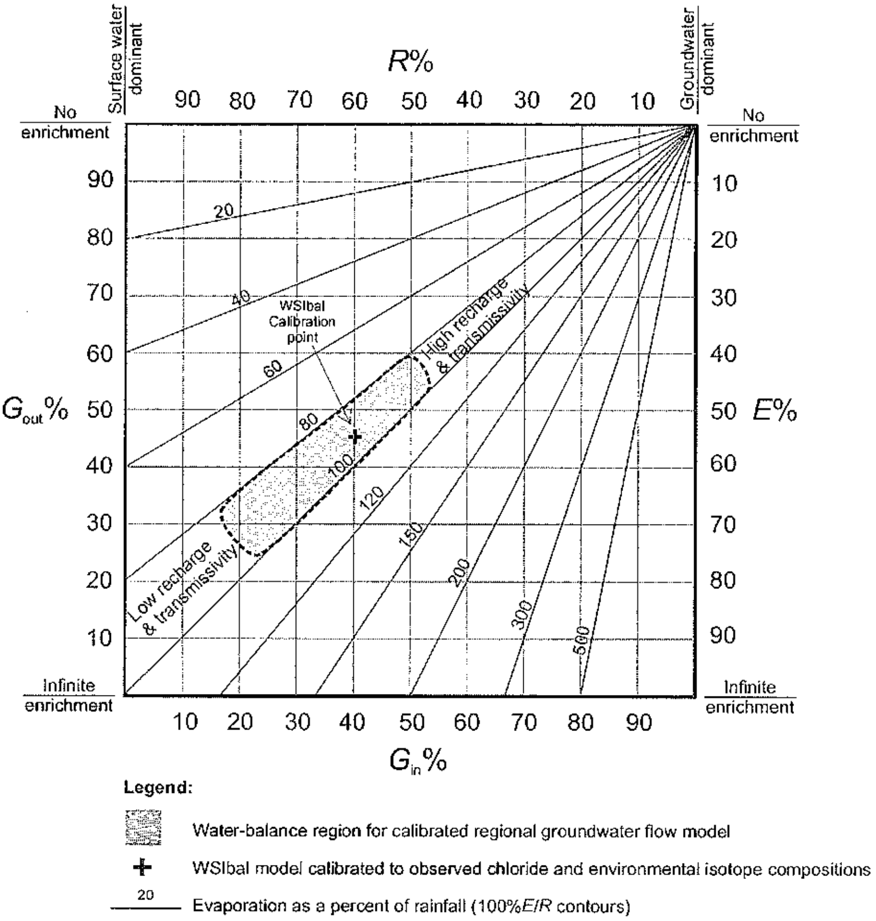

Fig. 5 Integration of the results from regional groundwater flow modelling and the WSIBal model of Lake Jasper.

20% and 30% of rainfall and the regional transmissivity is in the range 600–900 m^2 day^{-1}. It is also known that groundwater flow comprises approximately 50% of the lake's water balance and the simulated chloride concentration and stable isotope compositions in the lake are matched to the observed values.

CONCLUSIONS

Mapping the distribution of former lake water in groundwater using environmental tracers can delineate the release zone geometry of a lake. When this information is integrated with groundwater flow modelling and coupled mass balance modelling of water, solute and stable isotopes in the lake, an improved quantitative understanding of a lake's hydrology can be achieved. In the case of Lake Jasper, the results from the coupled mass balance model and isotopically delineated release zone geometry impose water balance constraints on the groundwater flow model, which otherwise is uncertain to calibrate. For the assumed model input values, there is only one relatively well-defined region in the water balance domain where the WSIBal model and groundwater flow model agree both with each other, and with the observed distributions of the environmental tracers in the lake and groundwater.

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