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Research papers

Using multiple lines of evidence to map groundwater recharge in a rapidly urbanising catchment: Implications for future land and water management

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ABSTRACT

Understanding how land-use change influences the water cycle is of critical importance to land and water management. Determining the timing, location and rates of groundwater recharge and their relationship to landuse is often challenging, leading to significant uncertainties in water budgets and water cycle planning. In this study, a combination of physical and hydrochemical/isotope techniques were used to estimate and map groundwater recharge rates and identify its key controlling factors in a rapidly urbanising catchment in southeast Australia. The primary objective was to provide qualitative and quantitative information regarding recharge, allowing comparison and monitoring of changes as future urbanisation takes place. The presence of significant tritium in shallow groundwater (> 1.0 TU), along with radiocarbon activities > 85 pMC and low salinity (e.g. EC < 600 µs/cm) allowed identification of areas where significant recharge has taken place in recent years. These were strongly associated with elevated topography on the basin margin, and the absence of volcanic clay - the dominant lithology underlying most of the region. This interpretation is supported by timeseries analysis of soil moisture profiles, which indicate minimal vertical propagation of precipitation below 1.5 m depth in volcanic clay soils. Estimation of recharge rates was conducted using chloride mass balance and water table fluctuation analysis in water table aquifer monitoring bores. Rates mostly ranged between 1.5 and 50 mm/ yr; however, recharge exceeding 100 mm/year was identified in a spatially restricted zone at the edge of the basin. Here, the volcanic lithology is absent and Quaternary sand directly overlies the lower Cainozoic sand aquifer. This area comprises a small percentage of land in the study area (approximately 15%) but is estimated to contribute a large proportion (nearly half) of recharge. The findings underscore the importance of characterising recharge locations and processes to support the protection of groundwater quality and quantity, for example, through careful land-use planning.

1. Introduction

The world's population is increasingly living in urban and periurban lands, resulting in the rapid expansion of cities' physical footprints globally (UN, 2017). Understanding how land use change (including urbanisation) affects the hydrological cycle is a critically important topic, with major implications for future water and land-use planning (Vorosmarty et al., 2000; Baker, 2003; USGS, 2015). While there have been significant advances in recent years understanding changes to surface hydrology during and following land conversion for urbanisation (Gupta, 2010), to date the effects on sub-surface hydrology, particularly groundwater recharge, are poorly understood (Lerner, 2002; Schirmer et al., 2013; Han et al., 2017).

Urbanisation results in significant changes to the physical structure of the land surface and shallow sub-surface, as well as water usage patterns, which have the potential to affect catchment and aquifer water balances and water quality (Fig. 1). With respect to groundwater recharge, Lerner (2002) and Schirmer et al. (2013) highlighted that, contrary to commonly held beliefs, conversion from agriculture or forest to urban or peri-urban land may result in increases in groundwater recharge or little change in net rates. However, such land-use change is commonly associated with significant changes in the location (s) and mechanism(s) of recharge.

Groundwater recharge is defined as the vertical flow of water reaching the water table, which adds to groundwater storage (Healy, 2010). Rates of recharge vary spatially and temporally by orders of magnitude, depending on the interplay between climate, geology and soil type, topography, surface hydrology, vegetation and land use

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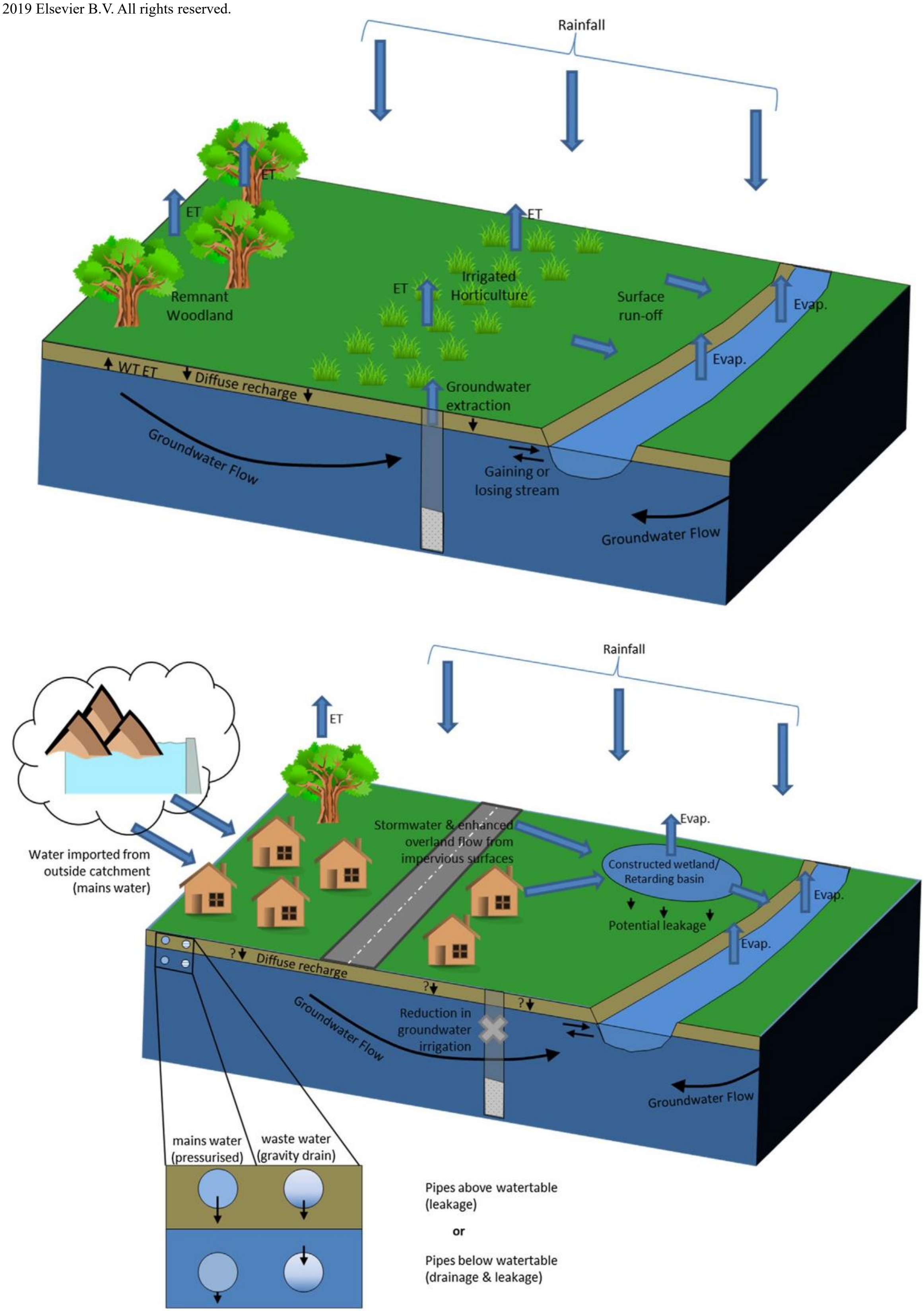

Fig. 1. Sub-surface hydrological cycle changes following urbanisation, showing typical water budget terms under (a) mixed agricultural land and (b) suburban residential housing. ET =evapotranspiration, WT = water table, Evap. =evaporation.

(Scanlon et al., 2006; McMahon et al. 2011). Numerous physical and tracer-based techniques have been developed to estimate recharge (e.g. Healy, 2010; Cartwright et al., 2017). Some of the most common include chloride mass balance (CMB), water table fluctuation (WTF) and water balancing. However, most techniques suffer from significant uncertainty (Scanlon et al., 2002), and it is rare for any single method to provide comprehensive spatial and temporal information about recharge mechanisms, rates and locations. As such, it is preferable to use multiple independent lines of evidence to constrain rates and determine key factors controlling these (Healy, 2010).

In this study, a combination of physical and hydrochemical methods were used to estimate rates of groundwater recharge across a catchment experiencing rapid urbanisation, and determine its spatial patterns and relationship to key influences such as soils, geology, elevation and surface infrastructure. This is required as a baseline from which to conduct ongoing assessment of the effects of future hydrogeological changes as urbanisation progresses over the coming decade(s), and to identify early indications of changes in recharge rate, location and mechanism(s) as this occurs. The primary aims of the study were to:

a) Identify areas of active groundwater recharge (i.e., where significant recharge over recent years or decades is evident);
b) Determine the key factors (e.g. soils, geology, topography) con-trolling groundwater recharge rates in different areas;
c) Quantify likely recharge rates throughout the catchment undercurrent-day conditions;
d) Explore the implications of these findings for future land and water management (e.g., given the current and future expected changes in land-use).

This information can be used to inform strategies to maximise the quality and quantity of groundwater recharge entering the underlying aquifer system as land-use change progresses, for example, through strategic protection of areas found to be high recharge zones. To our knowledge, this is one of the first studies to use multiple field-based techniques to independently estimate and map groundwater recharge rates and determine their relationships to other factors, in a catchment experiencing rapid urbanisation.

2. Study area

2.1. Geographic and hydrogeological setting

The study area comprises approximately 50 km^2 of land on the western margin of the Western Port Basin, located southeast of Cranbourne (Fig. 2), approximately 45 km southeast of the city of Melbourne in southeast Australia (Fig. 2). The location was selected because:

a) It has been previously identified as an important recharge area for groundwater in the Koo Wee Rup Water Supply Protection Area, where groundwater is the primary water supply (Lakey, 1980);
b) The area is currently undergoing widespread land use change (ur-banisation), with the potential to influence groundwater recharge. However, the rates, mechanisms and locations of recharge are to date poorly understood.

The local climate is temperate with mean temperatures ranging from 14.0 to 25.6 °C in summer and 6.2 to 13.6 °C in winter (Fig. 4). Long-term average annual rainfall (Bureau of Meteorology Station No. 86244) is 785 mm and is on average slightly higher in winter and spring than summer. Long-term average annual potential (pan) evaporation (1351 mm) exceeds annual precipitation, with considerably higher rates in summer (195 mm/month) than winter (51 mm/month). This results in favourable conditions for groundwater recharge predominantly occurring in winter, when average rainfall exceeds potential evaporation (Fig. 4). Surface water drainage across the basin consists of ephemeral and permanent streams flowing southward off upland areas (Fig. 2). The once extensive Koo Wee Rup swamp to the southeast of the study area has now been effectively drained by an extensive network of artificial drains, which convey much of the surface runoff in the catchment to Western Port Bay (primarily for the purpose of flood protection and to convert the swamp to agricultural land). These drains flow predominantly above Quaternary clays, and as such have relatively little interaction with groundwater (e.g. Lee et al., 2016). In the west of the Western Port Basin, some additional surface flow occurs in ephemeral channels, which only flow for short periods following heavy rain events (i.e., baseflow is minimal). Since the construction of new suburbs in the northern part of this area, stormwater flow is also channelled into a constructed wetland (adjacent to sites

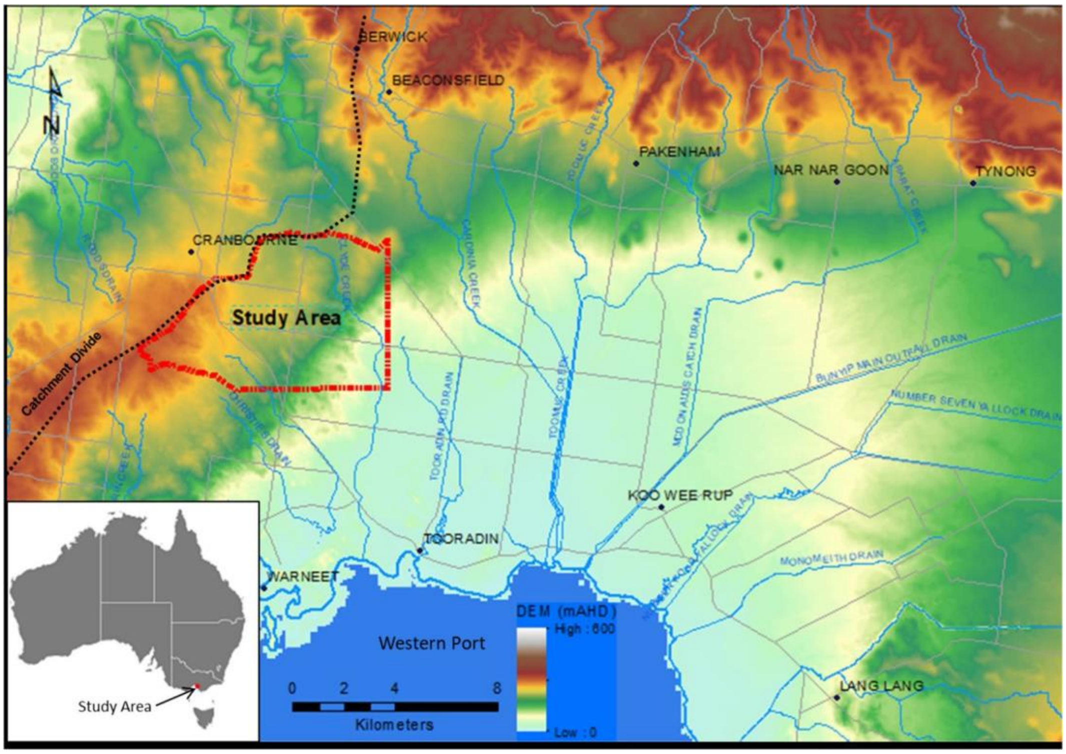

Fig. 2. Digital elevation model (DELWP, 2016) and outline of the study area.

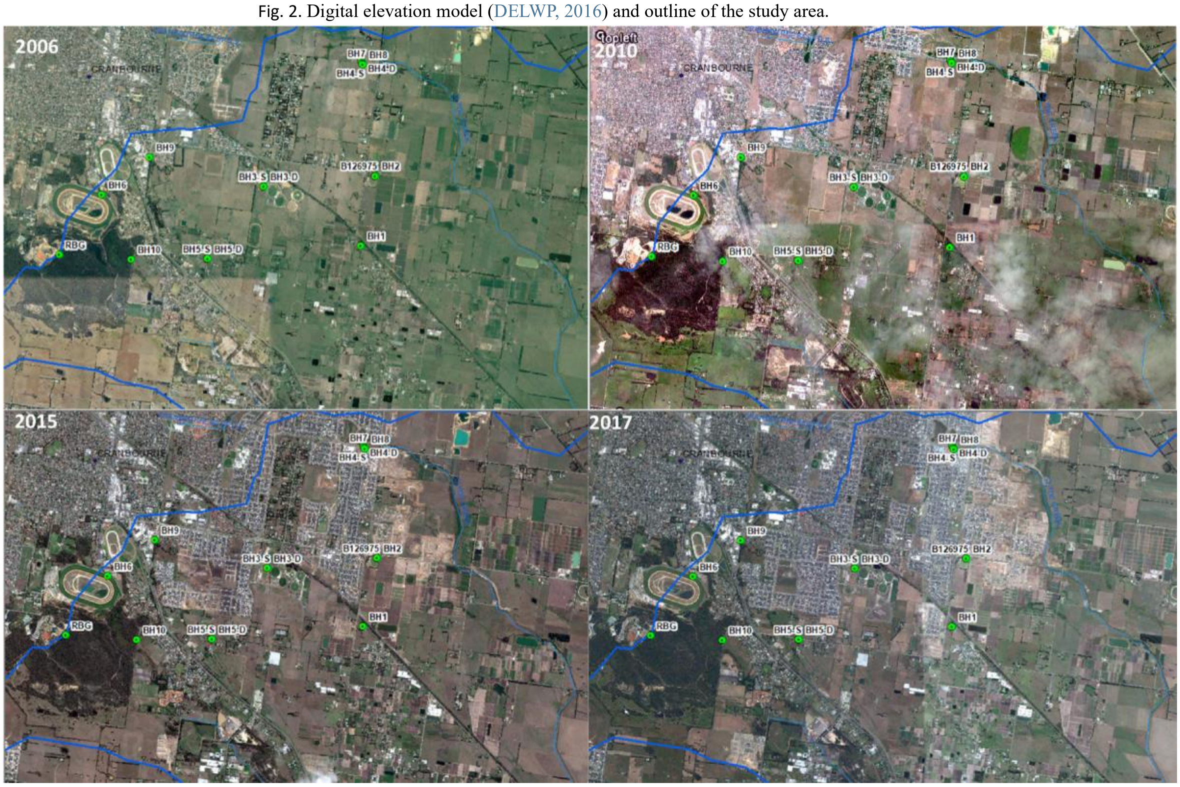

Fig. 3. Satellite images showing change in land use in the study area from 2006 to 2017. Groundwater monitoring bores installed for this study marked in green (imagery source: Google Earth). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

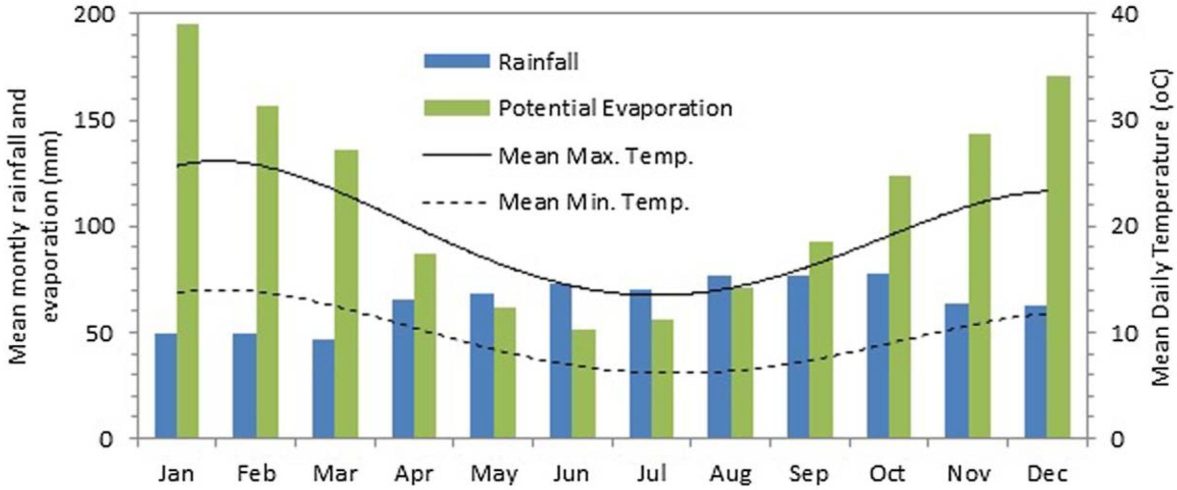

Fig. 4. Long-term mean monthly rainfall and pan evaporation and mean daily minimum and maximum temperature for Cranbourne South (data source: Bureau of Meteorology; Station ID: 86244).

BH4S on Fig. 3).

The geology and hydrogeology of the region are summarised in Lakey and Tickell (1981), Lee (2015) and others. Briefly, the Western Port Basin is a relatively shallow Cainozoic structure filled with a mixture of clay, silt, sand, minor coal and limestone and basalt lava flows (Jenkin, 1962). The basin is bounded to the west by the Tyabb Fault/Clyde Monocline, to the east by the Heath Hill Fault, and to the north by outcropping Palaeozoic bedrock (Fig. 5). The basin is typically less than 100 m deep in the west but thickens in the east, up to 300 m (Lakey and Tickell, 1980). Silurian meta-sediments including sandstone, mudstone and siltstone form the bedrock over the western part of the basin (Jenkin, 1962) and these outcrop in the southwest of the study area. Cainozoic deposition occurred through a series of marine transgressions and regressions and volcanic eruptions (Lakey and Tickell, 1981). The Paleocene-Oligocene Childers Formation consists of ligneous clay, dense silt and coarse sand and gravel deposited by alluvial and paludal processes. The Childers Formation contains fresh groundwater and has relatively high hydraulic conductivity (3–4 m/ day), forming a locally important aquifer confined by the overlying Older Volcanics (Lakey and Tickell, 1981). The Miocene Older Volcanics (Monbulk Volcanic Group) occur extensively across the basin with substantial outcrop and sub-crop near Cranbourne, and underlie younger Cainozoic sediments elsewhere in the basin (Fig. 5). The basalt flows are locally interbedded with clay, sand, gravel and coal (CarrilloRivera, 1975). This unit forms an important aquifer which can be classified as leaky-confined. Lakey and Tickell (1981) noted that the

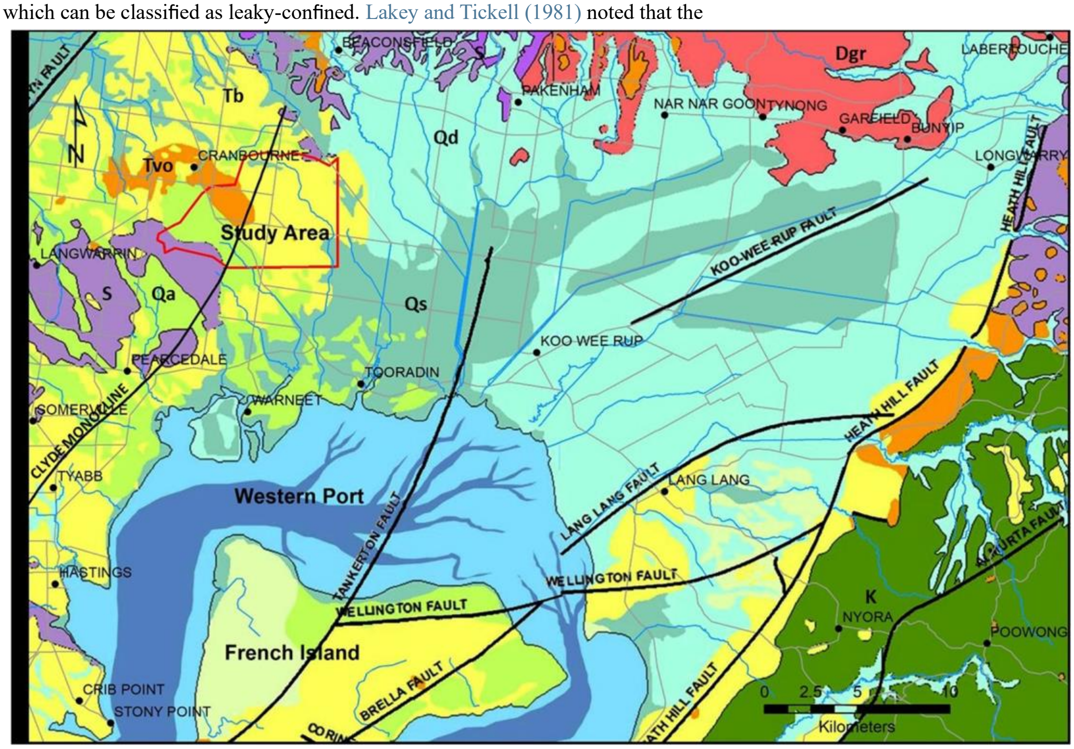

Fig. 5. Outcrop geology across Western Port Basin. Study area shown as red dashed line. Surface geology units: Qd (Quaternary alluvial deposits); Qa (Quaternary aeolian deposits); Qs (Quaternary swamp deposits); Tb (Baxter Formation); Tvo (Older Volcanics); K (Strzelecki Group); Dgr (Devonian granite); S (Silurian bedrock). Modified from Lee, (2015). Note that the Tb unit (Baxter formation) was not encountered during drilling in the study area and may be more restricted in distribution than is shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

basalts are often highly weathered to clay, both in sub-crop in the Cranbourne area and at deeper levels (between different lava flows) within the Western Port Basin.

Miocene marine and non-marine sediments (Baxter and Sherwood Formations) overlie the volcanics throughout much of the basin, however these units are largely absent in the study area, which is focussed in the west where urbanisation is taking place (Fig. 3; Fig. 5). Here, the Older Volcanics and/or Silurian bedrock are instead overlain by thin layers of Quaternary deposits, predominantly Pleistocene aeolian sand. This sand is quartzose, medium to coarse-grained and forms north-west to south-east aligned ridges in the Cranbourne area. Groundwater is extracted from thin, localised aquifers in these sands, however these have limited storage capacity.

2.2. Land use and future development plans

The study area includes the commercial centre of Cranbourne and surrounding market garden farms to the east and south (Fig. 2, Fig. 3). Since the 1980s the area has been dominated by irrigated horticulture. The source of irrigation water is a mixture of surface water, groundwater and, in more recent times, treated municipal wastewater. Since the mid-2000s, suburban development has begun to replace agricultural land. This is governed by the Victorian Planning Scheme and Urban Growth Boundary, which was extended in 2012 to take in a significant area of new land south and east of Cranbourne that was previously zoned for agricultural use. The City of Casey (the local government area) had an estimated population of 275,000 in 2013 and this is predicted to grow to 492,000 by 2041 (City of Casey, 2016). Cranbourne East, within the study area, currently has the highest rate of population growth in Australia (ABS, 2018). Accompanying this growth, agricultural land is being replaced by low density, residential housing sub-divisions (Fig. 1).

Fig. 3 shows satellite imagery of the area since 2006, indicating the extent of replacement of agricultural land with (sub)urban development up to 2017. Given the existing land-use change that has occurred since approximately 2013, and that the data in the study were collected between 2014 and 2017, the data and findings do not represent a complete 'pre-urbanisation' characterisation of the hydrological regime, but rather a snapshot during a (relatively) early stage of urbanisation. Much of the farmland visible on Fig. 3 has now been approved for re-development and is expected to be converted to residential suburbs over the next decade.

2.3. Previous studies of recharge

Previous studies (e.g. Carrillo-Rivera, 1975; Longley et al., 1978; Lakey, 1980; GHD, 2010; SKM, 2003) identified areas of out-cropping and sub-cropping Cainozoic formations along the western and eastern margins of the Western Port Basin as the most likely locations for groundwater recharge. Recharge was considered in these studies to occur through a combination of diffuse infiltration through sand or outcropping basalt and focussed recharge via losses from the Lang Lang River and wetlands on French Island (which both occur to the east, outside the studied area). Lakey (1980) applied the water table fluctuation (WTF) method over annual groundwater level time series to estimate a recharge rate of approximately 2,000 ML/year in the Cranbourne area (65 km^2). Lakey (1980) considered the Older Volcanics to be unconfined, comprising the main intake area for groundwater recharge in the west of the basin (our study area). Longley et al. (1978) calculated recharge as an input to a finite-difference groundwater model of the basin, estimating a percentage of rainfall infiltration over areas of outcropping Older Volcanics and adjusting this to achieve calibration to piezometric head data. This resulted in estimated recharge of 4400–5000 ML/year over 45 km^2 of land surrounding Cranbourne, equivalent to a rate of 100–113 mm/year or approximately 15% of rainfall. Recharge was also estimated in a later two-layer numerical finite difference groundwater model, applying a uniform rainfall infiltration rate and varying vertical hydraulic conductivities to achieve calibration to piezometric heads (SKM, 2003). This resulted in an estimated overall recharge of 5800 ML/yr in the Western Port Basin, with the majority occurring on the eastern side (e.g. near the Lang Lang River) rather than the west. These modelling studies did not involve any substantial spatial adjustment or refinement of recharge rates for specific areas, e.g., to reflect heterogeneity in surface conditions (such as soil texture).

Despite these previous attempts to estimate recharge rates in the basin, to date limited field data have been collected from the water table aquifer and shallow sub-surface within the hypothesised recharge area(s) to support or further investigate these estimates. As such, there is ongoing uncertainty as to the location, rates and mechanisms of recharge.

3. Data collection, sampling and analysis

3.1. Rainfall and soil moisture monitoring

Precipitation events were measured between 2014 and 2017 using a tipping bucket rain gauge (TB6, Hydrological Services) installed at Clyde Recreation Reserve (next to BH2; Fig. 5). The gauge was installed 2 m above the ground and clear of overhead obstructions as per the installation guidelines (Hydrological Services, 2008). Rainfall was collected and logged as 0.2 mm events, summed to daily totals for the purposes of data plotting, in conjunction with groundwater level and soil moisture time-series (e.g. Fig. S1).

Vertical profiles of soil moisture were monitored at 30 cm intervals to a depth of 1.5 m at two locations (near BH4 and BH2 – see Fig. 4 for locations), using capacitance sensors (Sentek) housed in PVC tubes. The sensors induce an electromagnetic field to measure changes in capacitance related to changes in soil moisture. Capacitance was converted to volumetric water content (θ_v) as described by Paltineanu and Starr (1997). These data were considered semi-quantitative, showing relative changes in soil moisture with time at different depths following rain events (as opposed to precise quantification of absolute volumetric soil moisture contents, which would require more detailed calibration – Paltineanu and Starr, 1997).

3.2. Monitoring bore installation and water level logging

Groundwater monitoring bores (n = 13) were installed during drilling campaigns in January 2014 and July 2016. Locations were selected to cover the area previously mapped as the zone of recharge (Lakey, 1980). Nested monitoring bores were installed at four locations to examine vertical hydraulic gradients and the relationship between the shallow and deeper aquifers (Fig. 4; Fig. 5). Boreholes were drilled using either mud-rotary boring (with few or no additives in the waterbased drilling fluid) or solid auger with U-tubes (Shelby Tubes) depending on the lithology, to provide accurate lithological samples wherever possible. Bores were constructed with 50 mm diameter class 18 uPVC casing with 3 m-long slotted sections. Bore annuli were backfilled with 1–2 mm diameter washed quartz sand filter pack to approximately 0.5 m above the top of screen and backfilled with bentonite and cement. Bores were developed through manual bailing, pumping and air-lifting to remove drilling fluid and ensure representative groundwater samples from the aquifer. Bore construction and lithology logs are included as electronic supplementary material (Appendix A).

Non-vented groundwater pressure transducers (Solinst Levelogger® and In-Situ Level Troll®) were deployed in twelve monitoring bores; five of these loggers also recorded electrical conductivity. Logging frequency intervals ranged from 15 to 60 min. A barometric pressure logger recorded atmospheric air pressure at the same frequency. Pressure readings were converted to water depth (D) correcting for density and barometric loading, according to Smith (2012). Water levels were also periodically manually checked using a Solinst™ interface probe, and logger data adjusted (where necessary), accordingly. Electrical conductivity loggers were periodically checked against a calibration standard, and measurements were taken as Specific Conductance (µS/cm or mS/cm) corrected to 25 °C.

3.3. Groundwater sampling, hydrochemical and radio-isotope analysis

Hydrochemical analyses were conducted on groundwater samples collected between 2014 and 2017 (n = 23). Samples were collected using a 12 V submersible pump (Proactive Supertwister) pumping at approximately 0.3L/min. Electrical conductivity (EC), temperature, pH, and dissolved oxygen (DO) were monitored using a HACH HQ40d or YSI 556 handheld water quality meter, and stabilisation of these parameters and water levels were achieved prior to sampling. Samples were collected in HDPE bottles filled to the top and capped to minimise headspace. Alkalinity titrations were performed in the field with a HACH digital titrator and Sulfuric acid (0.16 N or 1.60 N solution), using Bromocresol Green/Methyl Red indicator.

Samples for cation analysis were filtered through 0.45 µm filter paper or in-line filters (Aquapore™) and acidified in the field with HNO_3. Major ions were analysed at La Trobe University or the Monash University School of Earth, Atmosphere and Environment. At La Trobe University, potassium and sodium were analysed on a flame photometer, and chloride on a Sherwood Chloride Analyser, model 926. Calcium and magnesium were analysed using Inductively Coupled Plasma-Optical Emission Spectroscopy. At Monash University, major ions were analysed using an Ion Chromatograph (Metrohm) and ICPMS, following methods described in Cartwright et al. (2010). Bicarbonate concentrations were determined from alkalinity titrations and are precise to ±5%. Charge balance errors were less than 10% except in two instances.

Tritium analysis on samples collected in 2014 (n = 13) was conducted by liquid scintillation spectrometry following distillation and electrolytic enrichment at the National Isotope Centre, GNS, New Zealand, or the Australian Nuclear Science and Technology Organisation (ANSTO). Tritium concentrations are expressed in tritium units (TU). Samples from the National Isotope Centre have a precision of ± 0.06 TU at an average tritium concentration of recent rainfall (4 TU), and a detection limit of ±0.025TU (Morgenstern and Taylor, 2009). Samples from ANSTO have 1σ uncertainties between 0.02 and 0.03, with a minimum quantification limit of 0.15 TU. A further batch of tritium samples (n =3) were submitted to Isotech Laboratories (Champaign, IL, USA) in 2016. This analysis used the same techniques (electrolytic enrichment and liquid scintillation counting) but with a higher quantification limit of 1.0TU. Radiocarbon analyses (n =15) were completed at ANSTO and Isotech Laboratories, using accelerator mass spectrometry. At ANSTO, radiocarbon activities were determined on graphite targets using the 2MV tandetron accelerator STAR and reported as percent Modern Carbon (pMC) (Fink et al. 2004). This involves normalisation of $^{14}C/^{12}C$ ratios to ^{14}C activities, assuming $\delta^{13}C$ values of dissolved inorganic carbon (DIC) of −25‰ (e.g., Plummer and Glynn, 2013). The radiocarbon activities had a range of 1σ errors between 0.03 and 0.4.

3.4. Recharge estimation

3.4.1. Chloride mass balance

The concentration of chloride in rainfall was measured directly on 3 occasions in 2017, by collecting water in the rain-gauge following precipitation events of different sizes. Chloride concentrations ranged from 7.1 to 15.0 mg/L with a mean of 11.7 mg/L. This compares to a long-term study completed by Crosbie et al. (2012) in which monthly rainwater samples for more than four years were analysed in Melbourne, resulting in a weighted average of 5.4 mg/L. The higher concentrations observed in this study are attributed to the closer proximity to the coastline – the sampling station was located 9km from the coast, while that in Crosbie et al. (2012) was located approximately 20 km from the coast. This is line with a study of variation of chloride in precipitation with distance from the southern coast of Australia (Bresciani et al. 2014), which observed a decline from approximately 30 mg/L near the coast to approximately 16 mg/L at a distance 7 km inland (on non-vegetated land).

The average concentration of chloride in rainfall and in sampled groundwater from the bores were used to estimate recharge using the steady state chloride mass balance method (CMB), as described by Crosbie et al. (2010) – Eq. (2):

$$R = \frac{P \times Cl_p}{Cl_{gw}} \tag{2}$$

where R =recharge (mm/yr), P = rainfall precipitation (mm/yr), Cl_p =chloride concentration in rainfall (mg/L) and Cl_{gw} = chloride concentration in groundwater (mg/L).

It is acknowledged that this method provides an indication of longterm average recharge by vertical percolation, assuming steady-state hydrological conditions (which may over-simplify recharge processes in the catchment). Additionally, chloride deposition is known to be spatially variable, and may be significantly impacted by vegetation, which tends to increase deposition (Bresciani et al., 2014). This in turn could lead to calculated recharge rates that under-estimate true values. In the study area, vegetation is relatively sparse and has been for the past five or more decades, due to the high utilization of land for agriculture.

This method was applied to all bores constructed and sampled during the study (n = 14), in some cases on multiple dates, as well as data collated from government monitoring bores contained in the Victorian Water Measurement Information System (DELWP, 2017). A full download of this database was completed and 1975 bores containing water quality information were identified across the Western Port Basin. This was further refined to a subset of 168 bores with at least one full set of major ion data (including chloride). A 2 km buffer beyond the study area was applied to extend the data coverage. Where multiple concentrations of chloride were recorded at a bore at different times, the most recent value was used. These data were then converted into a map of CMB-based recharge estimates using ordinary point kriging.

3.4.2. Water table fluctuation

Monitoring bores screened across the water table which showed response(s) to rainfall events were selected for recharge estimation, according to Eq. (3) (Healy and Cook, 2002):

$$R = \frac{S_y \times \Delta h}{\Delta t} \quad (3)$$

where R =recharge, S_y= specific yield, Δh change in water level and Δt is the time period.

The change in water level, Δh, is the change specifically related to a rainfall event (or alternatively, the rainfall within a season) and accounts for the underlying natural recession in water level trends (Cuthbert, 2014). In some instances, the unsaturated zone thickness meant that that this technique was not appropriate for recharge estimation (Healy and Cook, 2002), due the significant lag time between rainfall and a water table response. One site (BH3D) was also excluded from analysis using this method as the hydrograph indicated influence from nearby groundwater pumping.

4. Results

4.1. Lithology and updated hydrogeological conceptualisation

Figs. 6 and 7 show groundwater elevations in the uppermost (unconfined) aquifer collected in 2016 along with mapping and interpolation of the extent and thickness of the Older Volcanics basalt and clay, based on the drilling results and existing lithology data (e.g. Appendix A). A revised conceptual model of the hydrogeology was developed on this basis, providing important constraints on the likely locations(s) of groundwater recharge (Fig. 7). Key aspects of this model are:

- The Older Volcanics are widespread in the central and eastern part of the study area where they sub-crop extensively, but absent along the western margin near the catchment divide. This unit forms the uppermost (unconfined) aquifer over most of the study area, except for a small area in the southwest (Fig. 6; Fig. 7).
- Where the Older Volcanics unit sub-crops, it is extremely weathered to clay with no rock fabric visible, typically for the top ~10 m. Below this depth, the Oder Volcanics transitions to moderately weathered to fresh basalt.
- Along the (western) margin of the catchment, Quaternary sand and clay outcrop and directly overlie the Childers Formation or Silurian siltstone. The Baxter Formation (Tbm), which appears on geological maps of the study area and overlies the Older Volcanics to the east (Lakey and Tickell, 1980) was not encountered during drilling.
- Groundwater flow is east to south-easterly and is driven by the topographic high along the margin of the catchment (Fig. 2; Fig. 6). The topography peaks locally at approximately 100 mAHD at the Cranbourne Royal Botanic Garden (Fig. 7).
- Upward vertical hydraulic gradients from the Childers Formation to the overlying Older Volcanics were observed at three nested bore locations; the Childers aquifer is thus confined by the overlying Older Volcanics.
- A downward vertical hydraulic gradient was encountered at BH2, the only nested site where both bores are screened in the Older Volcanics. This indicates potential for recharge via vertical percolation. The Older Volcanics is particularly thick (> 49 m) at this location.

4.2. Radiogenic isotopes

Tritium concentrations varied significantly across the study area (Fig. 8), with concentrations up to 2.40 TU and seven samples below the detection limit. The mean concentration of eight samples with detectable tritium was 1.50 TU. The presence of tritium indicates a component of 'modern' water in an aquifer, where modern is defined as recharge having occurred within approximately the last 50 years (Jasechko, 2016). Tritium occurs in the atmosphere and rainfall due to background cosmogenic production, however nuclear weapons testing during the 1950s and 1960s resulted in elevated concentrations in groundwater recharged since approximately 1960 worldwide (more pronounced in the northern than southern hemisphere). Concentrations in rainfall peaked in Australia in 1963 at approximately 160 TU and have since declined - the current concentration in Melbourne rainfall is approximately 3 TU, representing ambient background with minimal residual effect from the nuclear testing (Tadros et al., 2014). Given tritium's half-life (12.3 years), groundwater with a significant component of recharge from the past one to two decades should contain concentrations between approximately 0.5 to 2.5 TU. Groundwater recharged during the early 1960 s would also be expected to contain similar concentrations, following radioactive decay of tritium in rainfall from its peak level during this era.

Radiocarbon activities ranged from 14.77 to 100.8 pMC. Radiocarbon activity in groundwater reflects input from the atmosphere and soil gas CO_2 incorporated into the dissolved inorganic carbon (DIC) of recharging groundwater. Incorporation of water recharged during the 'bomb pulse' of the 1960s can result in elevated activities (> 100 pMC), while dilution of ^{14}C-active DIC with 'dead' carbon from the aquifer matrix leads to decreasing activities. Typically, in siliciclastic aquifers, radiocarbon activities above 90 pMC reflect a significant component of 'modern' recharge, i.e., water infiltrated since

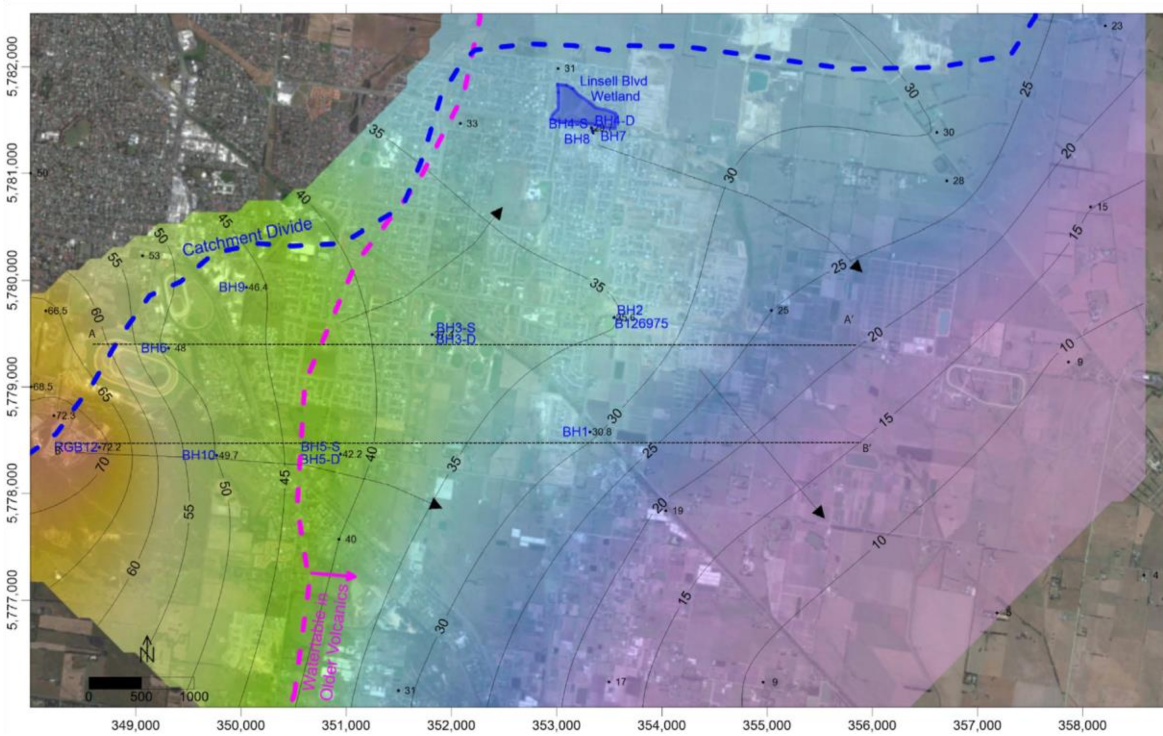

Fig. 6. Location of new bores installed or actively monitored for this study (blue labels) with groundwater elevation contours for the unconfined aquifer, as of 2016 (black labels) and location of cross sections (Fig. 7). Background image: Google Earth, 2017. Grid labels represent Eastings and Northings in Map Grid of Australia 1994. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the 1950s.

Most bores with tritium concentrations above 0.5 TU also contained radiocarbon activities between 85 and 101 pMC, consistent with a significant fraction of recent recharge. These bores are mostly located within approximately 1 km of the catchment divide and exhibited low groundwater salinities (EC < 600 µS/cm). As a general principle, groundwater in semi-arid areas with relatively high recharge rates typically contains relatively low salinities, as recharge from rainfall percolation is inversely proportional to evapotranspiration, which concentrates the residual solutes (Herczeg et al, 2001). Most samples with relatively low (or no detectable) tritium were also more saline (e.g. EC > 1500 µS/cm; Fig. 8), consistent with lower recharge rates and higher ET. In bores with relatively saline groundwater but measurable tritium, i.e., where there is evidence of recent recharge (e.g. BH4S), this may indicate an increase from historically low recharge rates to higher modern rates. Samples with low salinity as well as low ^{3}H and ^{14}C activities (such as at BH3D and BH4D) are interpreted as reflecting premodern recharge at significant rates elsewhere in the catchment (e.g., further up-gradient), which has not undergone further salinization (e.g. due to inter-aquifer mixing) during subsequent transit in the aquifer, on timescales of thousands of years.

4.3. Soil moisture profiles

Soil moisture was monitored at two locations in weathered Older Volcanics soils, and typically showed rapid changes at shallow depths in response to rainfall but limited or no response at deeper levels (Fig. 9). For example, the soil moisture at 0.3 m depth near BH4 fluctuated significantly following precipitation events (particularly during the latter part of the monitoring period). The magnitude of change in soil moisture following rainfall appeared to increase in the later months of 2016 and early 2017 (summer) as shallow soils dried out in the hotter weather, and with relatively longer periods between rainfall events. This potentially reflects a greater degree of shallow infiltration via macro-pores in the dry soils.

Soil moisture at intermediate depths (e.g. 0.9 m) showed only minor fluctuations in response to rainfall throughout the monitored period, although a significant rainfall event in December 2016 appeared to trigger a response at this depth. This may indicate soil moisture at this depth only becomes responsive to rainfall after development of cracks during summer and/or when a threshold rainfall event size is exceeded. Below 1 m depth, no significant fluctuation in soil moisture were recorded over the monitored period. Coupled with upward potential gradients (increasing soil saturation with depth), this indicates little or no recharge via vertical percolation at the monitored localities. Most rainfall is thus likely consumed by upwards flux via evapotranspiration; although, a component of bypass flow cannot be ruled out. Groundwater in BH4S shows a rapid, measurable recharge response to rainfall events (Fig. S1), interpreted as reflecting horizontal flow of water from a new constructed wetland adjacent to the bore, providing a mechanism of 'bypass' flow to the water table, as vertical percolation is not observed in the soil moisture profile (further detail regarding this mechanism is outlined in Hall, 2018).

A similar pattern of soil moisture variation with depth was observed at the second monitored profile (near BH2), with little or no fluctuation observed in response to any rainfall events at 1.5 m depth. At this site, the unsaturated zone is thicker than 10 m and composed of volcanic clay, and as such, the soil moisture data again indicate minimal potential for recharge via vertical percolation. This is consistent with high groundwater salinity in BH2 (EC of >10,000 µS/cm), likely corresponding to a high rate of evapotranspiration, at the expense of potential recharge. The presence of detectable tritium (0.06 TU) in this groundwater does indicate a very small component of recharge since the 1960s; this may represent input of recharge at very low rates over recent decades.

4.4. Recharge estimation

4.4.1. Water table fluctuation

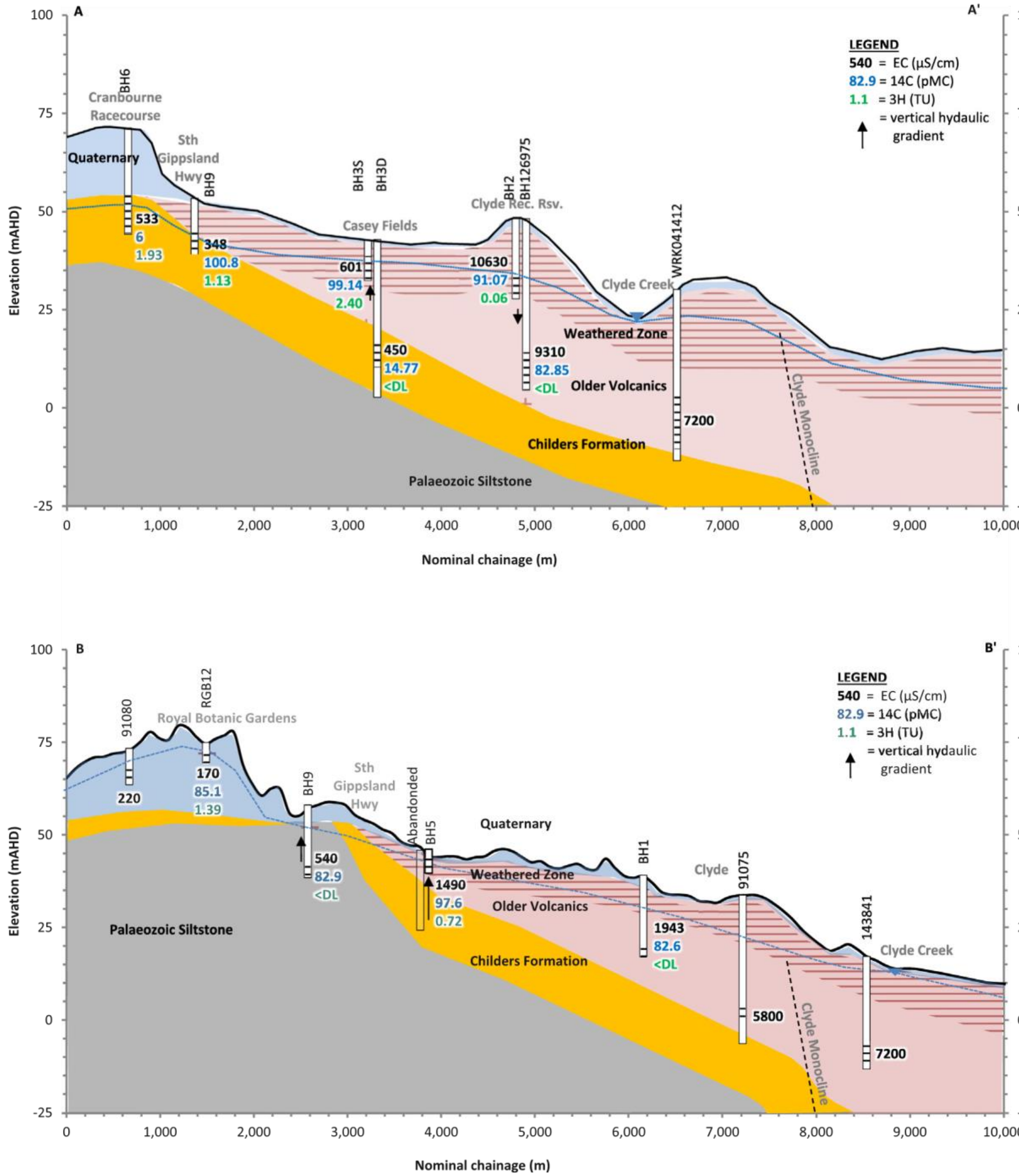

Fig. 7. Cross-sections A-A′ and B-B′ with groundwater electrical conductivity, interpreted geology and radio-isotope data. Refer to Fig. 6 for cross-section locations and Table 1 for isotope data. Note that the profiles do not intersect the highest point in the local topography, which is approximately 100 mAHD.

Groundwater levels showed a variety of responses to rainfall events and seasonal climate fluctuations across the study area. Three bores located near the western edge (BH5, BH10 and RBG12) showed significant responses to rainfall (Fig. S1), allowing for recharge estimation using the WTF method. Two of these hydrographs (BH10 and RBG12) showed water level responses sensitive to individual rain events (e.g., sharp increases within one day of rainfall), while BH5 showed a seasonal relationship, i.e., an overall rise in winter and fall in summer. The responses in these bores met the conditions considered acceptable for applying the water table fluctuation method (Healy and Cook, 2002), resulting in recharge rates between 12 and 133 mm/year (Table 2). The highest rates were calculated in RBG12 and BH10, which are located near the topographic high at the edge of the catchment, where volcanic clay is absent from the soil and lithological profile (Fig. 7). The WTF method was also applied to other monitored bores in the study area; however, the results should be viewed as having significant uncertainty, due to various limitations in the data (as explained in Table 2).

Overall, estimated recharge rates using the water table fluctuation method for bores screened in the Older Volcanics were relatively low, but not insignificant (e.g., <20 mm/yr). Exceptions to this were the high estimated rates for three bores located near the constructed wetland mentioned above (BH4, BH7 and BH8), which were installed for the purpose of investigating the wetland's interaction with groundwater. Of these three bores, estimated recharge is highest closest to the wetland (BH4). As described in Section 4.3, soil moisture profiles at this location (Fig. 9) showed no evidence of downward percolation of rainfall, and thus another mechanism – e.g., horizontal flux from the wetland – is interpreted as being responsible. This is discussed further in Hall (2018) and is not examined in detail here.

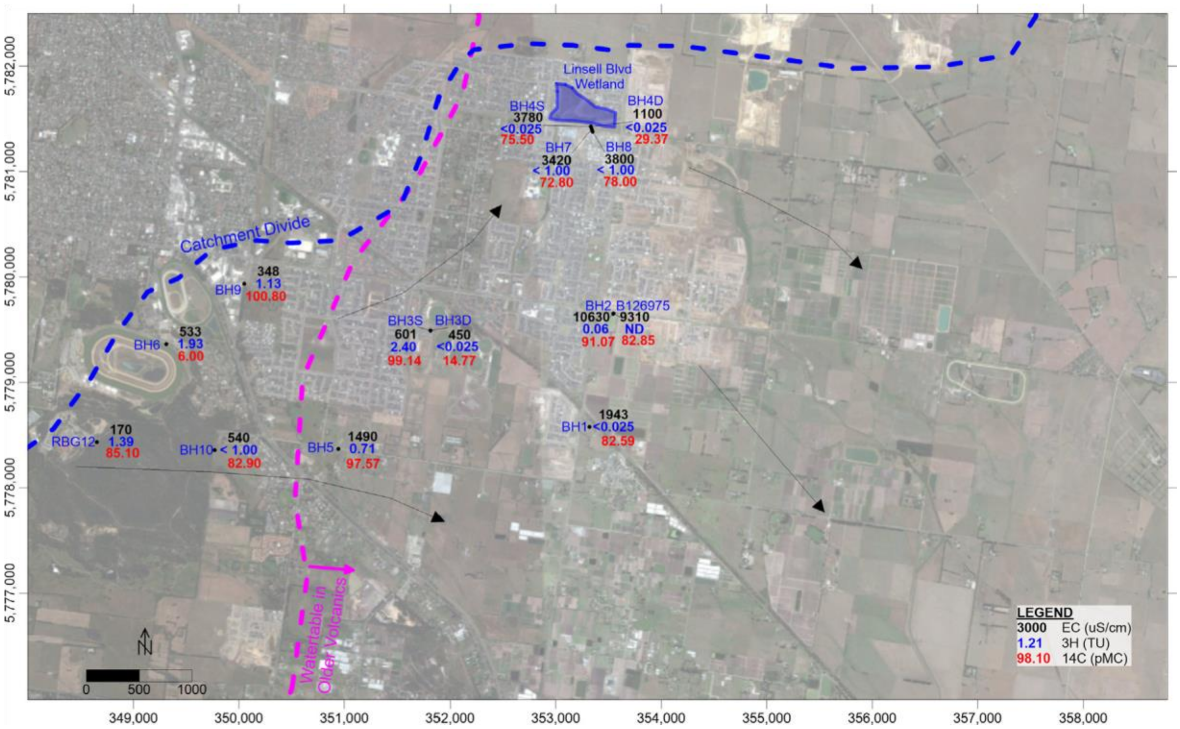

Fig. 8. Distribution of groundwater EC, ^{3}H and ^{14}C across the study area. Groundwater flow direction, catchment divide and extent of the unconfined Older Volcanics aquifer are indicated, as in previous maps.

4.4.2. Chloride mass balance

Recharge rates from the bores drilled for this study calculated using the chloride mass balance (CMB) method ranged from 1.5 to 136 mm/ year (Table 3), somewhat consistent with the rates determined using WTF. The highest rates occurred in groundwater in the Quaternary sediments and Childers Formation (22–136 mm/yr) near the western edge of the basin, with lower rates typically observed in the Older Volcanics (median =5.1 mm/year). The CMB method was further applied to historical data from across the study area (n =162) to improve the spatial coverage of recharge estimates (Fig. 10; Table 3). The estimated rates are highest (50–200 mm/year) in a restricted area extending east from the Cranbourne Royal Botanic Garden where the Quaternary sediments directly overlie the Childers Formation (i.e., the Older Volcanics are absent; Fig. 10). Recharge rates of less than 50 mm/ year occur above the Older Volcanics along the western margin of the basin, declining eastwards to less than 10 mm/year (Fig. 10).

Table 1
Radioisotope data and distance of sampling location from the Western Port Basin catchment divide. Aquifer codes: OV (Older Volcanics), wOV (weathered Older Volcanics), CF (Childers Formation); SST (Silurian Siltstone); ND (no data).

Bore ID	Distance from divide (m)	Aquifer	Tritium (TU)	^{14}C DIC pMC
BH1	2700	OV	< 0.03	82.59
BH2	2200	OV	0.06	91.07
B126975	2200	OV	< 0.03	82.85
BH3-S	1100	wOV	2.40	99.14
BH3-D	1100	CF	< 0.03	14.77
BH4S	500	wOV	< 0.03	75.50
BH4S	500	wOV	2.29	98.30
BH4-D	500	CF	< 0.03	29.37
BH5	2000	wOV	0.72	97.57
BH6	150	Qa/CF	1.93	ND
BH7	500	wOV	< 1.00	72.80
BH8	500	wOV	< 1.00	78.00
BH9	400	CF	1.13	100.80
BH10	1100	SST	< 1.00	82.90
RBG12	0	QA	1.39	85.10
Wetland	500	–	2.09	–

5. Discussion

5.1. Recharge rates: spatial variation and relationship to key controls

While our data provide some support to previous conceptualisations of recharge in the Western Port Basin (i.e., that active recharge occurs within the studied area), they provide significant refinement regarding the spatial distribution, rates and lithological controls on recharge.

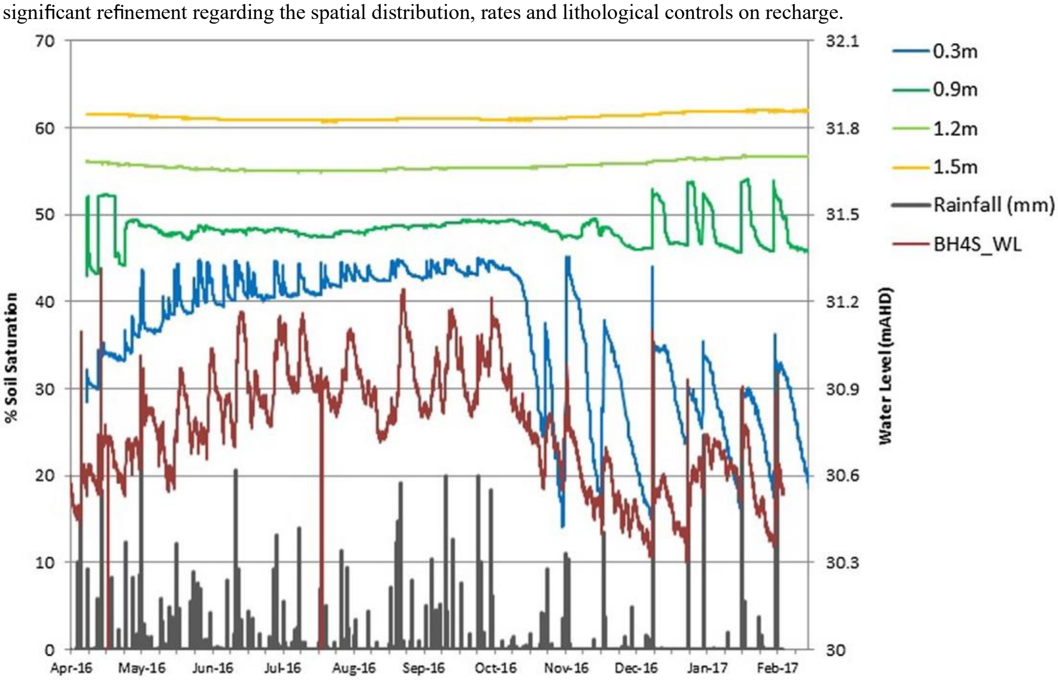

Fig. 9. Soil moisture time series from a vertical profile installed near BH4 along with rainfall and shallow groundwater level. Note that the record at 0.6 m depth was removed, due to a logger fault.

In areas where the Older Volcanics outcrop or sub-crop, recharge is limited (1.5–50 mm/year with a median of approximately 5 mm/year). Such rates may still be considered significant in the context of generally low recharge rates over much of the Australian continent (Crosbie et al., 2012); however, they are low compared to the rates estimated elsewhere in the catchment (e.g., where the volcanics are absent), and lower than previous estimates of recharge in the catchment based on numerical modelling (Longley et al., 1978) and other techniques (e.g. seasonal water level fluctuation analysis; Lakey, 1980). The general absence of detectable tritium in most of the shallow Older Volcanics monitoring bores (Table 1) confirms that recent recharge to this unit is limited, while the two localities where soil moisture profiles were recorded – both within volcanic clay – also indicated minimal vertical propagation of water occurring below the root zone. Recharge occurs at significantly higher rates (up to 220 mm/year) on Quaternary sand at

Table 2
Table 3
Estimated recharge rates (based on chloride mass balance – CMB) in bores drilled and sampled in this study. DtW =Depth to Water (m below ground level).

Bore ID	Lithology	DtW (mbgl)	CMB recharge	
			mm/yr	% rainfall
BH 2	wOV	14	1.5	0.2%
B 126975	OV	15	1.8	0.2%
BH 7	wOV	3	4.8	0.6%
BH 8	wOV	3	4.9	0.6%
BH4S (2014)	wOV	3	5.1	0.7%
BH 1	OV	6	11.3	1.3%
BH 5	wOV	2	14.1	1.4%
BH 4D	Childers Fm	3	22.1	2.7%
BH 10	Siltstone	2	41.1	5.3%
BH3-S	wOV	5	47.4	4.5%
BH 6	QA/Childers Fm	22	50.6	6.5%
BH 9	Childers Fm	10	60.3	7.7%
BH 4S (2016)	wOV	3	80.9	10.4%
RBG 12	QA	2	120.7	15.5%
BH 3D	Childers Fm	6	135.9	8.3%

the topographically elevated margin of the basin, as shown by both WTF and chloride mass balance estimates, which are broadly consistent (Tables 2 and 3).

This finding has important implications regarding the influence of urbanisation on groundwater in the study area. Much of the land currently being re-developed from agricultural to urban uses is located above the outcrop/sub-crop of the Older Volcanics, in the northern and western parts of the study area (Fig. 3). Given that our data indicate relatively minor recharge occurring via direct infiltration in this area, the influence of land-use change on the underlying groundwater system is likely to be relatively limited – at least in terms of recharge (e.g. Fig. 1). This finding runs counter to the hypothesis that urbanisation will result in significant changes to recharge rates in the area, due to significant modifications to the land-surface and water budget during urbanisation. Our findings are also somewhat contrary to previous modelling studies of the region (e.g. Longley et al., 1978), which hypothesised higher rates of recharge in this zone.

Based on the mapping of recharge rates derived from chloride mass balance calculations, approximately 48% of the total estimated recharge in the study area falls over approximately 15% of the land surface (the area enclosed by the contour where recharge is estimated to be > 50 mm/year). Approximately 20% of recharge occurs over just 3% of the land area, on the southwest margin of the study area

Estimates of recharge based on Watertable Fluctuation Method (QA =Quaternary, wOV= weathered Older Volcanics, NA =not applicable where aquifer is confined). DTW =Depth to Water (m Below Ground Level); WTF =Water table fluctuation-based recharge (Healy and Cook, 2002). Bore locations shown on Fig. 6.

Bore ID	Lithology	DtW (mbgl)	WTF		Comments
			mm/yr	% rainfall	
BH 1	OV	6	< 10	< 3	Minor seasonal response of water levels to rainfall but interrupted logger recording. Difficulty completing reliable analysis.
BH 2	wOV	14	NA	NA	Hydrograph did not exhibit sufficient response to daily or seasonal rainfall. Consistent with soil moisture data at this location.
BH 3S	wOV	5	5–12	0.6–1.6%	
BH 4S	wOV	3	80–200	10–25%	Other data (EC, soil moisture, isotopes) indicate that recharge is from periodic leakage from new constructed wetland, not vertical rainfall infiltration.
BH 5	wOV	2	12–16	1.5–2.1%	Seasonal water level response to rainfall
BH 6	QA/Childers Fm	22	40–120	5–15%	Data reliability low due to deep water table and short duration time series
BH 7	wOV	3	32–112	4–14%	Clear water table response for larger rainfall events (> 20 mm); likely influence from nearby wetland.
BH 8	wOV	3	16–72	2–9%	Clear water table response for larger rainfall events (> 20 mm); likely influence from nearby wetland.
BH 9	Childers Fm	10	NA	NA	Bore is screen in Childers Formation water table. However, no response in water level to rainfall events with overlying unsaturated Older Volcanics acting as confining layer.
BH 10	Siltstone	2	16–112	2–14%	Clear water table response for larger rainfall events (> 20 mm)
RBG 12	QA	2	70–133	9–17%	Clear water table response to rainfall events.

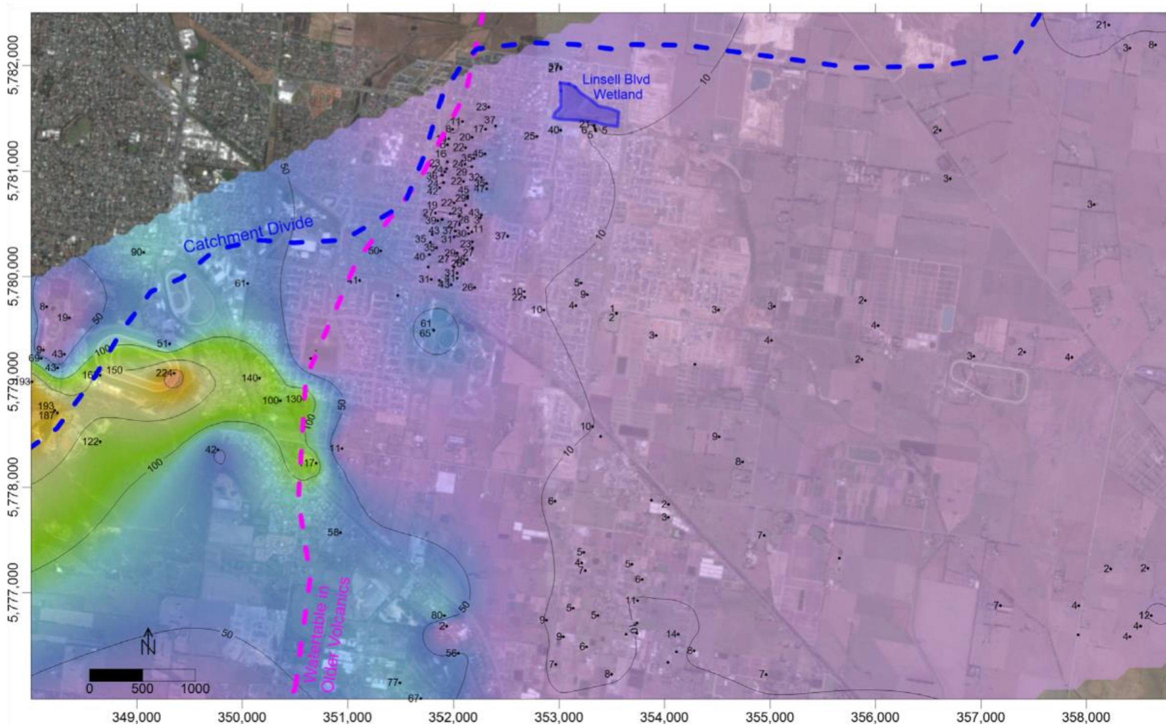

Fig. 10. Chloride mass-balance derived estimates of recharge (mm/yr) across the study area. Limit of the Older Volcanics is also shown (pink line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 10). These elevated recharge rates are consistent with WTF-based estimates and other lines of evidence (high tritium and radiocarbon activity; low groundwater salinity), indicating that this restricted geographic area is critical for providing recharge to the basin. The geology of this region is different to most of the study area, being composed of coarse-grained Quaternary sands with minor organic matter, overlying the Childers Formation. i.e., the Older Volcanics are absent.

Groundwater recharged in this area flows to the east (Fig. 6), where it is thought to replenish the important water supply aquifers of the Western Port Group (Baxter and Sherwood Formations) via vertical leakage (Lakey and Tickell, 1981). The Childers Formation may also provide some recharge to the overlying Older Volcanics aquifer east of the recharge areas(s), because hydraulic gradients are typically upwards in the nested bores monitoring these two units. However, the contribution of vertical leakage to the volcanics appears to be limited, possibly due to the presence of confining clays at the base of the basalts. Both salinity and radio-isotope data show that groundwater compositions in the two units are distinct, indicating that such leakage is not extensive (e.g., Table 1).

5.2. Implications for land and water management

The findings of this study have important implications for future management of land and water in the catchment, and for other similar areas experiencing urbanisation. Land use is rapidly changing, with agricultural land being replaced by residential sub-divisions (Section 2.3; Fig. 3). The construction of new suburbs involves earthworks which grade and compact soils and excavate them for the installation of underground pipes, construction of roads, pavements and dwellings. Likely associated hydrological effects include the reduction of open areas with opportunity for diffuse recharge, the introduction of new water sources from outside the catchment (e.g., through delivery of pressurised mains water), and more rapid channelling of rainfall runoff to specific points in the landscape, and ultimately out of the catchment via stormwater drainage networks, for flood protection (e.g. Lerner, 2002; USGS, 2015).

These modifications are likely to result in a shift from more diffuse recharge to more focussed sources of recharge, e.g. below leaking infrastructure such as mains and sewer pipes (Lerner, 2002) and/or below constructed wetlands, where storm runoff is channelled (this appears to be indicated by our data; but is not examined in further detail here). Concerns over the possible effect of urbanisation on recharge quantity in the study area appear not to be well-founded, as recharge appears to be inherently limited by the geology in most of the areas undergoing urbanisation (above the Older Volcanics). This underscores the importance of collecting direct observation data to map recharge rates and determine its variability and relationship to underlying geological and soil properties, as opposed to estimation based on catchment-wide water balances or numerical model calibration. In particular, the study illustrates the importance of considering spatial variation in recharge, as distinct from assuming recharge comprises (for example) a uniform proportion of rainfall. The use of multiple qualitative and quantitative recharge estimation techniques is valuable in this regard. Through this approach, more targeted approaches to land and water management can be developed in the face of rapidly changing landscapes, e.g., strategic protection of key areas where conditions favour high quality and/or quantity of recharge.

The highest rates of groundwater recharge in the study area – identified using tritium, radiocarbon and salinity data, and then quantified using chloride mass balance and water table fluctuations are associated with a small geographic area with specific geological characteristics (presence of sand and absence of clay), that are favourable for rapid sub-surface infiltration. As discussed above, this area accounts for approximately half of the recharge volume in the study area. Similar findings have been reported in other settings, where recharge 'windows' providing a disproportionate amount of overall recharge to an aquifer system have been identified, using environmental tracer data (e.g. Meredith et al., 2012).

Protection of the quality and quantity of sub-surface infiltration occurring in such areas – for example, by prohibiting activities that may introduce pollutants or compromise soil infiltration capacity – is one potential strategy by which groundwater quality and quantity can be maximised and maintained in the face of rapidly changing land-use. The land where the highest recharge rates occur in the study area is currently part of a protected reserve, associated with the Cranbourne Royal

Botanic Garden. As such, land-uses (such as suburban development), which may alter recharge rates or introduce contaminants, are currently prohibited. Maintaining this protection status is one relatively simple strategy by which the recharge rates and quality entering the Western Port Basin's aquifers can be maintained over the long-term, even as the catchment experiences significant hydrological changes.

5.3. Limitations and uncertainties

One of the primary limitations in our study – and one which is likely to be applicable in similar cases – is the absence of data regarding recharge under completely pre-urban conditions in the catchment. Determining the impact of urbanisation on recharge is therefore somewhat confounded by the fact that urban infrastructure is already having some influence on recharge, and the data collected therefore do not represent a true pre-development 'baseline'. Nonetheless, some of the data – e.g. radioisotopes and chloride in groundwater – do provide a relatively robust indication of recharge processes on timescales likely to predominantly reflect pre-urbanisation conditions (e.g., decades). Chloride mass balance is a technique which time-integrates recharge over many years (e.g. Allison and Hughes, 1983) and it is thus suitable for assessing averaged recharge rates over such timescales. Given that urban development in the area is mostly very recent, we believe the chloride-based estimates predominantly reflect pre-urbanisation recharge rates. This contrasts with other techniques such as water-table fluctuation or soil moisture monitoring, which effectively have no 'memory' and only indicate recharge under current, monitored conditions.

A further potential limitation in our study is the lack of surface water monitoring (which typically helps to constrain catchment water balances and improve recharge estimates). However, within the study area, the single major natural surface water body (Clyde Creek) is ephemeral, only containing water immediately following high rainfall events. Monitoring these flows is difficult in practice and would likely provide limited additional precision in estimates of groundwater recharge (in the absence of accurate estimates of ET).

6. Conclusions and implications

This study highlights the value of collecting a variety of independent field data to substantiate and refine conceptual models and quantify groundwater recharge. Without such data, mapping and analysis, the spatial dependencies and key factors controlling recharge would be difficult to determine, leading to uncertainty with respect to how future water budgets and water quality may change as land-use change (e.g., urbanisation) takes place. Using alternative techniques such as water balance analysis or numerical modelling without such field data, would be unlikely to provide the level of local detail about recharge rates, mechanisms and its controlling factors. For example, our data and findings allowed for a more refined understanding of the locations and rates of groundwater recharge in the study area, which in some cases, contradict previous modelling. Such detailed information is required to make planning decisions that optimise the potential quantities and quality of recharge during and following land-use change.

The findings have significant implications for future management of land and water in the study area, and urbanising catchments more generally. Our data provide evidence that a relatively small area provides a disproportionate amount of the water ultimately recharging the aquifers of the basin. The primary factor governing this is the surface and shallow geology, which exhibits local variation that is significant in terms of controlling recharge rates and volumes for the wider catchment. This underscores the importance and value of maintaining strict land-use control policies within this area – much like 'wellhead protection zones' enacted in north America to protect the quality of groundwater reaching municipal supply wells.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https:// doi.org/10.1016/j.jhydrol.2019.124265.

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