Water isotope characteristics of a flood: Brisbane River, Australia

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Keywords: deuterium, d18O, storm, nutrients, sediment, floodwater
Water isotope characteristics of a flood: Brisbane River, Australia

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Abstract

Flooding associated with tropical storms can cause extreme perturbations in riverine and coastal ecosystems. Measuring isotope variability of tropical storm events can help investigate the impacts of flooding. We measured the water isotope composition ($\delta$D and $\delta^{18}$O) of rain and associated floodwater collected during two storms and subsequent major and minor flooding events in the subtropical coast of eastern Australia. Compared to baseline regional rainfall isotope values of $-15.0 \pm 1.9\%$ for $\delta$D and $-3.3 \pm 0.2\%$ for $\delta^{18}$O, floodwater had lower values with $-33.8 \pm 2.5\%$ $\delta$D and $-5.1 \pm 0.4\%$ $\delta^{18}$O for the major flood and $-29.4 \pm 1.0\%$ $\delta$D and $-4.6 \pm 0.1\%$ $\delta^{18}$O for the minor flood. The low isotope composition of the floodwater was associated with the transport of large quantities of suspended sediments, with sediment loads 30 to 70 times larger than during base flow conditions. Floods carried up to 35% of the annual phosphorus and up to 208% of the currently calculated average annual nitrogen load of the Brisbane River. The dramatic changes caused by a rapid increase in discharge from 2 to 2,015 m$^3$ s$^{-1}$ over two days in the major flood would have major consequences in riverine and coastal ecosystems of the region. These changes could potentially be traced using the isotope composition of the floodwaters.

Keywords: deuterium; $\delta^{18}$O; storm; nutrients; suspended sediment; floodwater
**Introduction**

The hydrogen and oxygen isotope compositions of water ($\delta D$, deuterium, and $\delta ^{18}O$) have long been used to study hydrological and climatological processes (Gat, 1996). More recently, the use of $\delta D$ and $\delta ^{18}O$ has expanded in many areas. For instance, water isotopes have been used to assess sources of water for plants (Dawson et al., 2002) and to detect migration patterns of birds in North America (Hobson and Wassenaar, 1997). Water isotopes have also been used in forensics to uncover, for example, the place of origin of illegally hunted wildlife (Bowen et al., 2005), or to trace the place of origin of a commercial product, such as milk (Ehtesham et al., 2013). There is great potential for future use of $\delta D$ and $\delta ^{18}O$ in the many fields where water is the underlying driver of change.

Hydrological, ecological and forensic studies have benefited from long-term programs that monitor isotope variation in precipitation around the world (e.g. Global Network for Isotopes in Precipitation, GNIP) and produce gridded datasets (Bowen, 2014). However, in some locations, the isotope datasets have low spatial resolution, and the temporal sampling is too coarse (e.g. monthly sampling) to detect isotope variations that occur within a relatively short period of time (e.g. days), such as during storms (Araguás-Araguás et al., 2000). Storms have been recognized as the most important factor affecting isotope variability within precipitation of tropical regions (Kurita et al., 2009; Lachniet and Patterson 2009). Therefore, it is of strong interest to measure isotope variability during short-lasting, but powerful storm events that could explain the long-term rainfall isotope variability within the tropics.

The atmospheric moisture during tropical storms has a specific isotope composition with very low $\delta D$ and $\delta ^{18}O$ values that cannot be fully explained by usual assumptions of precipitation and temperature (Gat, 1996). The distinctive isotope composition of tropical
storms causes deviations of the seasonal isotope composition of rainfall. For example, in
southwest Australia, aseasonal strong rainfall events have an isotope composition significantly
lower than the annual minimum (Turner et al., 1987). Tropical storms in Central Amazon have
δ\textsuperscript{18}O values approaching -10‰ (Matsui et al., 1983), much lower than the annual range of
values of -2 to 2‰. Similarly, water isotope values near -6.5‰ for δ\textsuperscript{18}O have been measured
during tropical storms and low-pressure systems in Puerto Rico; these values are lower than
the annual range of 0 to -3‰ (Scholl et al., 2009). These low values have been explained by
the so-called “amount effect” with lower values associated with higher rainfall amounts
(Dansgaard, 1964), and more recently, by cloud altitude and atmospheric condensation
temperature (Scholl et al., 2009). The characteristic isotope composition of rainfall during
storms generates an almost immediate response in the isotope composition of the river flow
(Turner et al., 1987). However, there are only a handful of published studies that provide
values of water isotopes of rainfall during tropical storms and none, as far as we know, for
floodwaters. In this study, we provide the water isotope composition (δD and δ\textsuperscript{18}O) of rain and
associated floodwater collected during two storms and subsequent floods in the subtropical
coast of eastern Australia.

Floods can move large amount of nutrients and sediments into riverine and coastal
ecosystems (Mitchell et al., 1997). Large nutrient and sediment loads can cause cyanobacterial
blooms, hypoxia, seagrass loss and coral reef degradation (Hallock and Schlager, 1996;
Campbell and McKenzie, 2004; Paerl, 2008). In this study, we augment information about the
isotope values of rain and floodwater with the physicochemical measurements of the
floodwater, including nutrient and sediment loads. This information could be used in ecological
studies in riverine and coastal ecosystems that use the isotopic composition of water to trace
the impacts of flooding.
Methods

Study Area

Samples were collected in the Brisbane River catchment in Southeast Queensland, Australia (Fig. 1). The region is classified as subtropical, experiencing moderate temperatures year round, with a mean annual maximum temperature of 25.4°C and a mean annual minimum of 15.7 °C (Australian Bureau of Meteorology, ABM 1951–2000). The climate is characterized by a moderately cold and dry winter with an average total rainfall of 64 mm and monthly mean temperature of 22.3°C (June to August), and a hot and wet summer with a total rainfall of 597 mm and a monthly mean temperature of 30.0°C (December to February). The hottest month is January with a monthly mean of 30.2°C and the coldest months are June and July, both with a monthly mean of 21.9 °C. The average total annual rainfall for the region is 1,186 mm (ABM, Brisbane Station, 1999–2015 for temperature and 1951–2000 for rainfall).

The Brisbane River is 344 km long with a catchment area of 12,643 km² (Ozcoasts, 2015). The mean, minimum and maximum monthly discharge rates from the Brisbane River are 26, 7 and 122 m³ s⁻¹, respectively (State of Queensland, Department of Natural Resources and Mines, DERM, Station 143001C, Brisbane River at Savages Crossing, 1958-2015). The River has a 100-year recurrence interval flood (Q₁₀₀) of 16,437 m³ s⁻¹ (Shellberg and Brooks, 2007). The Brisbane River can be classified as hydrologically extreme with extreme flash flood behaviour and large annual variability in peak discharge (coefficient of variation of annual volume = 113%; Shellberg and Brooks, 2007). The Brisbane River is dammed by the Wivenhoe Dam, forming Lake Wivenhoe, which is connected and managed conjunctively with Somerset lake, formed by the damming of Stanley River (Fig. 1). The Brisbane River has eight main tributaries: Stanley River, Breakfast Creek, Moggil Creek, Bulimba Creek, Norman...
Creek, Oxley Creek, Bremer River and Lockyer Creek, with the Lockyer Creek joining the Brisbane River downstream of the dam (Fig. 1).

The catchment of the Brisbane River is considered to be in poor health due to agriculture, grazing, water storage and urban development (Healthy Waterways, 2014). Fine suspended sediment load in the Brisbane River is estimated to be around 247 kilotonnes yr\(^{-1}\) (Ozcoasts, 2015). Nutrient loads are estimated at 314 tonnes yr\(^{-1}\) for dissolved phosphorus (P), 1,687 tonnes yr\(^{-1}\) for fine sediment P, 1,686 for dissolved nitrogen (N) and 1,473 tonnes yr\(^{-1}\) for fine sediment N (Ozcoasts, 2015).

Methods

On the 24th of January 2013, tropical storm Oswald crossed the eastern coast of Australia and caused intense rainfall in a short period. In some locations, rainfall in excess of 1,000 mm was measured in 96 hours resulting in moderate to major flooding (ABM, 2013). A historical peak flood of 9 m was reached in the Lockyer Valley at Laidley; the flood wave moved towards the Brisbane River reaching 15 m in the Lockyer Creek (station 143207A, O’Reilleys Weir, Fig. 1) just before discharging into the Brisbane River. The resulting flood wave peaked at 12 m north of Brisbane City (Savages Crossing, Brisbane River station 143001C, Fig. 1), making the flood the 24th highest on record (ABM 2013; DERM). Between February 23th and March 4th, a second strong rainfall event (124 mm in one week) caused some minor flooding. During both floods, stream discharge increased considerably with peaks of 2,405 and 1,880 m\(^3\) s\(^{-1}\) for the first and second flood, respectively (DERM, station 143001C) (Fig. 2B). As part of the flood management, water from Somerset and Wivenhoe dam was systematically released during the flooding episodes (Fig. 2B, Seqwater).
Sampling was conducted within the mid Brisbane River (-27.4929°S, 153.0184°E) from a pontoon (Fig. 1). Rainwater was collected with a two-litre open container on the 27th and 28th of January, 2013. These were the days with the highest recorded rainfall in Brisbane during our sampling with 55 and 145 mm, respectively (ABM, 2013). The container was left 4-5 hours and the water was collected while the rain was falling in order to avoid evaporation. Rainwater was poured in 50 mL plastic containers and kept cool until analysis. Floodwater was collected every 2-3 hours from the river for the first three days of the first flood, then three times a day until the 1st of February. Afterwards, weekly samples were collected until the 19th of February, when daily sampling was resumed for the second flood event (total n = 29). River water was collected in clean 500 mL polyethylene terephthalate (PET) bottles, which were rinsed with surface water twice before sample collection at 20 cm below the water surface.

Conductivity and pH were recorded for each sample using an YSI-meter (Xylem Inc. Ohio, USA). Mean daily conductivity, water temperature, rainfall and river discharge were obtained from DERM (station 143001C, Fig. 1). Additionally, we included information on rainfall and river discharge from sampling stations 143203C and 143207A on Lockyer Creek, the tributary which contributed most to the flooding. Water samples were analysed for total suspended solids, dissolved nutrients (P as orthophosphates, N as nitrous oxides, N-NO₃⁻, and ammonium, NH₄⁺), δD and δ¹⁸O. Total suspended solids (TSS) were calculated by filtering a known volume of water through pre-weighted 47 mm glass microfibre GF/C Whatman filters of 1.2 µm pore size. Nutrients were analysed with EPA methods: 353.2 for NOₓ, 350.1 for NH₄⁺, and OP5A for P (SM-4500). Nutrient analysis detection limits were 0.005 µmol L⁻¹ for P and N-NO₃⁻, and 0.01 µmol L⁻¹ for NH₄⁺. Nutrient loads were estimated from nutrient concentrations and mean river discharge during the flood wave.
For δD and δ\(^{18}\)O analyses, rain and floodwater samples were kept in clean plastic bottles with minimum air space and in cool conditions to avoid evaporation before analysis. The water samples were analysed using a laser-based isotope analyser (LGR, Los Gatos Research, CA, USA). Measurements were calibrated with international standards SMOW, GISP, and SLAP, as well as five manufacture-supplied standards LGR1-LGR5 (Ahmad et al. 2012). The isotope values had errors (SD) < 2.0 ‰ for δD and < 0.3 ‰ for δ\(^{18}\)O. Conductivity was measured for each sample prior to analyses to avoid erratic results due to high salinity. Conductivity readings for all samples were below 1000 µS cm\(^{-1}\) with the majority below 250 µS cm\(^{-1}\), and were thus considered freshwater. Particulate organic matter was filtered out before analyses with nylon syringe filters of 0.22 µm pore size (Livingstone Int., NSW Australia). Liquid organic contamination was possible, although likely to be minor as most of the floodwater is derived from rain (Turner et al., 1987), most pollution from the Brisbane catchment derives from agriculture, not industrial sources (Healthy Waterways, 2014), and the sampling site was upstream of most of metropolitan Brisbane and its waste water discharges. Deuterium excess (d excess) was calculated as: d excess (‰) = δD – 8*δ\(^{18}\)O (Dansgaard, 1964). The d excess is an index of variation from the global meteoric water line (GMWL) and can be used to understand the prevailing conditions during the evolution of air masses as precipitation forms (Froehlich et al., 2002). Averages are reported as mean with standard errors, unless otherwise stated.

Long-term precipitation data for the Brisbane region was obtained from the International Atomic Energy Agency/ Water Resource Program, the Global Network of Isotopes in Precipitation (Brisbane Station, IAEA/WMO, GNIP database 1962-2002, at: http://www.iaea.org/water). From this dataset we calculated the local meteoric water line.
Results

The physicochemical characteristics of the water changed during the floods. During the first and major flood, water temperature decreased from 27.4°C to 23.4°C, after which it stabilized at 24.7 ± 0.1°C (Fig 2C). During this flood, conductivity was low reaching a minimum of 203 µS cm⁻¹, after which it stabilised at 976 ± 30 µS cm⁻¹ (Fig. 2C). Water pH was low in both flooding events, decreasing from ~7.70 during pre-flood conditions to a minimum of 6.24 at the peak of the major flood and to 6.77 at the peak of the minor flood (Fig. 2D).

Floodwater had large amounts of TSS, especially during the major flood when values reached 1.5 g L⁻¹ (pre-flood conditions were < 0.1 g L⁻¹, Ozcoast, 2015). During the minor flood, TSS reached a maximum value of 0.3 g L⁻¹ (Fig. 2E). Total sediment loads were more than double in the major flood with 481,266 tonnes or 28,148 ± 10,689 tonnes d⁻¹ compared to the minor flood, which had 208,795 tonnes or 13,938 ± 3,120 tonnes d⁻¹. The suspended sediment carried by the river during floods was 30 to 70 times larger than during base flow conditions, which is 407 tonnes d⁻¹. The large amount of TSS transported during floods was equivalent to 85-195% of the mean annual discharge estimated for the Brisbane River, which has been estimated to be 247,200 tonnes (Ozcoast, 2015).

Floodwater had high dissolved nutrient concentrations. During the major flood, floodwater had maximum concentrations of 9 µmol L⁻¹ for P, 42 µmol L⁻¹ for N-NO₃⁻ and 16 µmol L⁻¹ for N-NH₄⁺ (Fig 2F). These concentrations are equivalent to 9 ± 2 tonnes d⁻¹ of P, 288 ± 62 tonnes d⁻¹ of N-NO₃⁻ and 21 ± 5 tonnes d⁻¹ of N-NH₄⁺. During the minor flood, only N-NO₃⁻
increased to 28 µmol L\(^{-1}\) (Fig. 2F) with a load of 276 ± 65 tonnes d\(^{-1}\) of N-NO\(_x\)^\(^-\). Nutrient loads during floods, especially during the major flood, were more than 10 times larger than base flow conditions for P and N-NO\(_x\)^\(^-\), and almost 50 times larger for N-NH\(_4\)^\(^+\); base flow values for P, N-NO\(_x\)^\(^-\) and N-NH\(_4\)^\(^+\) are 0.7 ± 0.3, 28.3 ± 10.2 tonnes d\(^{-1}\), and 0.4 ± 0.1 tonnes d\(^{-1}\), respectively.

Thus every flood transports about 110 ± 3 tonnes of P, 3,245 ± 210 tonnes of N-NO\(_x\) and 269 ± 19 tonnes of N-NH\(_4\)^\(^+\). This represents about 35% of the annual P and 208% of the annual N estimated for the Brisbane River (Ozcoasts, 2015).

The water isotope composition varied significantly as floodwater moved through the river (Fig. 2G,H, Table 1). Mean values for the major flood were -33.8 ± 2.5‰ for δ\(^D\) and -5.1± 0.4‰ for δ\(^{18}\)O. Minimum and maximum values at this time were -43.7‰ and -20.3‰ for δ\(^D\) and -6.7‰ and -3.1‰ for δ\(^{18}\)O. There were high δ\(^D\) and δ\(^{18}\)O values at the beginning of the flood and a few days after the flood peak, probably due to water release from the Wivenhoe-Somerset dam (Seqwater, 2013; Fig. 2B). Prior to the flood, lake water in this large reservoir probably had increased δ\(^D\) and δ\(^{18}\)O values due to evaporation as this data fell off the GMWL and the LMWL (black circles, Fig. 3), as expected for evaporated waters. During the minor flood, water isotopic composition was also low, but less than during the major flood. Mean values during the minor flood were -29.4 ± 1.0‰ for δ\(^D\) and -4.6 ± 0.1‰ for δ\(^{18}\)O, with minimum and maximum values of -33.6 and -27.0‰ for δ\(^D\), and -5.3‰ and -4.3‰ for δ\(^{18}\)O. For comparison, mean values for precipitation in Brisbane during January and February are -15.0 ± 1.9‰ for δ\(^D\) and -3.3 ±0.2‰ for δ\(^{18}\)O (Brisbane Station, IAEA/WMO, GNIP 1962-2002).

In a dual isotope diagram, the data collected during this study had a wide range of values (range of 36‰ for δ\(^D\) and 6‰ for δ\(^{18}\)O) and some of the data points from the first day of the major flood deviated from the GMWL and LMWL (grey circles, Fig. 4). The lowest and
highest $d$ excess values were measured during the peak of the major flood and had respective values of 1.6 and 14.5‰ (Fig. 2I). For comparison, mean $d$ excess values for precipitation in Brisbane during January and February are $12.2 \pm 0.5‰$ (Brisbane Station, IAEA/WMO, GNIP 1962-2002).

The isotope composition of rainfall was different between flooding events. During the major flood accompanying the tropical storm, rainfall had a mean $\delta D$ value of $-36.1 \pm 6.3‰$ and a mean $\delta^{18}O$ value of $-5.6 \pm 0.7‰$; during the minor flood, mean rainfall $\delta D$ values were $-18‰$ and rainfall $\delta^{18}O$ values were $-3.8‰$ (Table 1). River values followed the isotope composition of floodwater, indicating that most of the water during the peak flood was rain. The values from the rainfall during the major flood were 20‰ lower for $\delta D$ and 2.3‰ lower for $\delta^{18}O$ compared to the long-term mean values for January and February. The isotopic value of rainfall during the minor flood was similar to the long-term monthly mean.

The historical data (1962-2002, IAEA/WMO, GNIP) shows that most flooding events in the Brisbane region, some of them resulting from tropical storms, are associated to rainfall with low isotope composition (Fig. 4A). Therefore, tropical storms in the region could partly explain the high variability of monthly values of long-term data that has standard deviations of 14.3 for $\delta D$ and 1.7 for $\delta^{18}O$ (Fig. 4B). Overall, there was a long-term trend of low water isotopic composition accompanying high rainfall amounts (Fig. 4C).

Discussion

Floods throughout southeast Australia are major disruptions to riverine and coastal ecosystems (Olds et al., 2014). In this study, we have shown that tropical storms in Brisbane Australia have distinctly low isotope compositions, twice as low as the long-term mean for the
The distinct isotope value of the rain was traced in the floodwater as it moved through the river towards the coastal zone. The low isotope composition of the floodwater was associated with the transport of large quantities of suspended sediments, with sediment loads 30 to 70 times larger than during base flow conditions. The floods also carried up to 35% of the annual P and up to 208% of the calculated mean annual N load of the Brisbane River. These dramatic changes were caused by a rapid flow increase, from 2 to 2,015 m$^3$ s$^{-1}$ in two days during the onset of the major flood in the Lockyer Valley. These changes would have major consequences in riverine and coastal ecosystems of the region and could be traced using the specific water isotopic composition of floodwaters.

Measuring the isotope composition of floodwater could help trace flood effects on riverine and coastal ecosystems. For example, during a tropical storm, mangroves can rapidly take up floodwater and nutrients that can be traced in the plant tissues (Feakins and Sessions 2010; Lovelock 2011). Similarly, aquatic molluscs can acquire the isotope composition of floodwater within days (Bortolotti et al., 2013), so that the subsidy effect of floods to aquatic foodwebs could be estimated. The effects of flooding could also be used to estimate fish growth and movement using high-resolution analyses of 3-5 days of $\delta^{18}$O in fish otoliths (Patterson, 1998; Walther and Thorrold, 2009). Additionally, seasonal variations in $\delta^{18}$O in cave speleothems have been associated with the frequency of intense rainfall events (Treble et al., 2005). Thus, summers of intense activity, such as the austral summer of 1976 (Fig 4A) could produce significant changes in the seasonal $\delta^{18}$O mean of palaeoecological records (Treble et al., 2005).

The water isotope composition of rainfall during other tropical storms also has been reported to be low. For example, during the passage of Hurricane Sandy, a category-three
hurricane in the eastern United States, rivers and rainfalls had low $\delta D$ values of -40‰ and -50‰, respectively (Higgins, 2012). These values were 20-25‰ lower than the regional background values (Higgins, 2012). The floodwater from our study had a wide range of isotopic values, 23‰ for $\delta D$ and of 3.6‰ for $\delta ^{18}O$ during the major flood. This suggests large variations in water source and/or precipitation mechanisms (Bowen, 2012). Datasets from tropical storms, including ours, show a large range in $d$ excess values with many points lying well below and above the GMWL (Bowen, 2012).

After the flood peak, the isotopic composition of floodwater was influenced by the water released as part of flood management of the dams upstream of our sampling point, resulting in an increase in the isotopic composition of floodwater. Without the influence of the dam, the curve of change of the isotopic composition of the floodwater likely would have remained low for longer. The influence of water releases from dams is likely to dilute the flood signal in dammed rivers. Nevertheless, during the flood peak, the isotopic composition of floodwater was very close to that of rain, indicating that the composition of the flood during its peak is representative of floodwater from the tropical storm.

In conclusion we found that during a tropical storm in Brisbane Australia and the floods that followed it, rain and floodwater were characterized by low water $\delta D$ and $\delta ^{18}O$ isotopes compared to regional mean values. The distinct isotopic value of the rainfall could be followed into the river and floodwater as the flood moved to the coastal zone carrying large quantities of suspended sediments, and dissolved nutrients. The increased knowledge of $\delta D$ and $\delta ^{18}O$ values during tropical storms and flooding may lead to better understandings of hydrological oscillations and the ecological consequences of extreme weather events.
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ABM, Australian Bureau of Meteorology


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Table 1. $\delta$D, $\delta^{18}$O ($‰$) and $d$ excess values of floodwater and rain during two flood events in the Brisbane River in 2013. Values are mean ± standard deviations of replicates within the same sample.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sampling time</th>
<th>$\delta$D ($‰$)</th>
<th>$\delta^{18}$O ($‰$)</th>
<th>$d$ excess</th>
</tr>
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<tbody>
<tr>
<td><strong>Floodwater</strong></td>
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<tr>
<td><em>1st flood</em></td>
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</tr>
<tr>
<td>27-Jan</td>
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<td>-1.3 ± 0.2</td>
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<td>-2.2 ± 0.0</td>
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<td><strong>2nd flood</strong></td>
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<td>-3.8 ± 0.5</td>
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Figure legends

Figure 1. Sampling location within the Brisbane River (cross), long-term GNIP station (Brisbane City station, IAEA/WMO), and sampling stations for rainfall, river discharge, conductivity, pH and water temperature (DERM, State of Queensland).

Figure 2. (A) Daily rainfall (mm) in the upper Brisbane River (station 143001C) and in the Lockyer Creek (station 143203C), (B) river discharge (m$^3$s$^{-1}$, stations 143001C and 143207A) and releases from Wivenhoe-Somerset dam, (C) daily mean conductivity (µS cm$^{-1}$), temperature (°C) at station 143001C, (D) pH; (E) total suspended solids (TSS; g L$^{-1}$); (F) dissolved nutrients: orthophosphates, P, nitrogen as nitrogen oxides, N-NO$_x$, and nitrogen as ammonium, N-NH$_4$ (µmol L$^{-1}$), and DIN:DIP, (G) δD‰, (H) δ$^{18}$O‰ (vs. V-SMOW) of floodwater collected from the Brisbane River and rain, and (I) $d$ excess. Dashed lines represent expected TSS, dissolved nutrients and isotopic composition baselines as predicted by Ozcoasts, Healthy Waterways and Bowen et al. (2014). Data for rainfall, river discharge, temperature and conductivity was obtained from the Department of Natural Resources and Mines, Brisbane River stations. Data from dam Wivenhoe-Somerset dam releases were obtained from Seqwater. Ph, TSS, nutrients and isotope values were measured by the authors from the Brisbane River sampling point (see Fig. 1).

Figure 3. Floodwater δD and δ$^{18}$O (‰ vs. V-SMOW) plotted against the global meteoric water line (GMWL) and the local meteoric water line (LMWL) calculated from the GNIP database (Brisbane Station 1967-2002, IAEA/WMO). Black circles are values of floodwater during release of water from the upstream dam (Wivenhoe-Somerset dam); grey circles are values from the beginning of the major flood.
Figure 4. (A) Long-term monthly δD values of precipitation from 1972-2002 for the Brisbane River, light grey bars represent moderate and minor floods, dark grey bars represent major floods (ABM, 2015); (B) monthly mean from 1962-2002 and predicted values (dashed line, Bowen 2014) of precipitation for Brisbane; (C) precipitation amount (log mm) against δD values for Brisbane for 1962-2002. Data are from Brisbane Station, GNIP, IAEA/WMO.
Figure 1. Sampling location within the Brisbane River (cross), long-term GNIP station (Brisbane City station, IAEA/WMO), and sampling stations for rainfall, river discharge, conductivity, pH and water temperature (DERM, State of Queensland).

210x296mm (300 x 300 DPI)
For Peer Review
$y = 8.0x + 10\%$

$y = 7.3x + 11.2\%$

GMWL

LMWL

$\delta D \%$ vs. V-SMOW
Hydrological Processes

Cyclone David and low pressure system from Cyclone Alan

Low pressure system

Log10 precipitation (mm)

http://mc.manuscriptcentral.com/hyp