Hydrol. Earth Syst. Sci. Discuss., 10, 5225–5267, 2013
www.hydrol-earth-syst-sci-discuss.net/10/5225/2013/
doi:10.5194/hessd-10-5225-2013

Hydrology and Earth System Sciences
Open Access
Discussions

Examining the spatial and temporal variation of groundwater inflows to a valley-to-floodplain river using ^{222}Rn, geochemistry and river discharge: the Ovens River, southeast Australia

M. C. L. Yu[1], **I. Cartwright**[1,2], **J. L. Braden**[1], **and S. T. de Bree**[1]

[1]School of Geosciences, Monash University, Wellington Road, Clayton,
Victoria 3800, Australia
[2]National Centre for Groundwater Research and Training, Flinders University, GPO Box 2100,
Adelaide, South Australia 5001, Australia

Received: 4 March 2013 – Accepted: 8 April 2013 – Published: 24 April 2013

Correspondence to: M. C. L. Yu (mcyu1@student.monash.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Radon (^{222}Rn) and major ion geochemistry were used to define and quantify the catchment-scale river-aquifer interactions along the Ovens River in the southeast Murray-Darling Basin, Victoria, Australia, between September 2009 and October 2011. The Ovens River is characterized by the transition from a single channel river residing within a mountain valley in the upper catchment to a multi-channel meandering river on flat alluvial plains in the lower catchment. Overall, the river is dominated by gaining reaches, receiving groundwater from both alluvial and basement aquifers. The distribution of gaining and losing reaches is governed by catchment morphology and lithology. In the upper catchment, rapid groundwater recharge through sediments that have high hydraulic conductivities in a narrow valley produces higher baseflow to the river during wet (high flow) periods as a result of hydraulic loading. In the lower catchment, the open and flat alluvial plains, lower rainfall and finer-gained sediments reduce the magnitude and variability of hydraulic gradient between the aquifer and the river, producing lower and constant groundwater inflow. With a small difference between the water table and the river height, small changes in river height or in groundwater level can result fluctuating gaining and losing behaviour along the river. The middle catchment represents a transition in river-aquifer interactions from upper to lower catchment. High baseflow in some parts of the middle and lower catchments is caused by groundwater flow over basement highs. Mass balance calculations based on ^{222}Rn activities indicate that groundwater inflow is 4–22 % of total flow with higher baseflow occurring in high flow periods. Uncertainties in gas exchange coefficient and ^{222}Rn activities of groundwater alter the calculated groundwater inflow to 3–35 %. Ignoring hyporheic exchange appears not to have a significant impact on the total groundwater estimates. In comparison to ^{222}Rn activities, Cl concentrations yield higher estimates of groundwater influxes by up to 2000 % in the upper and middle catchments but lower estimates by 50–100 % in the lower catchment. Hydrograph separation yields far higher baseflow fluxes than ^{222}Rn activities and Cl concentrations. The high baseflow estimates using

Cl concentrations may be due to the lack of distinct difference between groundwater and surface water Cl concentrations. The other mismatches may indicate the input of other sources of water in additional to regional groundwater.

1 Introduction

Defining the relationship between rivers and adjacent groundwater systems is a crucial step in developing programs and policies for protecting riverine ecosystems and managing water resources. Rivers interact with various water stores, such as groundwater in local and regional aquifers, water in river banks, water in unsaturated zone, and soil water. Rivers can recharge groundwater (loosing streams) or receive groundwater as baseflow (gaining streams). These interactions can vary with topography along a course of river, for example rivers may be gaining in narrow valleys in the hills but losing when they flow across the broad plains. Furthermore, the direction and magnitude of water fluxes can change with times; a gaining stream, for instance, can become losing if the river rises above the water table during a storm event. The three main controls on catchment-scale groundwater-surface water (GW-SW) interactions are: (1) the basin morphology and the position of the river channel within landscape; (2) the hydraulic conductivities of the river channel and adjacent alluvial aquifer; (3) and the relation of river stage to water table level in the adjacent aquifer which is closely related to precipitation patterns (Sophocleous, 2002; Pritchard, 2005). Without a sound understand of GW-SW interactions in a catchment it is not possible to identify potential pathways for water contamination and to calculate water budgets for water allocation. The latter has become an important issue in Australia because of the growing demands from both the human and environment in a drought dominated continent.

GW-SW interactions can be investigated by several techniques. Hydrograph separation is a straightforward method for assessing baseflow at a catchment scale. However, it cannot be used for losing or highly-regulated systems, and the slowflow component isolated by the method may aggregate several water storages (such as bank return flow or interflow) rather than representing only regional groundwater inflow (Griffiths and Clausen, 1997; Halford and Mayer, 2000; Evans and Neal, 2005). Geochemistry, such as major ion concentrations, stable isotopes and radiogenic isotopes may also be used in GW-SW studies (Brodie et al., 2007; Cook, 2012). The requirements for using geochemical tracers to study GW-SW interactions are that the concentration of the tracer in groundwater is significantly different to that in river water and that concentrations in groundwater are relatively homogeneous (or that any heterogeneities are known). Radon (^{222}Rn) is powerful tracer for examining GW-SW interactions from qualitative and quantitative perspectives (Ellins et al., 1990; Cook et al., 2006; Mullinger et al., 2007; Baskaran et al., 2009). ^{222}Rn is a radiogenic isotope produced from the decay of ^{226}Ra in the uranium decay series. In surface water, the ^{222}Rn activity is usually low because of low dissolved ^{226}Ra activities, the relatively short half life of ^{222}Rn (3.825 days) and the rapid degassing of ^{222}Rn to the atmosphere. Groundwater has ^{222}Rn activities that are commonly two to three orders of magnitude higher those of surface water due to the near-ubiquitous presence of U-bearing minerals in the aquifer matrix (Ellins et al., 1990; Cook et al., 2003; Mullinger et al., 2007; Cartwright et al., 2011). Due to the short half-life, the activity of ^{222}Rn reaches secular equilibrium with ^{226}Ra over two to three weeks (Cecil and Green, 1999). Thus, ^{222}Rn may be used for detecting groundwater inflows into rivers, especially where the difference in major ion concentrations between groundwater and surface water is small, such as in many upper catchment streams.

The change in ^{222}Rn activities in a gaining stream (dC_r/dx) is governed by groundwater inflow, in-stream evaporation, hyporheic exchange, degassing, and radioactive decay as follows:

$$Q\frac{dC_r}{dx} = I(C_\mathrm{i} - C_\mathrm{r}) + wEC_\mathrm{r} + F_\mathrm{h} - kdwC_\mathrm{r} - \lambda dwC_\mathrm{r} \quad (1)$$

(Cook et al., 2006; Mullinger et al., 2007). In Eq. (1), Q is the stream discharge ($\mathrm{m}^3\,\mathrm{day}^{-1}$), C_r is the ^{222}Rn activity within the stream ($\mathrm{Bq\,m}^{-3}$), x is distance in the direction of flow (m), I is the groundwater inflow rate per unit of stream length

($m^3\,m^{-1}\,day^{-1}$), C_i is the ^{222}Rn activity in the inflowing groundwater, F_h is the flux of ^{222}Rn from hyporheic zone ($Bq\,m^{-1}\,day^{-1}$), w is the width of the river surface (m), E is the evaporation rate ($m\,day^{-1}$), k is the gas transfer coefficient (day^{-1}), d is the mean stream depth (m) and λ is the radioactive decay constant ($0.181\,day^{-1}$). Groundwater inflow can be calculated by rearranging this equation. Equation (1) can also be used for other tracers. For major ions, such as Na or Cl, that do not degas to the atmosphere or decay, the last two terms on the right-hand side are redundant.

This study uses ^{222}Rn activities and major ion geochemistry in conjunction with physical hydrological data to determine the GW-SW relationships and the contribution of baseflow along the Ovens River (Fig. 1), from its upper catchment to its discharge point at the Murray River. The study covers a period of 26 months that include the end of the 2000s Australian drought and the 2010 Victorian floods. From hydraulic heads and river heights, CSIRO (2008) indicated that the Ovens River is gaining in the upper catchment, alternately gaining and losing in the middle catchment and mainly losing in the lower catchment. However, the precise distribution of gaining and losing reaches, the temporal of GW-SW exchange and the quantity of baseflow to the river remains unknown. The results will provide an important background for future GW-SW studies in this and other catchments in the Murray-Darling Basin, and elsewhere.

2 Study area

2.1 The Ovens River

Located in the south-east margin of the 1 061 469 km^2 Murray-Darling Basin, the Ovens Catchment (Fig. 1) occupies just 7813 km^2 but contributes 6–14 % of the total flow of the Murray River (CSIRO, 2008). The Ovens River is the main river in the Ovens Catchment with a length of approximately 202 km that originates in the northern flank of the Victorian Alps and flows north-westwards. The catchment is characterised by multiple narrow V-shaped mountain valleys in the upper catchment and broad flat alluvial flood plains in the lower catchment. In the upper catchment, the river is 5–10 m wide and 1–2 m deep. It has small rapids with a steep channel gradient of around 6.5 m km^{-1} (Victorian Government Department of Sustainability and Environment, 2010a). Downstream of Porepunkah, the valley broadens and transits into open alluvial flood plains. The river in the lower catchment has a low gradient of less than 1 m km^{-1} (Victorian Government Department of Sustainability and Environment, 2010a) and develops a network of meandering and anastomosing channels downstream of Everton. In its lower reaches, it is 40–50 m wide and up to 8 m deep. It flows pass the Warby Ranges before discharging to the Murray River at Bundalong. The Ovens River is perennial and receives water from three main tributaries: the Buckland, Buffalo and King Rivers. The monthly flow at the gauging station located at Peechelba toward the discharge point varies between 200 and 30 200 ML day^{-1} with high flow occurring in Australian winter months (June–September) (Victorian Water Resource Data Warehouse, 2011). The river in the upper and middle regions is unregulated, but the flow downstream is partially regulated due to the storages on the Buffalo and King tributaries.

2.2 Groundwater along the Ovens River

The stratigraphy of the Ovens Catchment comprises Palaeozoic basement overlain by Tertiary-Recent fluviatile sediments (Lawrence, 1988; van den Berg and Morand, 1997). The basement in the upper and middle catchments is generally 10–50 m below the surface while the basement is up to 170m below the surface in the lower catchment. Several basement highs and local outcrops exist at Myrtleford in the middle catchment and between Killawarra and Peechelba in the lower catchment. The basement predominantly consists of metamorphosed Ordovician turbidites intruded by Silurian and Devonian granites that form a fractured-rock aquifer with a hydraulic conductivity of 0.3–10 m day^{-1} and a transmissivity of $< 10\,\mathrm{m}^2\,\mathrm{day}^{-1}$ (Slater and Shugg, 1987). The overlying sediment consists of, from the base to top, the Calivil Formation, the Shepparton Formation and the Coonambigal Formation. The sedimentary cover has the maximum thickness in the lower catchment, and thins and pinches out over basement highs and in the valleys toward the highlands. The terrestrial Tertiary Calivil Formation has a thickness of up to 45 m. It does not crop out and occurs between 20 and 100 m below ground surface. It comprises consolidated gravel, sand slit, clay and rubbles with a hydraulic conductivity of 5–50 m day^{-1} (Shugg, 1987; Cheng and Reid, 2006). The Quaternary fluvio-lacustrine Shepparton Formation has similar composition. The alluvial deposits of the Holocene Coonambnidgal Formation in the river valleys are contiguous with and undistinguishable from those of the underlying Shepparton Formation. The Shepparton Formation and Coonambnidgal Formation together are up to 170 m thick and comprise a heterogeneous mixture of clay and silt, and "shoestring lenses" of sand and gravel (Tickell, 1978). As a result, they form a complex semi-confined to unconfined aquifer with varying degrees of interconnectivity. The alluvial sediments transits from unsorted cobbles and coarse gravels with fragment of basement rocks and minerals upstream to mature fine weathered sand and silt downstream. The hydraulic conductivity of the Shepparton and Coonambigal Formations is 0.1–10 m day^{-1} with an average of 0.2–5 m day^{-1} (Tickell, 1978). The Ovens River is within the Coonambidgal Formation, except for several locations upstream where it incises into the basement, for example, in Smoko, Bright and Myrtleford. The surface aquifers receive recharge mainly through direct infiltration on the valley/alluvial floors, and through exposed and weathered bedrocks at the margins of valley during the winter months. The head gradients in the Ovens catchment are usually downward, and the regional groundwater flow is down valley. The groundwater has a total dissolved solids (TDS) content of 100–500 mg L^{-1} which is higher than that of the Ovens River (TDS of 25–48 mg L^{-1}) (Victorian Water Resource Data Warehouse, 2011).

2.3 Climate and land use

The climate of Ovens catchment is mainly controlled by the topography. The average rainfall decreases from 1127 mm in the alpine region in Bright to 636 mm on the alluvial plains in Wangaratta with most rainfall occurring in winter months (Bureau of Meteorology, 2011). In the 2000s Australian drought (particularly 2006–2009), rainfall in the

Ovens Catchment was between 40 % and 80 % of the long term average (Victorian Government Department of Sustainability and Environment, 2010b, c). Potential evaporation increases northwards and ranges from 0–100 mm day^{-1} to 200–400 mm day^{-1} in winter and summer respectively (Bureau of Meteorology, 2011). The riverine plains and alluvial flats are primarily used by agricultural activities while the hills and mountains are covered by native vegetation and plantation forests. Water extraction from both surface and groundwater resources is relatively low, being 10 % of the total water resource available in the catchment (Victorian Government Department of Sustainability and Environment, 2010c).

3 Sampling and analytical techniques

Eight sampling rounds took place over a period of 26 months (September 2009, March 2010, June 2010, September 2010, December 2010, March 2011, June 2011, and October 2011), involving a "run-of-river" survey of ^{222}Rn activity, electrical conductivity (EC) and major ion geochemistry. Samples are designated by distance downstream of the uppermost sampling site at Harrietville (Fig. 1). Areas between Harrietville and Porepunkah (0–34 km), between Porepunkah and Everton (34–97 km), and between Everton and Bundalong (97–202 km) are defined as upper, middle and lower sub-catchments respectively. These sub-catchments broadly represent the mountain valley, the transition from valley to alluvial plains and the broad flat alluvial flood plains. During the March 2011 and June 2011 sampling rounds, detailed EC and ^{222}Rn surveys were also made between Bright and Porepunkah (22–34 km). This section includes a 2 km long and 2–4 m deep canyon in the basement followed by the beginning of the transition from the valley to the alluvial flood plains. River samples were collected from approximately 1 m above the riverbed using a collection beaker attached to a pole. In September 2009, groundwater was sampled from the Coonambigal and Shepparton Formations close to the Ovens River; some bores were re-sampled in the following rounds. The groundwater was sampled by using an impeller pump set at the screened interval, and at least 3 bore volumes of water were purged prior to sampling. ^{222}Rn activities were measured using a portable in-air monitor (RAD-7, Durridge Co.) following methods described by Burnett and Dulaiova (2006) and expressed as Becquerels of radioactivity per cubic metre of water (Bq m^{-3}). ^{222}Rn is degassed from a 500 mL Buchner flask via a closed circuit of a known volume for 5 min. Counting times were 3 or 4 cycles over 2 h for river water and 20 min for groundwater samples. Based on replicate analyses ^{222}Rn activities are precise to less than 3 % at 10 000 Bq m^{-3}, increasing to around 8 % at 200 Bq m^{-3}. EC was measured in the field using TPS meter that was calibrated onsite. Anion concentrations were measured on filtered and unacidified samples using a Metrohn ion chromatograph at Monash University. Cations were analysed using a Varian Vista ICP-AES at the Australian National University or a ThermoFinnigan OptiMass 9500 ICP-MS at Monash University on samples that were filtered and acidified to pH < 2. The precision of major ion concentrations based on replicate analyses is ±2 %. River discharge for Harrietville (0 km), Bright (22 km), Myrtleford (65 km), Wangaratta (140 km) and Peechelba (187 km) was obtained from the Victoria Water Resources Data Warehouse (2011).

4 Results

4.1 Flow conditions

Between September 2009 and June 2010, the discharge of the Ovens River at Peechelba was between 160 and 4360 ML day^{-1} with several moderately high flow events up to 11 420 ML day^{-1} during the 2009 winter (Fig. 2) (Victorian Water Resource Data Warehouse, 2011). Multiple extremely high flow events of up to 93 570 ML day^{-1} occurred between August 2010 and March 2011. The unusual wet periods during the spring and summer (November–March) were contributed by the 2010–2011 La Niña event. The river flow returned to 1910–3800 ML day^{-1} in the period of March–June 2011, followed by multiple moderately high flow events of up to 25850 ML day^{-1}

between July and September 2011. The September 2009, September 2010, December 2010, and March 2011 sampling rounds all took place during high flow conditions with the September 2009 (10 178 ML day^{-1}) and December 2010 (18 520 ML day^{-1}) rounds on the rising limb of a flow event, and the September 2010 (6635 ML day^{-1}) and March 2011 (4894 ML day^{-1}) rounds on the receding limb of a flow event. The discharge in the March 2010, June 2010, June 2011 and October 2011 sampling rounds were 995 ML day^{-1}, 1114 ML day^{-1}, 2292 ML day^{-1} and 2606 ML day^{-1} respectively, and these sampling rounds were conducted during low flow periods.

4.2 Groundwater levels

The bore hydrographs of shallow bores ($<$ 20 m deep) at Bright indicate that recharge occurred on the valley alluvial plain in June 2010–February 2011 and June–September 2011 (Fig. 3a). The annual hydraulic head variation at Bright in the upper catchment between 2009 and 2011 was 0.5–3.0 m (Victorian Water Resource Data Warehouse, 2011). There was a high lateral head gradient of $\sim$ 0.007 between the edge of valley (B57144) and the river bank (B51747 & B51743) towards the river. There were several head reversals between the bores in the bank prior to June 2010. As with upper catchment, there was uniform recharge at Eurobin and Myrtleford in the middle catchment in the same period (Fig. 3b and c). However, the annual hydraulic head variation was only 0.5–1.0 m. Furthermore, the lateral head gradient toward the river in the middle catchment was 0.002–0.004. The head gradients were reversed in the river bank at Myrtleford during recharge periods (May 2009 and August 2010). No data is available for the groundwater level near the river in the lower catchment during the study period. However, the historical data at Peechelba indicates the hydraulic heads in the flood plains (B11308 & B11307) varies by only a few millimetres per year (Fig. 3d). In contrast, the hydraulic head in the river bank (B11306) shows greater a variation of up to 1.5 m. The lateral head gradient toward the river in the lower catchment is $\sim$ 0.0001.

4.3 Electrical conductivity

The EC values of the Ovens River increases from ~ 30 µS cm^{-1} in the upper catchment to 37–55 µS cm^{-1} at Peechelba in the lower catchment (Fig. 4). There is always rapid increase in the EC values in the first 5 km river reach from Harrietville. However, most of the increase in EC values occurs from the middle catchment downstream. Higher EC values (35–55 µS cm^{-1}) were recorded in March 2010, March 2011 and June 2011 at the end of summer or during low flow. The EC trend in the Bright-Porepunkah river section has a small peak (an increase of 2.8 µS cm^{-1} in March 2011, 1.2 µS cm^{-1} in June 2011) in the Canyon (at 28 km) followed by a progressive increase in EC values downstream towards Porepunkah.

The EC values of shallow groundwater (< 60 m) increases down catchment from 50–100 µS cm^{-1} in the upper catchment to 100–400 µS cm^{-1} in the middle catchment and to 520–1200 µS cm^{-1} in the lower catchment (Table 2). EC values for groundwater throughout the study period and after the 2010 Victorian floods remained similar.

4.4 Major ion chemistry

The cations in the Ovens Rivers are in the following order of mass abundance: Na (36–58 %), Mg (15–30 %), Ca (18–29 %) and K (4–22 %). The relative mass abundance of the anions are HCO_3 (48–90 %), Cl (3–44 %), SO_4 (1–16 %) and NO_3 (0.5–7 %) (although HCO_3 were not measured for all sample rounds). The concentrations of major ions in the river mirror the trends of EC values, progressively increasing downstream. For example, sodium concentrations increase from 1.80–3.50 mg L^{-1} in the upper catchment to 3.10–7.30 mg L^{-1} in the lower catchment (Fig. 5a). Likewise, chloride concentrations rise from 0.70–1.90 mg L^{-1} in the upper catchment to 1.60–4.90 mg L^{-1} at Peechelba (Table 3) (Fig. 5b). The molar Na/Cl ratios in the upper catchment are 2.80–8.60; these decrease downstream to 135 km and then remain at a similar level (between 1.60–3.50) in the lower catchment (Fig. 5c). The only exception to this trend is the September 2010 sampling round where the Na/Cl ratio remained between 1.70 and 2.70 along the entire river. Other cations/Cl ratios have similar trends to the Na/Cl.

Groundwater in the upper and middle catchment is dominantly of a mixed magnesium and sodium or potassium bicarbonate type. Na comprises 22–58 % of the total cations with 20–43 % Mg, 16–30 % Ca and 3–21 % K, and HCO_3 accounts for 64–95 % of anions with 5–18 % Cl, 1–20 % SO_4 and > 1–25 % NO_3. Groundwater in the lower catchment is a sodium or potassium chloride type with relative cation concentrations of 38–83 % Na, 4–54 % Ca, 2–27 % Mg, and > 1–3 % K, and relative anion concentrations of 29–64 % Cl, 20–68 % HCO_3, > 1–16 % and > 1–4 % NO_3. Molar Na/Cl ratios of the low salinity (TDS < 100 mg L^{-1}) groundwater from the upper and middle catchments are mainly between 1.0 and 3.9 with some up to 11, whereas the more saline groundwater from the lower catchment has Na/Cl ratios close to those of rainfall (0.8–1.5).

4.5 Radon activities

While the Ovens River at uppermost site (0 km) in Harrietville has consistently low ^{222}Rn activities (112–245 Bq m^{-3}), other river reaches in the upper catchment have ^{222}Rn activities between 373 and 2903 Bq m^{-3} (Fig. 6a). The location at 4.8 km often records the highest ^{222}Rn activity, with the exception of September 2010 and March 2011. ^{222}Rn activities in the upper catchment were highest in September 2009, June 2011 and October 2011 and lower in March 2011, September 2011 and December 2011. In the Bright-Porepunkah river section, there was a significant ^{222}Rn peak of 905 Bq m^{-3} (March 2010) and 817 Bq m^{-3} (June 2010) at 28 km in the canyon (Fig. 6b), which is the site where the small increase in EC values was observed. The ^{222}Rn activities in the last 1.5 km of this river section were 881–1243 Bq m^{-3}. A small stream and spring on the floodplain at Porepunkah had ^{222}Rn activities of 2663 Bq m^{-3} (March 2010) and 8083 Bq m^{-3} (June 2010), and 10 488 Bq m^{-3} (March 2010) and 50 450 Bq m^{-3} (June 2010) respectively. In the middle catchment, ^{222}Rn activities generally decrease downstream from 601–2174 Bq m^{-3} to 231–440 Bq m^{-3}, with several ^{222}Rn peaks occurring between 46.6 and 62.6 km (Fig. 7a). High ^{222}Rn activities were recorded in September 2009 and June 2011, whereas activities were lowest in December 2010. River reaches in the lower catchment have the lowest ^{222}Rn activities, ranging between 80 and 754 Bq m^{-3}. The temporal variation in the ^{222}Rn activities in the lower catchment is minimal with a maximum difference of ~ 200 Bq m^{-3}. Despite the low activities, locations between 140 and 187 km in September 2009 and March 2010 exhibited elevated ^{222}Rn activities (699 and 754 Bq m^{-3} respectively).

The ^{222}Rn activities of groundwater in the upper catchment are in the range of 30 000–110 000 Bq m^{-3} (Table 5). The groundwater ^{222}Rn activities are 20 000–42 000 Bq m^{-3} in the middle catchment and 10 000–20 000 Bq m^{-3} in the lower catchment. The decrease trend in the groundwater ^{222}Rn activities across the subcatchments reflects a change in lithology from immature sediments containing abundant fragments of granitic and metamorphic materials, which contain a significant amount of U-bearing minerals, in the alluvial valleys to more mature weathered sediments that are dominated by quartz and feldspar on the plains. There were no significant differences in groundwater ^{222}Rn activities between the sampling rounds even after the 2010 floods.

5 Discussion

The geochemistry of the Ovens River allows the major geochemical process to be defined and the distribution and magnitude of groundwater inflows to be calculated. There are no occurrences of halite in the Ovens Valley, and Cl in groundwater and surface water is derived from rainfall (Cartwright et al., 2006). Since the molar Na/Cl ratio of the rainfall in the region is 1.0–1.3 (Blackburn and McLeod, 1983), the high river Na/Cl (Fig. 5c) and other cation/Cl ratios in the upper reaches of the Ovens River most probably reflect rock weathering by surface runoff in the upper catchment. The decrease in river Na/Cl ratios down the catchment is likely caused by influxes of both groundwater in the valley aquifers and surface runoff from the middle and lower catchments, both of which have relatively low Na/Cl ratios. Thus, Na and other cations are derived from rainfall and rock weathering. Overall, the high ^{222}Rn activities in the upper and middle catchments of the Ovens River (Fig. 6) together with the progressive downstream increase in EC values (Fig. 4) and major ion concentrations (Fig. 5a and b) suggest that the Ovens River receives groundwater inflows. ^{222}Rn is used to identify gaining reaches and to calculate baseflow in this study because the difference of ^{222}Rn activities between groundwater and river water in the Ovens Catchment is 2–3 orders of magnitude, whereas the difference in the EC values and concentrations of major ions in the groundwater and river water are much smaller. For comparison, baseflow fluxes are also calculated using Cl, which is conservative in this catchment, and estimated from the hydrographs. Assessing other potential methods of estimating baseflow is valuable as river discharge and major ion data are far more extensive than the ^{222}Rn data.

5.1 Baseflow fluxes calculation using ^{222}Rn activities

Groundwater influxes to the river for the sampling rounds were calculated by rearranging Eq. (1). ^{222}Rn activities are from Table 4. Stream discharges were estimated by linear interpolation of data from the five gauging stations. River depths and widths were estimated in the field; river depths vary from 1.2–8.0 m in winter and 0.3–6.7 m in summer, and river widths range from 15–100 m in winter and 7–90 m in summer. Evaporation rates were estimated as 0.05 m day^{-1} and 0.2 m day^{-1} for winter and summer months respectively (Australian Bureau of Meteorology, 2011). Based on the distribution of groundwater ^{222}Rn activities (Table 5), ^{222}Rn activities of 76 000 Bq m^{-3}, 32000 Bq m^{-3} and 19 000 Bq m^{-3} were assigned to the upper, middle and lower catchments respectively. Hyporheic exchange can also cause an elevation in ^{222}Rn activity in rivers where there is no or low groundwater input (or groundwater has low radon activities) (Cook et al., 2006; Lamontagne and Cook, 2007; Cartwright et al., 2011; Cook, 2012). This exchange needs to be accounted for in ^{222}Rn mass balance to prevent over-estimating groundwater inputs although it can be difficult to estimate for larger rivers. The Ovens River and groundwater have generally high ^{222}Rn activities.

Thus errors associated with hyporheic exchange are likely to be small, and initially the F_h term was omitted. Gas exchange coefficients (k) were estimated using the modified gas transfer models of O'Connor and Dobbins (1958) and Negulescu and Rojanski (1969) as described by Mullinger et al. (2007):

$$k = 4.87 \times 10^{-4} \left(\frac{v}{d}\right)^{0.85} \tag{2}$$

$$k = 9.301 \times 10^{-3} \left(\frac{v^{0.5}}{d^{1.5}}\right) \tag{3}$$

where v is the average stream velocity (m day^{-1}) derived from the steam discharge, river depth and river width data. Equations (2) and (3) give a maximum and minimum k value respectively, and these values were used to calculate maximum and minimum groundwater influxes. The k values for the winter months are generally 3.0–8.0 day^{-1} in the upper catchment, decreasing to 0.2–1.0 day^{-1} in the lower reaches. Lower values were obtained for the summer months, from 3.0–4.0 day^{-1} in the upper catchment to 0.2–0.3 day^{-1} in the lower catchment. High values of k in the upper catchment reflects the high velocities caused by the shallow river depth and steep channel gradient, while low values of k in the lower catchment is the result of lower velocities due to the greater rive depth and low channel gradient. Studies on low-gradient rivers indicated that the k values typically vary from 0.5 to 2.5 day^{-1} (Raymond and Cole, 2001; Cook et al., 2003; Cartwright et al., 2011). k values for shallow and turbulent rivers have been estimated to be up to 34 day^{-1} (Mullinger et al., 2007). Thus the calculated k values are within the range recorded in other studies. Each sub-catchment was assigned an average value of k from all individual reaches within the sub-catchment to calculate the maximum and minimum groundwater influxes. The ^{222}Rn dilution at the three confluences was calculated by combining the ^{222}Rn activity and the discharge at the sampling site downstream of the confluence with the ^{222}Rn activity (Table 4) and the discharge near the exit of the tributary.

The calculations indicate most reaches are gaining ($I > 0\,\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$), except for one reach in the upper catchment (at 11 km, June 2011) and few reaches in the middle and lower catchments. Reaches with $I < 0\,\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ are assigned as having zero baseflow flux. For maximum groundwater inputs (using values from Eq. 2), the baseflow fluxes are 0.2–9.0 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the upper catchment, 0.2–24.4 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the middle catchment and 0.1–24.1 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the lower catchment during the high flow periods (September 2009, September 2010, December 2010, March 2011) (Fig. 7a); and 0.1–0.6 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the upper catchment, 0.1–4.5 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the middle catchment and 0.4–3.7 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ for the lower catchment during the low flow periods (March 2010, June 2010, June 2011 and October 2011) (Fig. 7b). Relatively higher groundwater inflows occur in the upper and middle catchment. In addition, there are high groundwater inputs of up to 24 $\text{m}^3\,\text{m}^{-1}\,\text{day}^{-1}$ at several locations (65–72 km and 166–188 km) in the middle and lower catchments. Furthermore, groundwater inputs, particularly in the upper catchment, often increase during the high flow periods. The increase in groundwater influxes during the high flow periods is also reflected by the higher cumulative groundwater influxes in September 2009 (2 400 000 $\text{m}^3\,\text{day}^{-1}$), December 2010 (740 000 $\text{m}^3\,\text{day}^{-1}$) and March 2011 (660 000 $\text{m}^3\,\text{day}^{-1}$) (Fig. 8a) compared to the low flow periods in March 2010 (230 000 $\text{m}^3\,\text{day}^{-1}$), June 2010 (150 000 $\text{m}^3\,\text{day}^{-1}$) and June 2011 (350 000 $\text{m}^3\,\text{day}^{-1}$) (Fig. 8b). The cumulative groundwater inflow for the catchment during the study period was 150 000–2 400 000 $\text{m}^3\,\text{day}^{-1}$ or 4–22 % of total flow.

Repeating the calculations with values from Eq. (3) (minimum k) reduces groundwater influxes by 18–70 %. The large percentage changes often occur in the gaining reaches with a declining ^{222}Rn activity and in the gaining reaches with a small increase in ^{222}Rn activity. Sensitivity to k has been found to increase with lower groundwater inflow rate (that is a small dC_r/dx) (Cook et al., 2006; Cook, 2012). It also results in additional two losing reaches in the upper catchment and increases the number of losing reaches in the middle and lower catchments. Overall, the minimum *k* values decreases the cumulative groundwater influxes for the catchment to 130 000–650 000 $\mathrm{m^3\,day^{-1}}$ or 3–14 % of total flow. The calculations were repeated by assigning different groundwater ^{222}Rn activities (±1 standard deviation of the sub-catchment ^{222}Rn activity) to understand the impact of spatial variation in ^{222}Rn groundwater activities on groundwater inflows. The standard deviations of groundwater ^{222}Rn activity in the upper, middle and lower catchments are 76 000 $\mathrm{Bq\,m^{-3}}$, 32 000 $\mathrm{Bq\,m^{-3}}$ and 19 000 $\mathrm{Bq\,m^{-3}}$ respectively. An increase in the groundwater ^{222}Rn activity reduces groundwater influxes by 19–30 %, whereas a decrease in the groundwater ^{222}Rn activity increases groundwater influxes by 30–80 %. The cumulative groundwater inflows are also adjusted according to the newly assigned groundwater ^{222}Rn activities: 3–17 % predicted when using higher groundwater ^{222}Rn activities and 10–35 % when using lower groundwater ^{222}Rn activities. The impact of ignoring hyporheic flow was also assessed by subtracting the background river ^{222}Rn activities from the measured river ^{222}Rn activities in September 2009 and recalculating the groundwater influxes for that sampling round. The background river ^{222}Rn activities for each sub-catchment are derived from the lowest river ^{222}Rn activities in the upper and lower catchments: 220 $\mathrm{Bq\,m^{-3}}$, 175 $\mathrm{Bq\,m^{-3}}$ and 130 $\mathrm{Bq\,m^{-3}}$ for upper, middle and lower catchments respectively. The revised groundwater influxes are 3–70 % lower. The large discrepancies usually occur in some reaches of the middle and lower catchments where these reaches have a relatively low ^{222}Rn activity. However, these reaches only contribute a small proportion of baseflow to the catchment, and these large discrepancies will only have a small effect on the catchment-scale groundwater inflow. The over-estimation on the cumulative groundwater inflow in September 2009 due to ignoring hyporheic flow is about 17 %.

5.2 Baseflow fluxes calculation using Cl concentrations

Groundwater inputs to the river were also calculated by Cl concentrations (Table 3) via:

$$I = \left(Q\frac{d\mathrm{Cl_r}}{dx} - wE\mathrm{Cl_r} \right) \Big/ (\mathrm{Cl_i} - \mathrm{Cl_r}) \tag{4}$$

(Cartwright et al., 2011), where $\mathrm{Cl_r}$ and $\mathrm{Cl_i}$ are Cl concentrations in the river and groundwater respectively. Based on the distribution of Cl concentrations in groundwater (Table 2), three average $\mathrm{Cl_r}$ concentrations were used for distance 0–65 km, 65–127 km and 127–202 km: 3.25, 45.0 and 275 mg $\mathrm{L^{-1}}$ respectively. Comparing with the ^{222}Rn mass balance calculations, Cl mass balance calculations indicate fewer gaining reaches in the upper, middle and lower catchments (Fig. 9). The locations of high groundwater inflow do not always mirror the ones predicted by the ^{222}Rn activities. The groundwater influxes for the upper and middle catchments based on Cl concentrations are higher than those based on ^{222}Rn activities. Conversely, Cl concentrations often yield lower groundwater influxes in the lower catchment than ^{222}Rn activities. Several reaches in the middle catchment have extremely high calculated baseflow of up to 1414 $\mathrm{m^3\,m^{-1}\,day^{-1}}$. The best match between ^{222}Rn and Cl derived groundwater influxes are the ones in the upper catchment in March 2010 and June 2010, and the ones in the lower catchment in December 2012. During the high flow periods, groundwater influxes of 5.7–32.1, 0.1–9.9 and 0.4–2.9 $\mathrm{m^3\,m^{-1}\,day^{-1}}$ are predicted for the upper, middle and lower catchment respectively. For the low flow periods, groundwater influxes are lesser: 0.08–3.4 $\mathrm{m^3\,m^{-1}\,day^{-1}}$ for the upper catchment, 0.2–4.6 $\mathrm{m^3\,m^{-1}\,day^{-1}}$ for the middle catchment and 0.01–0.2 $\mathrm{m^3\,m^{-1}\,day^{-1}}$ for the lower catchment. Except for the two high flow conditions (September and December 2010), the Cl mass balance calculations indicate lower cumulative groundwater influxes, for example 1 000 000 $\mathrm{m^3\,day^{-1}}$ in September 2009, 17 000 $\mathrm{m^3\,day^{-1}}$ in March 2010, and 140 000 $\mathrm{m^3\,day^{-1}}$ in June 2011. September and December 2010 had a cumulative groundwater inflow of 810 000 and 6 700 000 $m^3 day^{-1}$ respectively. Overall, the cumulative groundwater inflows are 2–36 % of total flow.

When the assigned groundwater Cl concentrations were adjusted by ±1 standard deviation (0.9, 17 and 120 $mg L^{-1}$ for the upper, middle and low catchments) for their spatial variations, the groundwater fluxes for individual reach also vary accordingly: a 25–37 % decrease for the higher assumed groundwater Cl concentrations and a 62–150 % increase for the lower assumed groundwater Cl concentrations. Sensitivity analysis on both ^{222}Rn and Cl mass balance calculations shows that decreasing groundwater end-member concentration (C_i, Cl_i) makes a greater change in groundwater fluxes compared with increasing C_i or Cl_i. As the difference between groundwater and river concentrations (C_i–C_r) or (Cl_i–Cl_r) get smaller by decreasing C_i or Cl_i, it is more likely to magnify any errors in the mass balance calculation. The greater sensitivity is more apparent in the Cl mass balance calculations because the difference between Cl_i and Cl_r is already low at the beginning.

5.3 Baseflow fluxes calculation via hydrograph separation

Hydrograph separation employs a low pass filtering technique to separate the slowflow component (assuming to be mainly baseflow) that shows a low frequency of variation from the high frequency signals associated with surface runoff and interflow. Recursive digital filters developed by Nathan and McMahon (1990) and Eckhardt (2005) were used in this study. The filter equation for Nathan and McMahon (1990) is:

$$f_k = \alpha f_{k-1} + \frac{(1+\alpha)}{2}\left(y_k - y_{k-1}\right) \quad (5)$$

where y is the total stream discharge, f is the filtered quick flow, k is the time step number, and α is the recession constant. Discharge data used in the calculations are from the period of October 2000–October 2011 from the three gauging stations: Bright (22 km), Myrtleford (65 km) and Peechelba (187 km). α is the gradient of the falling limb of a hydrograph and was determined via linear regression following Eckhardt (2008):

$$Q_{t+1} = \alpha Q_t \tag{6}$$

The calculated α values are 0.976 for Bright, 0.970 for Myrtleford and 0.967 for Peechelba. The filter was applied in three passes (forward, backward, forward) across the hydrograph as suggested by Nathan and McMahon (1990). The calculated percentages of baseflow in the May–October (wet) and November–April (dry) periods are 47 % and 83 % at 22 km, 51 % and 78 % at 65 km, 49 % and 79 % at 187 km respectively. The algorithm for the Eckhardt's filter is:

$$b_k = \frac{(1-\mathrm{BFI}_{\max})\,ab_{k-1} + (1-a)\,\mathrm{BFI}_{\max}y_k}{1-a\mathrm{BFI}_{\max}} \tag{7}$$

(Eckhardt, 2005), where b is the filtered baseflow ($bk \leq yk$), and $\mathrm{BFI}_{\max}$is the maximum value of the baseflow index (BFI) that can be modelled by the algorithm. $\mathrm{BFI}_{\max}$ cannot be measured but is assigned based on the catchment lithology and river flow regime. Eckhardt (2005) proposes 0.8 for perennial streams with porous aquifers, 0.5 for ephemeral streams with porous aquifer and 0.25 for perennial steams with hard rock aquifers. Considering the change in lithology from the small and highly conductive aquifers and the large bedrock aquifer in the upper catchment to the less conductive aquifers in the lower catchment, an area weighted $\mathrm{BFI}_{\max}$ of 0.31 was assigned for the upper catchment, 0.36 for the middle catchment and 0.47 for the lower catchment. The filter was applied in a single pass across the hydrograph as suggested by Eckhardt (2005). In comparison to the Nathan and McMahon filter, the Eckhardt filter produces lower percentages of baseflow: 36 % and 52 % at 22 km, 43 % and 58 % at 65 km, and 54 % and 66 % at 187 km, in the May–October and November–April periods respectively. However, these values are still substantially higher than those estimated by ^{222}Rn activities: 3 % and 2 % at 22 km, 10 % and 9 % at 65 km, and 16 % and 12 % at 187 km.

5.4 Variations in baseflow

5.4.1 Spatial variations in baseflow

The baseflow fluxes derived from ^{222}Rn activates indicate high groundwater inflows in the upper catchment. The high groundwater influx is likely caused by the catchment morphology and aquifer lithology. In the upper catchment, the narrow valley creates a high hydraulic gradient of ~ 0.007 between the alluvial aquifers and the river (Fig. 3a). Furthermore, the high rainfall and high rates of recharge (120–180 mm yr^{-1}) through the coarse grained sands and gravels in the upper catchment (Cartwright and Morgenstem, 2012) maintains the high hydraulic gradients. High groundwater inflow commonly occurs in the first few river sections (0–11 km) of the river (Fig. 7). These river reaches are located at the edge of the alluvial valley, rather in the centre of the valley. It is likely that groundwater is discharged to the river at these break of slopes as a result of the sudden change in topography. Moderate to high groundwater inflows also occur between 31 and 34 km at Porepunkah as indicated by the progressively increase in EC values and ^{222}Rn activities (Figs. 4b and 6b). This location is coincident with springs and a spring fed stream. The river reach at 27.8–29.5 m is in a moderately steep canyon. As the flow leaves the canyon, it cuts a channel deep through shallow sediments on the alluvial valley plains at this location. As the water table follows the topography, it is likely to intercept with the river channel to produce springs on the river plains and to recharge the river as baseflow. Groundwater inflows in the upper and middle catchments are also derived directly from the basement aquifer as evidenced by the presence of ^{222}Rn and EC peaks in the canyon (28.4–28.7 km) (Figs. 4b and 6b). The magnitude of groundwater influx from the basement aquifer may be large and seasonal (up to 16 m^3 m^{-1} day^{-1} in March 2011). Since fractured bedrock aquifers often have very limited storativity, they deplete very quickly, discharging less groundwater to the river toward the end of summer as in June 2011.

Groundwater influxes in the middle catchment are generally equal to or lower than those in the upper catchment (Fig. 7). The middle catchment represents a transition from a narrow valley to open alluvial flood plains with the river in the middle of the valley. Therefore, the lateral head gradient toward the river is lower than that in the upper catchment (Fig. 3b and c). The aquifer sediments also have lower hydraulic conductivities, and both these factors cause a reduction of groundwater influxes to the river. The difference between the river stage and the water table is also small and thus, any small changes in river height or groundwater level can result in the observed fluctuating gaining and losing behaviour along the river.

Groundwater inflows are further reduced in the lower catchment. This is the result of the shallow hydraulic gradient developed between the river and the groundwater in the open and flat alluvial flood plains in a semi-arid environment (Fig. 3d). Furthermore, groundwater inflows are likely to be restricted by the less conductive alluvial sediments.

Despite the widening of alluvial plains, several locations (between 65 and 72 km and between 166 and 188 km in the middle and lower catchments) receive significant baseflow (up to 24 $m^3\,m^{-1}\,day^{-1}$) (Fig. 7). This gaining behaviour is probably caused by basement highs that deflect groundwater flow and induce upward head gradients. Between 65 and 72 km several large outcrops of bedrocks are found near the river, while the river meanders closely to the Warby Ranges between 166 and 188 km (Fig. 1) (van den Berg and Morand, 1997).

5.4.2 Temporal variations in baseflow

Groundwater inflows in the upper catchment increase during high flow periods (Figs. 7a and 8a). The increased rainfall over autumn, winter and occasionally summer produces high surface runoff and also recharges the groundwater. Due to the coarse sediments, the hydraulic heads in the upper catchment can increase up to 3 m throughout a year (Fig. 3a). The rapid rising heads within the narrow river valley induces hydraulic loading, causing more groundwater to flow toward the river and resulting a greater amount of groundwater inflows. However, the magnitude of groundwater inflows do not always increase proportionally with river flows. For instance, the discharge in December 2010 was greater than that in September 2009, and yet the December 2010 around had a lower cumulative groundwater influx than the September 2009 around (Fig. 9a). The lower baseflow fluxes may be caused by the high river stage as a result of multiple floods in the previous winter/spring months which reduces the hydraulic gradient between the river and the adjacent water table. In contrast, the river was relatively dry in September 2009 after a period of drought, allowing a greater hydraulic gradient to be developed during the recharge period and thus producing a greater amount of baseflow (Fig. 2). The groundwater influxes in the upper catchment can be low during low flow periods. The coarse aquifer sediments enable relatively quick drainage of groundwater into the river during winter and spring months. The water table near the river is likely to drop to the river height, and thus there is less groundwater influxes to the river over summer months.

The baseflow fluxes in the lower catchment are similar at both high and lower flow conditions. The constant baseflow fluxes are probably caused by the limited fluctuation in the water table. The water table in this region is relatively constant, ranging 0.5–1.5 m near the river and less than millimetres away from the river (Fig. 3d). The constant water table is due to low recharge rate of 30–40 mm yr^{-1} on the floodplains (Cartwright and Morgenstem, 2012) which is the result of reduced rainfall, flat topography and low conductivity of alluvial sediments. Since the water table near the river does fluctuate, it is possible for the river to recharge the adjacent aquifers and river banks during high flow conditions.

5.5 Comparing Rn with Cl concentrations and hydrograph separation

In the upper and to some extent, the middle catchment, the baseflows estimated from Cl concentrations are often greater than those based on ^{222}Rn activities by 30–2000 % (Fig. 9). If ^{222}Rn activities do better indicate the variability in groundwater inflows, there must be sources of error in using Cl concentrations to estimate baseflows. Underestimating evaporation is unlikely since evaporation is a minor process in the catchment (Cartwright and Morgenstem, 2012). Another possible error is ignoring potential saline groundwater inputs. However, if the assigned groundwater Cl concentration was increased to 5 mg L^{-1} which is the highest Cl concentration in the upper catchment, the groundwater influxes would only decrease by 20–50 %. Thus, saline groundwater input is probably not the sole reason for the overestimation. The error is likely the result of the similarity between groundwater and river Cl concentrations in the upper and middle catchment. If the difference in the two end-member concentrations is small, it requires a significant input of groundwater in order to detect a rise in river Cl concentrations associated with the influx of groundwater. It also magnifies any calculation and measurement errors in mass balance calculations, particularly groundwater end-member concentration (Cook, 2012). The large increases in some of the river Cl concentrations (and thus large estimation of groundwater influxes) may be due to accumulation of Cl over several reaches or may come from other sources, such as water in the unsaturated zone or in pools on riverine plain.

In the lower catchments, the Cl-derived baseflow fluxes are usually lower than ^{222}Rn-derived ones by 50–100 % (Fig. 9). If the assigned groundwater Cl concentrations in the calculations are reduced, the amount of baseflows would progressively increase, matching ones derived from the ^{222}Rn activities. This may be interrupted as the amount of saline regional groundwater contributing to the river probably being low. Rather, the majority of baseflows in this area probably come from the less saline water in the mid-channel bars and river banks. Using regional groundwater concentration in the mass balance calculations would under-estimate the total groundwater discharge to the river but correctly identify the amount of regional groundwater discharge if the groundwater discharge comprises of both bank storage and regional groundwater (McCallum et al., 2010). The infilling of these mid-channel bars and river banks is supported by the larger variable hydraulic heads near the river (Fig. 3d). While these water stores are being replenished during high flow period, regional groundwater is likely to be the only source of groundwater inflows as evident by the agreement of the Cl- and ^{222}Rn-derived baseflow influxes during the rising limb of a high flow event in December 2010. Simultaneously river bank refilling and regional groundwater discharge are also suggested on the Riverine Plain (Cartwright et al., 2011).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

In comparison to ^{222}Rn mass balance, hydrograph separation yields larger estimates of accumulative baseflow fluxes across the catchments. However, some assumptions behind this method may not hold for the Ovens River as some reaches in the middle and lower catchment are losing and partly regulated. For Eckhardt's filter, the calculations are sensitive to the value of $\mathrm{BFI}_{\mathrm{max}}$ which can only be assigned subjectively. The cumulative baseflow flux could increase by 2–40 % if the $\mathrm{BFI}_{\mathrm{max}}$ was increased by 0.1. Finally, hydrograph separation cannot isolate the individual components of the slowflow component; this might include groundwater, bank returns and interflows and draining of pools on the floodplains. The baseflow fluxes calculated using hydrograph separation are likely to include these slowflow components rather than just regional groundwater. The idea of these slowflow components contributing to the river is also suggested by the Cl concentrations data above.

6 Conclusions

The Ovens River is dominated by gaining reaches. The river and aquifer interactions are mainly controlled by the catchment geomorphology, aquifer sediments and rainfall distribution. In the upper catchment, the reaches are mostly gaining. Rapid groundwater recharge through the coarse sediments in the narrow valley creates hydraulic loading and causes higher baseflow flux during high flow periods. In the lower catchment, the open plains, fine sediments and reduced rainfall ensure low water table variability, leading to relatively lower and constant groundwater influx. The reaches also experience fluctuating gaining and losing conditions due to the similarity between the water table and river height on the open alluvial plains. The middle catchment represents a transition in river-aquifer interactions from upper to lower catchment. Basement highs in the middle and lower catchment also play role in inducing groundwater influx to the river. Groundwater from alluvial and basement aquifers contributes 4–22 % of total river discharge with higher baseflow during high flow periods while water from unsaturated zone and river bank is likely to play a greater contribution to the river flow.

During drought, bore hydrographs in the upper catchment the groundwater levels may fall below those of the river implying that some reaches will become losing. As the conductivities of sediments across the catchment vary, it is likely the onset of reduced baseflow would occur at various time with the upper reaches first being affected. The use of multiple baseflow quantification techniques provide a better insight into the relationship of a river to its adjacent groundwater system, allowing a better water resource and/or riveine ecosystem management for this type of catchment.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/10/5225/2013/hessd-10-5225-2013-supplement.pdf.

Acknowledgements. Stable isotope and major ion analyses were made with the help of Massimo Raveggi and Rachelle Pierson. Funding for this project was provided by ARC grant DP0984539 and the National Centre for Groundwater Research and Training (program P3). The National Centre for Groundwater Research and Training is an Australian Government initiative supported by the Australian Research Council and the National Water Commission.

References

Baskaran, S., Ransley, T., Brodie, R. S., and Baker, P.: 2009. Investigating groundwater–river interactions using environmental tracers, Aust. J. Earth Sci., 56, 13–19, 2009.

Blackburn, G. and McLeod, S.: Salinity of atmospheric precipitation in the Murray-Darling Drainage Division, Australia, Aust. J. Soil Res., 21, 411–434, 1983.

Brodie, R., Sundaram, B., Tottenham, R., Hostetler, S., and Ransley, T.: An Overview of Tools for Assessing Groundwater-Surface Water Connectivity, Bureau of Rural Sciences, Canberra, 2007.

Bureau of Meteorology: Commonwealth of Australia Bureau of Meteorology, available at: http://www.bom.gov.au (last access: 15 March 2011), 2011.

Burnett, W. C. and Dulaiova, H.: Radon as a tracer of submarine groundwater discharge into a boat basin in Donnaucata, Sicily, Cont. Shelf Res., 26, 862–873, 2006.

Cartwright, I. and Morgenstem, U.: Constraining groundwater recharge and the rate of geochemical process using tritium and major ion chemistry: Ovens Catchment, southeast Australia, J. Hydrol., 47, 137–149, 2012.

Cartwright, I., Weaver, T. R., and Fifield, L. K.: Cl/Br ratios and environmental isotopes as indicators of recharge variability and groundwater flow: An example from the southeast Murray Basin, Australia, Chem. Geol., 231, 38–56, 2006.

Cartwright, I., Hofmann, H., Sirianos, M. A., Weaver, T. R., and Simmons, C. T.: Geochemical and ^{222}Rn constraints on baseflow to the Murray River, Australia, and timescales for the decay of low-salinity groundwater lenses, J. Hydrol., 405 333–343, 2011.

Cecil, L. D. and Green, J. R.: Radon-222, in: Environmental tracers in subsurface hydrology, edited by: Cook, P. G. and Herczeg, A. L., Boston, Kluwer, 175–194, 1999.

Cheng, X. and Reid, M.: Progress Report for Groundwater Modelling Approach in the Ovens Catchment – Conceptual Model Department of Primary Industry, Bendigo, 2006.

Cook, P. G.: Estimating groundwater discharge to rivers from river chemistry surveys, Hydrol. Process., in press, 2012.

Cook, P. G., Favreau, G., Dighton, J. C., and Tickell, S.: Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers, J. Hydrol., 277, 74–88, 2003.

Cook, P. G., Lamontagne, S., Berhane, D., and Clark, J. F.: Quantifying groundwater discharge to Cockburn River, southeastern Australia, using dissolved gas tracers 222Rn and SF6, Water Resour. Res., 42, W10411, doi:10.1029/2006WR004921, 2006.

CSIRO: Water Availability in the Ovens: A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO, Canberra, 2008.

Eckhardt, K.: How to construct recursive digital filters for baseflow separation, Hydrol. Process., 19, 507–515, 2005.

Eckhardt, K.: A comparison of baseflow indices, which were calculated with seven different baseflow separation methods, J. Hydrol., 352, 168–173, 2008.

Ellins, K. K., Roman-Mas, A., and Lee, R.: Using ^{222}Rn to examime groundwater/surface discharge interaction in the Rio Grande De Manati, Puerto Rico, J. Hydrol., 115, 319–341, 1990.

Evans, R. and Neal, B.: Baseflow analysis as a tool for groundwater – surface water interaction assessment, International Water Conference, International Association of Hydrogeologists, Auckland, New Zealand, 2005.

Griffiths, G. A. and Clausen, B.: Streamflow recession in basins with multiple water storages, J. Hydrol., 190, 60–74, 1997.

Halford, K. J. and Mayer, G. C.: Problems associated with estimating ground water discharge and recharge from stream-discharge records, Ground Water, 38, 331–342, 2000.

Lamontagne, S. and Cook, P. G.: Estimation of hyporheic water residence time in situ using ^{222}Rn disequilibrium, Limnol. Oceanogr., 5, 407–416, 2007.

Lawrence, C. R.: Murry Basin, in: Geology of Victoria, edited by: Douglas, J. G. and Ferguson, J. A., Geological Soceity of Australia (Victoria Division), Melbourne, 352–363, 1988.

McCallum, J. L., Cook, P. G., Brunner, P., and Berhane, D.: Solute dynamics during bank storage flows and implications for chemical base flow separation. Water Resour. Res., 46, W07541, doi:10.1029/2009WR008539, 2010.

Mullinger, N. J., Binley, A. M., Pates, J. M., and Crook, N. P.: Radon in Chalk streams: Spatial and temporal variation of groundwater sources in the Pang and Lambourn catchments, UK, J. Hydrol., 339, 172–182, 2007.

Nathan, R. and McMahan, T.: Evaluation of automated techniques for baseflow and recession analysis, Water Resour. Res., 26, 1465–1473, 1990.

Negulescu, M. and Rojanski, V.: Recent research to determine reaeration coefficients, Water Res., 3, 189–202, 1969.

O'Connor, D. J. and Dobbins, W. E.: Mechanisms of reaeration in natural streams, T. Am. Soc. Civil Eng., 123, 641–684, 1958.

Pritchard, J. L.: Dynamics of stream and groundwater exchange using environmental tracers, Flinders University, Flinders, 2005.

Raymond, P. A. and Cole, J. J.: Gas Exchange in Rivers and Estuaries: Choosing a Gas Transfer Velocity, Estuaries, 2, 312–317, 2001.

Shugg, A.: Hydrogeology of the Upper Ovens Valley, Victoria Department of Industry, Technology and Resources, 1987.

Slater, D. and Shugg, A.: Hydrology of the Ovens Valley at Myrtleford, Geological Survey of Victoria, 1987.

Sophocleous, M.: Interactions between groundwater and surface water: the state of the science, Hydrogeol. J., 10, 52–67, 2002.

Tickell, S. J.: Geology and hydrogeology of the eastern part of the Riverine Plain in Victoria, Geological Survey of Victoria, 1978.

van den Berg, A. H. M. and Morand, V. J.: Wangaratta 1:250,00 Geological Map Series, Geological Survey of Victoria, 1997.

Victorian Government Department of Sustainability and Environment: Report for Ovens Valley Water Resource Appraisal: Data Analysis and Conceptual Model Development, Victorian Government Department of Sustainability and Environment, Melbourne, 2010a.

Victorian Government Department of Sustainability and Environment: Victorian Water Accounts 2007–2008: A Statement of Victorian Water Resource, Victorian government Department of Sustainability and Environment, Melbourne, 2010b.

Victorian Government Department of Sustainability and Environment: Victorian Water Accounts 2008–2009: A Statement of Victorian Water Resource, Victorian Government Department of Sustainability and Environment, Melbourne, 2010c.

Victorian Water Resource Data Warehouse: available at: www.vicwaterdata.net/vicwaterdata/home.aspx (last access: 10 December 2011), 2011.

Table 1. EC values of the Ovens River. Notes: nm – not measured

					EC (µS cm^{-1})							
Site No.	Site Name	Easting	Northing	Distance km	September 2009	March 2010	June 2010	September 2010	December 2010	March 2011	June 2011	October 2011
Ovens River												
SW19	Bundalong	042773	6007835	202	37.8	39.9	47.3	50.5	nm	54.7	54.8	72.4
SW18	Peechelba	043119	5997555	187	26.3	45.6	42.8	49.3	61.6	57.0	53.4	73.1
SW17	Killawara	043417	5984065	165	34.7	55.9	47.3	49.6	60.3	55.6	61.9	65.4
SW16	Wangaratta	043861	5956675	140	33.1	42.7	42.3	45.2	56.2	52.4	47.0	59.2
SW15	South Wang	044237	5974395	127	33.7	52.6	37.8	44.1	41	48.6	48.8	61.1
SW14	Tarrawingee	045113	5970115	115	30.4	40.5	36.8	42.4	57.6	50.9	48.6	54.3
SW13	Everton	045732	5966695	97	32.2	46.5	36.1	43.3	40	47.5	46.6	52.7
SW12	Whorley	046451	5959045	80	31.7	40.3	38.4	40.4	38.6	44.6	33.7	47.2
SW11	Whorley East	047013	5966685	72	32.4	40.6	37.7	38.1	37.5	43.5	43.8	45.9
SW10	Myrtleford	047453	5952805	65	30.3	47.9	33.8	34.2	35	39.2	40.3	38.8
SW9	Salziers Ln	047837	5949855	57	30.1	84.7	33.2	35.3	35.9	39.8	38.2	39.1
SW8	Ovens	048239	5947285	50	33	38.5	32.7	34.8	34.5	40.7	37.6	40.1
SW7	Eurobin	048684	5945025	47	39.3	53.7	32.3	33.3	34.2	38.9	37.0	37.9
SW6	Porepunkah N	048833	5941035	39	29.7	36.6	33.7	32.8	34	39.3	35.9	38.8
SW5	Porepunkah	049182	5938925	34	30.2	46.4	34.1	36.1	37.1	41.5	41.0	43.0
SW4	Bright	049936	5935505	22	31.6	44.4	36.5	34.0	36.8	39.7	39.0	41.5
SW3	Smoko	050568	5927365	11	24.7	39.7	32.1	31.4	33.8	37.4	36.9	37.7
SW2	Trout Farm	050560	5918975	5	30.4	41.9	34.6	33.2	34.2	37.1	39.0	
SW1	Harrietville	050566	5917175	0	28.2	36.0	30.6	32.9	28.4	30.7	31.1	32.9
Tributaries												
SW22	King @ Oxley	044442	5966735		33.0	37.7	42.6	43.7	43.1	50.8	85.2	51.9
SW21	Buffalo @ Myrtleford	047182	5954215		34.8	37.3	37.6	36.6	34.6	39.2	39.4	41.0
SW20	Buckland @ Porepunkah	049049	5938625		33.2	34.1	30.7	30.0	32.8	33.2	31.6	34.9
Bright-Porepunkah												
SW5		049182	593892	33.8						41.5	41.0	
BC8		0493028	5937880	32.2						39.9	37.8	
BC7		0494855	5936181	29.7						37.2	36.8	
BC1		0495297	5936079	29.2						38.5	37.1	
BC2		0495387	5935740	28.8						38.4	37.0	
BC3		0495519	5935501	28.5						39.3	37.6	
BC4		0495640	5935350	28.2						39.9	37.6	
BC5		0495703	5935212	28.0						38.3	37.1	
BC6		0496330	5935344	27.8						35.5	36.4	
BU4		0496796	5925419	27.3						38.2	36.3	
BU1		0497316	5935587	26.3						38.4	37.1	
BU2		0498227	5935171	25.2						38.9	35.7	
BU3		0498714	5935382	24.7						39.0	36.2	
SW4		049936	5935505	22.0						39.7	39.0	
Bright-Porepunkah (At Location BC8)												
SR	Spring fed Stream									48.6	49.0	
SS	Spring									64.1	52.2	

Table 2. EC values and Cl concentrations of groundwater in the Ovens Catchment. Notes – *: if single value is reported, the value represents the depth of the middle of the bore screen below ground surface.

							September 2009		March 2011	
Bore No.	Location	Catchment	Easting	Northing	Bore Screen Depth (m)*	Distance to River (km)	EC (μS cm^{-1})	Cl (mg L^{-1})	EC (μS cm^{-1})	Cl (mg L^{-1})
B51743	Bright	Upper	499291	5935508	5–11	0.0206	82.1	2.80		
B51747	Bright	Upper	499190	5935414	2–20	0.160	58.1	3.10		
B1	Bright	Upper	499270	5935517	2–4	0.0095			94.7	2.95
B2	Bright	Upper	499260	5935513	2–4	0.0156			82.0	2.87
B51745	Bright	Upper	499139	5935375	5–11	0.225	63.1	2.16		
B51744	Bright	Upper	498933	5934911	6–12	0.725	56.3	2.73		
B51737	Bright	Upper	498445	5935658	36–42	0.261	110.6	2.41		
B51738	Bright	Upper	498397	5935420	58-63	0.0262	199.5	2.39		
B51735	Bright	Upper	498391	5935314	30–42	0.0708	74.4	3.58		
B51736	Bright	Upper	498382	5935299	20–26	0.0824	53.1	3.29		
B109461	Bright	Upper	497818	5935267	20–26	0.339	82.8	3.42		
B109462	Bright	Upper	497818	5935267	45–51	0.339	100.4	3.48		
B88271	Porepunkah	Upper	493294	5938062	8–14	0.219	99.5	3.98	106.5	3.75
B88274	Porepunkah	Upper	493256	5938067	35–53	0.210	64.3	1.85		
B48069	Eurobin	Middle	487803	5944698	5–8	0.506	128.5	3.59	122.0	4.07
B48068	Eurobin	Middle	487657	5944643	7–13	0.357	74.3	3.52	68.9	3.42
B48067	Eurobin	Middle	487519	5944594	12.0	0.203	92.1	4.14	77.4	3.24
B48066	Eurobin	Middle	487411	5944553	9–15	0.0914	77.9	3.90	70.3	3.97
B83232	Myrtleford	Middle	474884	5953288	6–12	0.447	106.5	9.33		
B83231	Myrtleford	Middle	474704	5953010	8–14	0.126	49.1	2.08		
M1	Myrtleford	Middle	474605	5952919	4–6	0.0049			90.0	2.37
M2	Myrtleford	Middle	474605	5952936	4–6	0.0215			67.6	2.43
B83229	Myrtleford	Middle	474607	5952916	8–14	0.0128	86.7	2.01		
B83230	Myrtleford	Middle	474604	5952937	8–14	0.0359	45.1	1.87		
B102783	Whorouly	Middle	464087	5959833	5.1–11.27	0.0048	106.9	10.32		
T1	Tarrawingee	Lower	451112	5970209	5–7	0.0056			367.0	46.89
T2	Tarrawingee	Lower	451121	5970212	5–7	0.0142			364.0	47.78
T3	Tarrawingee	Lower	451136	5970245	6–8	0.0509			315.0	45.96
B110738	Oxley	Lower	444240	5966742	18.5–44	0.0048	106.9	10.32		
B11326	Wangaratta	Lower	439879	5982755	23.7	2.79	106.3	15.42		
B11493	Wangaratta	Lower	439422	5982189	16.5	2.13	1341	192.03		
B302296	Boorhamman East	Lower	437925	5992950	70.5–77	3.52	920	134.21		
B11323	Boorhamman East	Lower	437924	5992953	17.4	3.52	567	95.15		
B50788	Boorhamman	Lower	442072	5999081	60–72	9.93	536	89.17		
B50789	Boorhamman	Lower	442072	5999081	18–30	9.93	3800	654.13		
B11306	Peechelba	Lower	432684	5994603	15.8	0.469	12020	2331.00		
B11311	Bundalong	Lower	427007	6005559	16.2	0.3780	1194	163.46		
B11310	Bundalong	Lower	427237	6005560	13.9	0.191	2270	389.07		

Table 3. Cl concentrations of the Ovens River.

					Cl ($mg\,L^{-1}$)							
Site No.	Site Name	Easting	Northing	Distance km	September 2009	March 2010	June 2010	September 2010	December 2010	March 2011	June 2011	October 2011
Ovens River												
SW19	Bundalong	042773	6007835	202	2.47	2.30	1.62	2.51		4.03	4.54	4.93
SW18	Peechelba	043119	5997555	187	2.39	2.29	1.95	2.48	5.00	3.82	4.30	5.05
SW17	Killawara	043417	5984065	165	2.39	2.55	1.77	2.32	4.64	3.10	3.89	4.32
SW16	Wangaratta	043861	5956675	140	2.34	1.96	1.59	2.41	4.39	3.19	3.34	3.90
SW15	South Wang	044237	5974395	127	1.91	1.99	1.65	2.33	2.80	2.62	2.61	3.71
SW14	Tarrawingee	045113	5970115	115	1.81	1.78	1.63	2.35	3.64	5.61	3.12	3.05
SW13	Everton	045732	5966695	97	1.88	1.80	1.54	2.22	2.72	2.38	2.48	3.11
SW12	Whorley	046451	5959045	80	1.9	1.73	1.57	2.17	2.44	2.01	2.02	2.23
SW11	Whorley East	047013	5966685	72	1.96	1.68	1.63	2.26	2.38	1.89	1.90	2.10
SW10	Myrtleford	047453	5952805	65	1.54	1.37	1.51	2.2	1.50	1.23	1.40	1.47
SW9	Salziers Ln	047837	5949855	57	1.61	1.32	1.52	2.19	1.66	1.49	1.39	1.45
SW8	Ovens	048239	5947285	50	1.49	1.30	1.47	2.32	2.30	1.21	1.39	1.40
SW7	Eurobin	048684	5945025	47	1.47	1.43	1.51	2.13	1.41	1.44	1.32	1.38
SW6	Porepunkah N	048833	5941035	39	1.5	1.15	1.48	2.01	1.38	1.36	1.35	1.35
SW5	Porepunkah	049182	5938925	34	1.31	1.25	1.42	1.98	1.44	1.21	1.25	1.34
SW4	Bright	049936	5935505	22	1.39	1.03	1.32	1.89	1.56	1.03	1.21	1.15
SW3	Smoko	050568	5927365	11	1.09	0.85	1.28	1.88	1.27	0.75	0.92	0.90
SW2	Trout Farm	050560	5918975	5	0.99	0.82	1.31	1.87	1.00	0.69	0.95	0.89
SW1	Harrietville	050566	5917175	0	1.03	0.67	1.25	1.92	0.78	0.71	0.81	0.76
Tributaries												
SW22	King @ Oxley	044442	5966735		2.77	2.10	2.21	2.31	3.02	3.20	3.14	3.46
SW21	Buffalo @ Myrtleford	047182	5954215		2.12	1.64	1.61	2.31	2.21	3.34	1.80	1.87
SW20	Buckland @ Porepunkah	049049	5938625		1.52	1.05	1.57	1.76	1.39	1.18	1.17	1.20
Bright-Porepunkah (At Location BC8)												
SR	Spring feed Stream									1.57	2.15	
SS	Spring									1.85	2.21	

Table 4. ^{222}Rn activities of the Ovens River.

					Radon (Bq m^{-3})							
Site No.	Site Name	Easting	Northing	Distance km	September 2009	March 2010	June 2010	September 2010	December 2010	March 2011	June 2011	October 2011
Ovens River												
SW19	Bundalong	042773	6007835	202	199	242	109	119	nm	30	159	161
SW18	Peechelba	043119	5997555	187	699	325	127	205	123	179	118	148
SW17	Killawara	043417	5984065	165	230	754	130	211	105	83	185	135
SW16	Wangaratta	043861	5956675	140	138	693	169	227	136	161	267	225
SW15	South Wang	044237	5974395	127	227	193	179	240	127	186	318	224
SW14	Tarrawingee	045113	5970115	115	222	206	227	385	169	257	363	387
SW13	Everton	045732	5966695	97	297	263	239	439	231	275	440	325
SW12	Whorley	046451	5959045	80	245	293	450	514	296	185	374	548
SW11	Whorley East	047013	5966685	72	1296	623	562	536	413	654	555	414
SW10	Myrtleford	047453	5952805	65	2318	639	628	674	230	500	643	413
SW9	Salziers Ln	047837	5949855	57	640	293	538	744	225	567	625	662
SW8	Ovens	048239	5947285	50	715	545	569	746	408	301	1337	530
SW7	Eurobin	048684	5945025	47	1669	533	530	970	297	928	945	867
SW6	Porepunkah N	048833	5941035	39	1544	573	552	770	399	930	803	942
SW5	Porepunkah	049182	5938925	34	2174	1040	1005	1126	601	983	1243	1155
SW4	Bright	049936	5935505	22	2903	630	707	754	654	580	1032	1007
SW3	Smoko	050568	5927365	11	2781	1063	844	641	793	631	707	1062
SW2	Trout Farm	050560	5918975	5	2659	1265	1168	679	783	373	1403	1103
SW1	Harrietville	050566	5917175	0	222	112	238	213	169	224	245	226
Tributaries												
SW22	King @ Oxley	044442	5966735		419	155	142	211	107	102	146	209
SW21	Buffalo @ Myrtleford	047182	5954215		605	620	637	503	358	378	678	682
SW20	Buckland @ Porepunkah	049049	5938625		339	450	740	824	644	267	928	1165
Bright-Porepunkah												
SW5		049182	593892	33.8						983	1243	
BC8		0493028	5937880	32.2						881	1060	
BC7		0494855	5936181	29.7						317	835	
BC1		0495297	5936079	29.2						469	627	
BC2		0495387	5935740	28.8						688	640	
BC3		0495519	5935501	28.5						905	817	
BC4		0495640	5935350	28.2						740	712	
BC5		0495703	5935212	28.0						374	617	
BC6		0496330	5935344	27.8						455	682	
BU4		0496796	5925419	27.3						371	792	
BU1		0497316	5935587	26.3						680	657	
BU2		0498227	5935171	25.2						564	738	
BU3		0498714	5935382	24.7						555	562	
SW4		049936	5935505	22.0						580	1032	
At Location BC8												
SR	Spring fed Stream									2652	8083	
SS	Spring									10488	50450	

Table 5. ^{222}Rn activities of groundwater in the Ovens Catchment.

							Radon (Bq m^{-3})					
Bore No.	Location	Catchment	Easting	Northing	Bore Screen Depth (m)*	Distance to (km)	September 2009	March 2010	June 2010	March 2011	June 2011	October 2011
B51737	Bright	Upper	498445	5935658	36–42	0.261	116 750		100 230			
B51743	Bright	Upper	499291	5935508	5–11	0.0206	75 880	59 000	67 210	64 500	72 375	82 500
B51744	Bright	Upper	498933	5934911	6–12	0.725				85 875	26 125	23 200
B51747	Bright	Upper	499190	5935414	2–20	0.160	50 650					
B1	Bright	Upper	499270	5935517	2–4	0.0095				28 225	90 125	71 750
B2	Bright	Upper	499260	5935513	2–4	0.0156				39 563	73 250	76 750
B88271	Porepunkah	Upper	493294	5938062	8–14	0.219	58 880			48 125		
B48066	Eurobin	Mid	487411	5944553	9–15	0.0914	42 910	34 740	45 620	28 350		
B48067	Eurobin	Mid	487519	5944594	12	0.203	28 150	25 010	24 360	30 925		
B48068	Eurobin	Mid	487657	5944643	7–13	0.357				31 163		
B48069	Eurobin	Mid	487803	5944698	5–8	0.506				30 088		
B83229	Myrtleford	Mid	474607	5952916	8–14	0.0128	26 180		25 980			
B83230	Myrtleford	Mid	474604	5952937	8–14	0.0359	31 260		35 870			
M1	Myrtleford	Mid	474605	5952919	4–6	0.0049				10 325	19 400	18 788
M2	Myrtleford	Mid	474605	5952936	4–6	0.0215				19 500	30 238	25 063
B102873	Whorouly	Mid	464087	5959833	5.1–11.27	0.513	28 660					
B110738	Oxley	Lower	444240	5966742	18.5–44	0.0048	31 090					
T1	Tarrawingee	Lower	451112	5970209	5–7	0.0056				5988	15 150	23 300
T2	Tarrawingee	Lower	451121	5970212	5–7	0.0142				14 938	15 738	18 325
T3	Tarrawingee	Lower	451136	5970245	6–8	0.0509				16 325	22 738	18 867
B11326	Wangaratta	Lower	439879	5982755	23.7	2.79	35 100					
B11493	Wangaratta	Lower	439422	5982189	16.5	2.13	21 900					
B11323	Boorhamman East	Lower	437924	5992953	17.4	3.52	14 360		15 210			
B50789	Boorhamman	Lower	442072	5999081	18–30	9.93	9260					
B11306	Peechelba	Lower	432684	5994603	15.8	0.469	12 980	10 460	14 890			
B11310	Bundalong	Lower	427237	6005560	16.2	0.191	21 360					
B11311	Bundalong	Lower	427007	6005559	13.9	0.3780	18 290	18 130				

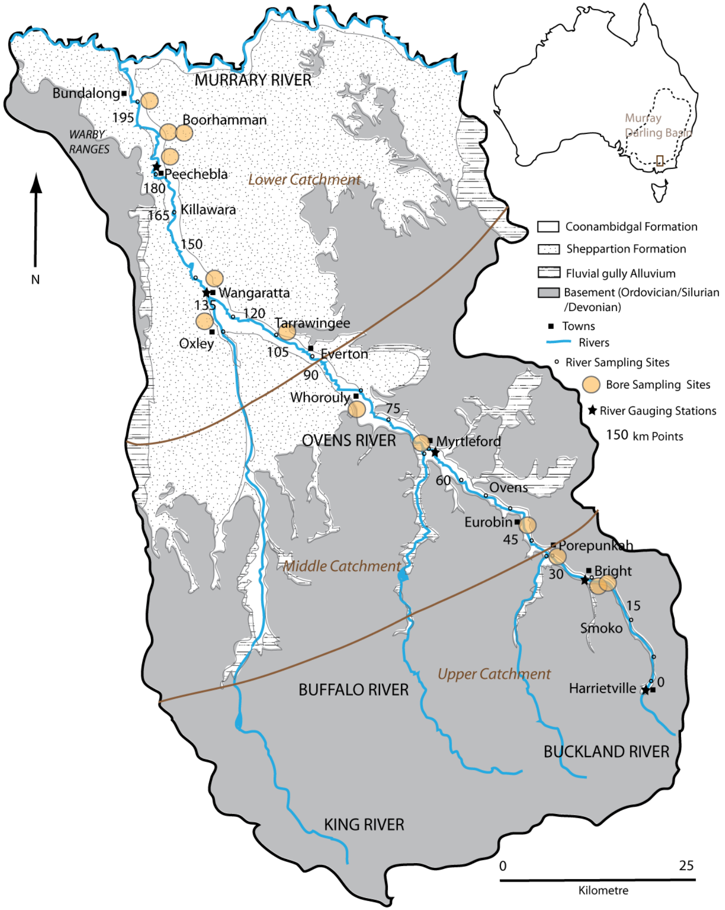

Fig. 1. Map of the Ovens River Catchment showing surface geology, sampling points and gauging stations. Data from van den Berg and Morand (1997); Water Resources Data Warehouse (2011).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

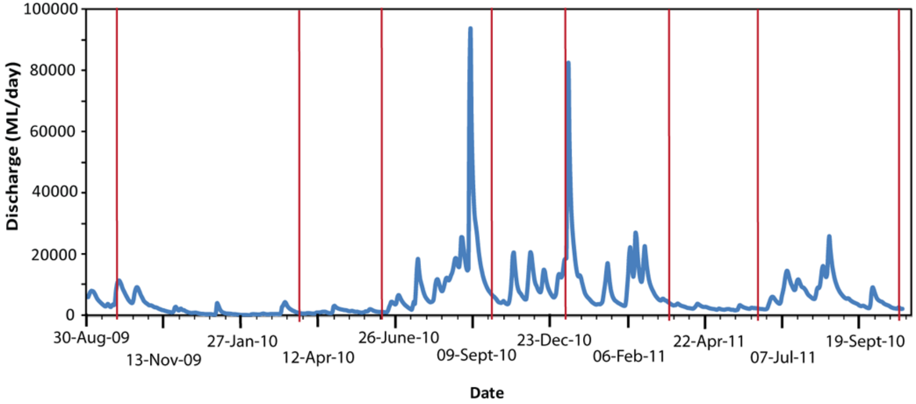

Fig. 2. Variation in discharge of the Ovens River at Peechelba during the study period (September 2009–October 2011) (Victorian Water Resource Data Warehouse, 2011). Low flow condition prior to June 2010 was due to drought, followed by several flood events in September–December 2010. Times of sampling round are indicated by the red lines.

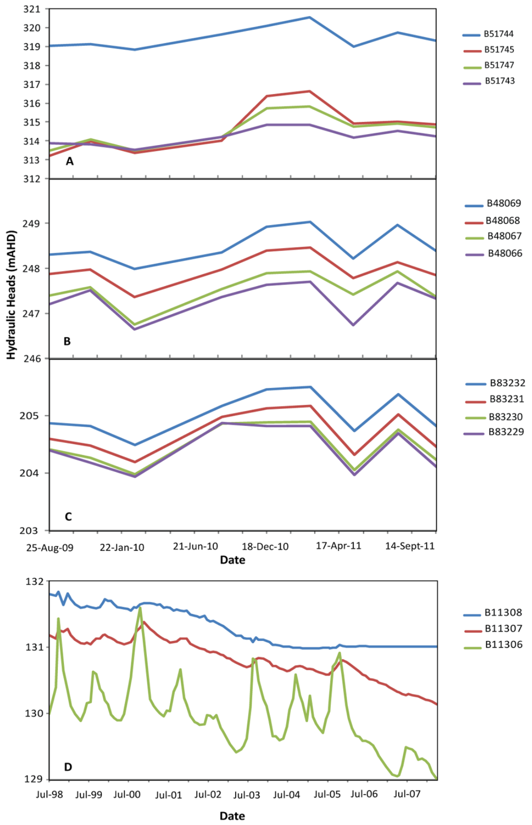

Fig. 3. Seasonal variation in bore hydrographs at **(A)** Bright in the upper catchment, **(B)** Eurobin and **(C)** Myrtleford in the middle catchment, and **(D)** Peechelba in the lower catchment (Victorian Water Resource Data Warehouse, 2011). Bores listed in order of decreasing distance from the river. Annual head variations and hydraulic gradients toward the river decrease downstream. mAHD (m Australia Height Datum) refers to metres above the mean sea level around the coast of Australia continent.

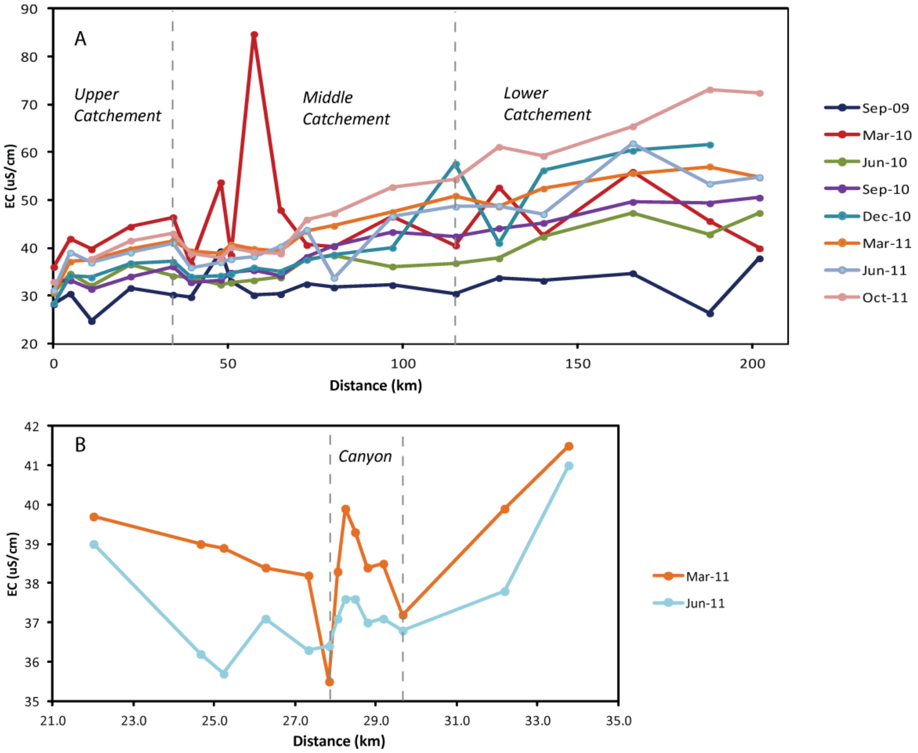

Fig. 4. (A) EC values along the course of the river (Table 1). EC values gradually increase downstream. **(B)** EC values along the Bright-Porepunkah reach in March and June 2011. Distinct EC peaks at 28.5 km, followed by a gradual increase in EC values in both sampling rounds.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

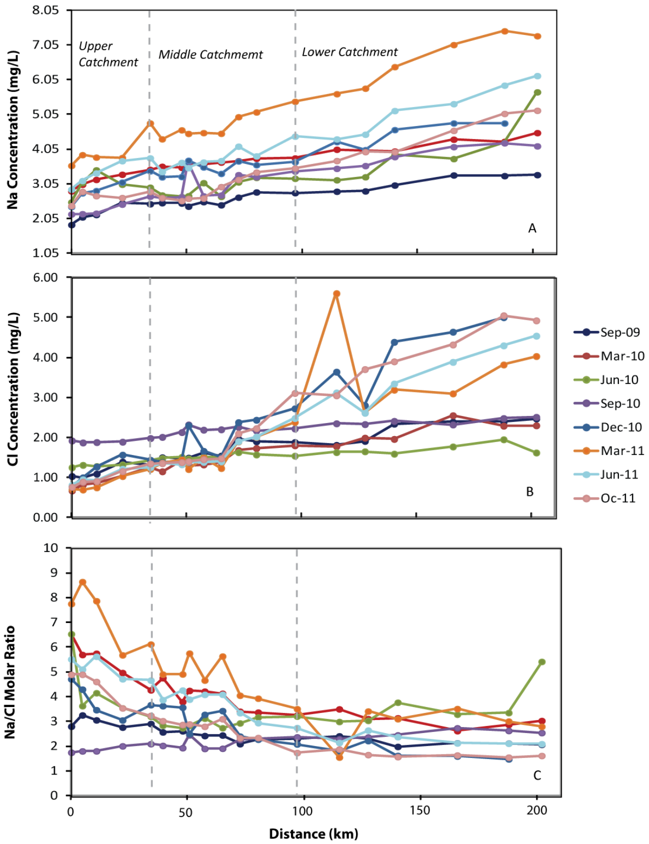

Fig. 5. Variation in Na **(A)** and Cl **(B)** concentrations, and Na/Cl ratio **(C)** along the river. Na and Cl concentrations increase progressively downstream whereas the Na/Cl ratios decrease downstream.

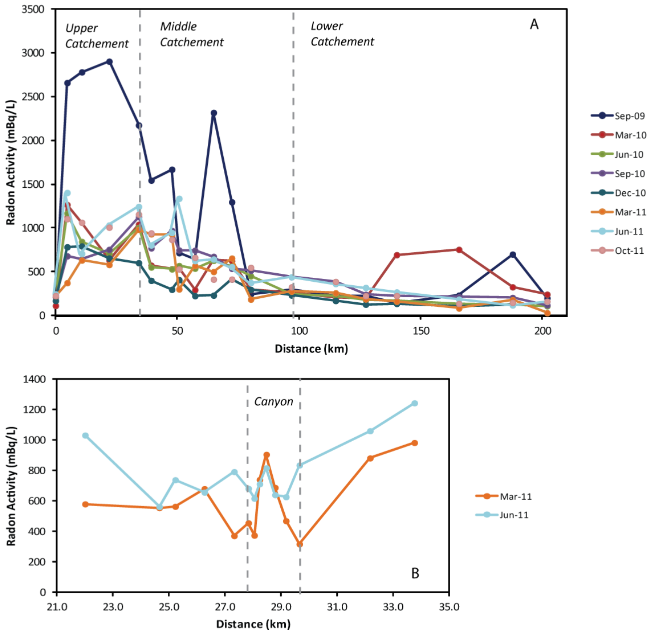

Fig. 6. (A) Variation of ^{222}Rn activities in the River (Table 4). High ^{222}Rn activities are recorded in the upper catchment and decrease down the valley. Temporal variation in the ^{222}Rn activities is minimal in the lower catchment. **(B)** ^{222}Rn activities along the Bright-Porepunkah reach in March and June 2011. Distinct ^{222}Rn peaks at 28.5 km (at which higher EC values are also found (Fig. 4c), followed by a gradual increase in ^{222}Rn activity in both sampling rounds.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▌
▶▌
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

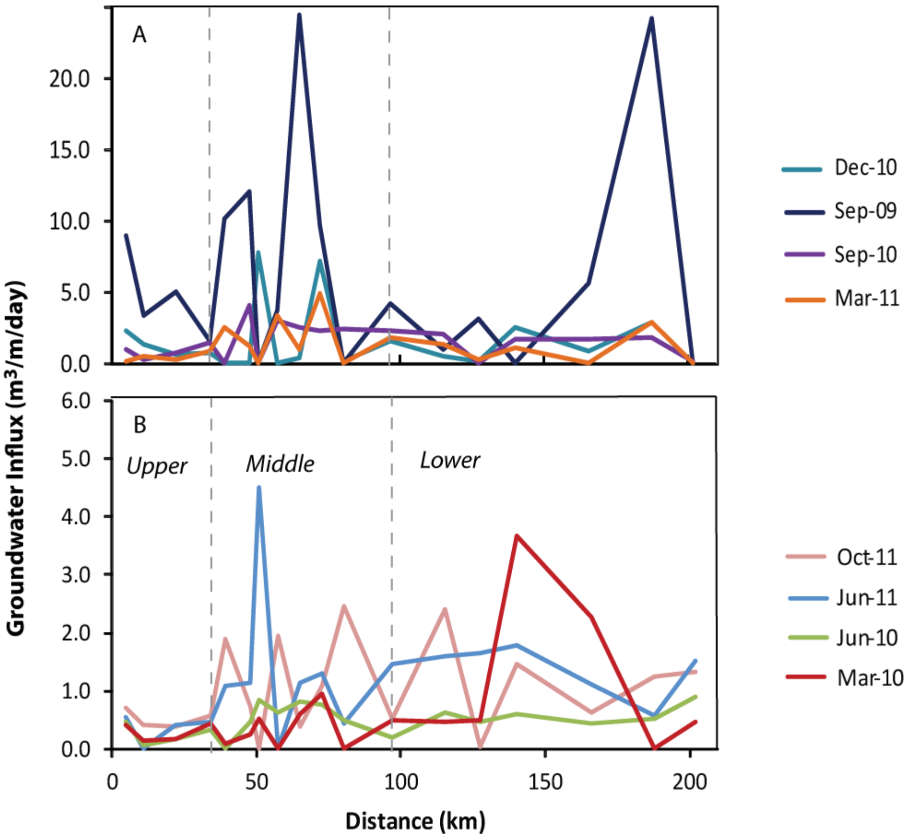

Fig. 7. Groundwater influxes calculated from ^{222}Rn activities, based on high k values, in flow conditions of 4894–18 520 ML day^{-1} **(A)** and of 995–2606 ML day^{-1} **(B)**. High baseflows occur in the upper catchment and often increase during high flow conditions. High baseflows also occur 65–72 km and 166–188 km.

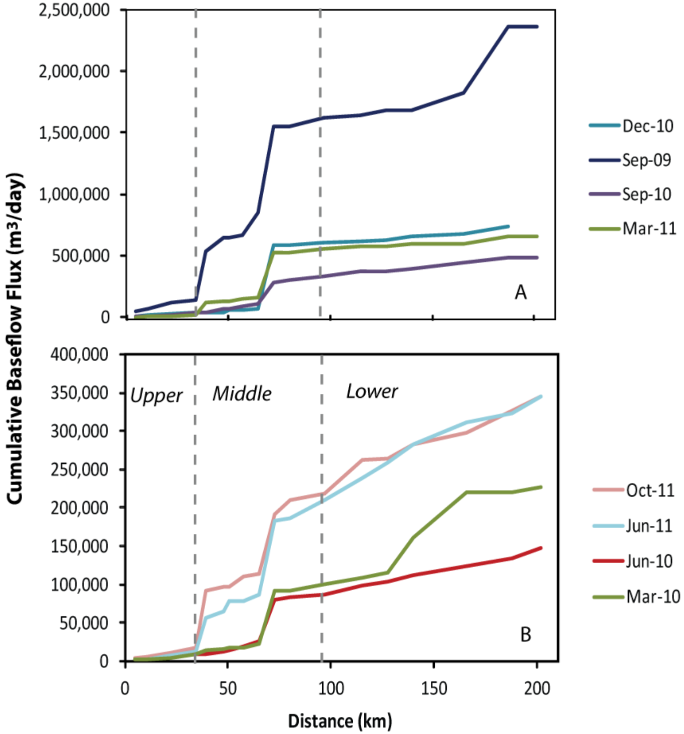

Fig. 8. Cumulative baseflow estimated from ^{222}Rn activities, based on high k values, in flow conditions of 4894–18 520 ML day^{-1} **(A)** and of 995–2606 ML day^{-1} **(b)**. High cumulative baseflow usually occur in high flow conditions.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

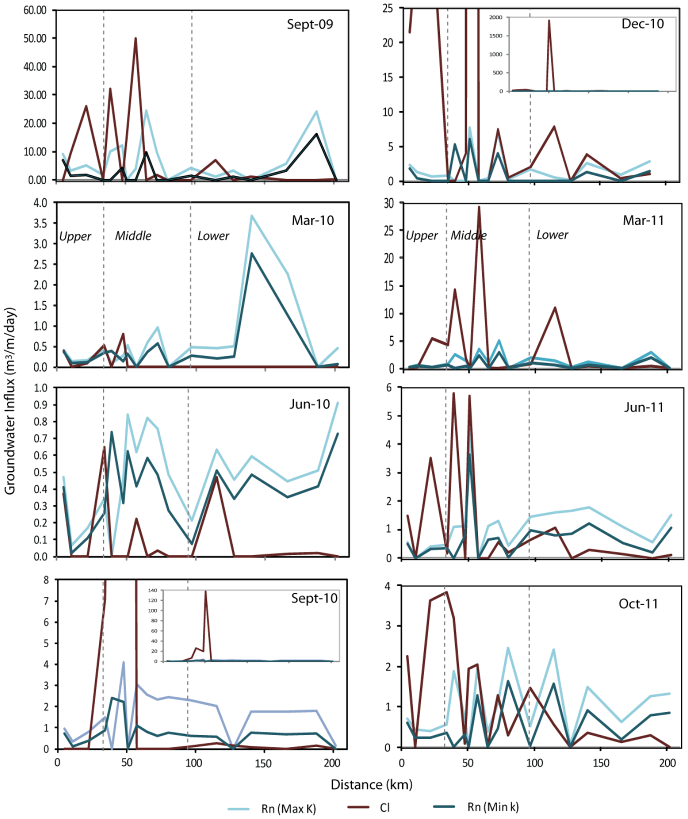

Fig. 9. Comparison of baseflow fluxes in each sampling round, estimated from ^{222}Rn activities and Cl concentrations using Eqs. (1) and (4) respectively. In comparison to ^{222}Rn activities, Cl concentrations yield higher baseflow fluxes in the upper catchment but lower baseflow fluxes in the lower catchment.