Transport of nutrients and eutrophication control by an urban runoff diversion system protecting a drinking water reservoir

M. L. Tran, J. Bahng, S. Pankratz and I. H. Suffet

ABSTRACT

Urban runoff from five storms during the 2003–2004 and 2004–2005 rainy seasons was sampled at the exit point of runoff diversion forebays leading to engineered retention ponds to protect a drinking water reservoir. Samples were collected from three different drainage areas both years and were analysed for water quality parameters including total dissolved solids, electrical conductivity (EC), dissolved organic carbon, bacterial count and nutrients in the water phase. In the second year of the study, samples were also taken at the entry point into the forebays and analysed to determine if the forebays contributed to removal of analytes prior to diversion in the retention ponds. EC, which had been used as the determining factor of whether runoff is used to recharge or diverted to holding ponds, did not relate to nutrient levels. This indicated that EC is insufficient to determine water quality because runoff with low EC may contain high levels of nutrients that can support eutrophication. Monitoring of nutrients themselves is essential for decisions.

Key words | drinking water quality, eutrophication, nutrients, runoff, urban runoff diversion system (URDS)

INTRODUCTION

Urban non-point runoff from storm water increases loading of nutrients and can lead to amplified eutrophication of drinking water in reservoirs in the Southwestern US (McPherson et al. 2002). Nutrient accumulation can lead to algal blooms causing taste and odour problems increasing the cost of drinking water treatment (Paul & Meyer 2001). This study investigated urban runoff in the Sweetwater Reservoir, located in the Sweetwater River watershed. The reservoir is expected to receive rising amounts of nutrients as the urbanised area upstream expands. In order to protect the water in the Sweetwater Reservoir, an urban runoff diversion system (URDS) consisting of a collection system and retention ponds was built adjacent to the reservoir. The URDS was designed to divert polluted first-flush and dry weather flows around the reservoir (Thompson 2004). Electrical conductivity (EC) as a surrogate for total dissolved solids (TDS) is the current criterion used to determine whether runoff is used to recharge the reservoir or is diverted to the URDS.

This research studied non-point source runoff of nutrients, namely phosphorus and nitrogen, into and within the URDS to evaluate its performance. Specific objectives included: 1) assessment of the potential impacts of storm-water runoff on reservoir eutrophication, 2) estimation of the efficiency of the constructed ponds to retain nutrients, and 3) characterisation of transport pathways of nutrients from different drainage basins into the URDS to identify input sources. To assess water quality of runoff entering compared to water leaving the URDS system, EC, TDS, dissolved organic carbon (DOC), nitrate, nitrite, ammonia, Kjeldahl nitrogen and soluble phosphorus were measured in the water and the suspended solids phase from runoff.
during two storms in the 2003–2004 (Year 1) and three storms in the 2004–2005 (Year 2) rainy seasons. Runoff retained in the holding ponds was sampled and analysed over 5 weeks to examine nutrient behaviour over time in the URDS.

**METHODOLOGY**

The Los Angeles County Department of Public Works defines the wet season in Southern California as lasting from October 1 to March 31. All field sampling was completed during this period for the 2003–2004 and 2004–2005 wet seasons. During the first season, runoff samples were taken on November 12 of 2003 and February 3 of 2004, referred to as Storms 1 and 2, respectively. During the second season samples were taken on October 17 and October 20 of 2004 and February 11 of 2005, referred to as Storms 3, 4 and 5, respectively.

Storm runoff from three drainage basins was monitored in this study. After leaving each basin, runoff drains through a vegetated forebay before reaching a diversion point where it is routed to the reservoir or to the retention ponds. In Year 1, samples were taken from the diversion point and in Year 2, samples were also taken from the inlet to the forebay. The three sampling locations are Alacena 1, Alacena 2 and Gumtree. Alacena 1 and 2 drain two different catchments, but share one retention pond while Gumtree drains into its own pond. One-gallon water samples for nutrient analysis were taken with a polypropylene bucket lowered into the diversion channel. The water was placed in Wheaton amber glass bottles that had been acid washed, dried and rinsed thrice with each respective sample. Sampling commenced 30–90 minutes after the start of rainfall and ended when runoff was no longer sufficient in the channel to constitute a consistent water depth of at least 1 inch or after 6 hours, whichever came last. Flow data was logged using a flow meter (4150 Area Velocity Flow Logger, ISCO, Lincoln, NE) and reaffirmed using water depth and channel dimension measurements. Figure 1 shows the sampling plan for the Sweetwater study.

Samples were labelled with location, date and time and placed in insulated coolers with ice for transport to UCLA. Water samples were filtered on 0.40 μm Millipore Isopore™ membrane filters (Millipore 142 mm Hazardous Waste Pressure Filter System, Billerica, MA). The filtrate was divided into subsamples for nutrients including nitrite/nitrate analysis (Method 10-107-04-1-A), and ammonia (Method 10-107-06-1-A) according to QuikChem methods (Switala 1999; Wendt 1999). TKN analysis was performed using the standard Kjeldahl procedure (Carlson 1978). Soluble phosphorus (Method 4500-P), DOC and ultraviolet absorption at 254 nm (UV) (Method 5910), TDS (Method 2540 C), pH (Method 4500 B), and electrical conductivity (Method 2510 A) in accordance with *Standard Methods for the Examination of Water and Wastewater*, 20th Ed (APHA 1998). Samples were collected separately in sterile polyethylene bottles for microbial analysis. One-gallon grab samples were collected from Alacena Pond the day after the first storm of each season and weekly thereafter for 5 weeks. The pond retains runoff from the watershed and allows for insight into equilibrium partitioning and persistence of nutrients in the water and sediment phases.

**RESULTS**

**Storm events—EC and TDS**

EC and TDS have been used to determine when to divert runoff to the URDS or use it to recharge the reservoir. Runoff with TDS above 1,000 mg/L is diverted to the retention ponds while runoff below is sent via bypass channels to recharge. Figure 2 shows EC and TDS exhibit the same general trend over time where both increase
towards the end of a storm due to decreasing flow. However, the pattern and levels vary between storms for the same forebay. While TDS levels are below the Sweetwater Authority criterion of 1,000 mg/L, 14 of 19 samples have a TDS concentration above the 500 mg/L secondary standards for taste in drinking water (USEPA 2002).

\[
EMC = \frac{\sum_{i=1}^{N} CiQi\Delta t_i}{\sum_{i=1}^{N} Qi\Delta t_i}
\]

(1)

In order to compare TDS from different sites between years, an event mean concentration (EMC) must be computed. The EMC is the total pollutant load discharged during a storm event divided by the total runoff and can be calculated using Equation (1), where \(N\) is the total number of measurements, \(Qi\) and \(Ci\) are flow rate and concentration at each time interval \(\Delta t_i\).

Figure 3 shows TDS at the three sampling sites during all five storms. Gumtree could not be monitored during storms 1 and 4 because it was inaccessible to sampling teams. However, when Gumtree was sampled, its runoff contained the highest concentrations of dissolved solids. TDS levels at Alacena Forebay 1 were lower than Gumtree, but consistently higher than Alacena 2. Aside from location differences, temporal differences also exist. Storms 1 and 2 are 4 months apart and yet their TDS levels across the sampling sites are more similar than for Storms 3 and 4 that were only 3 days apart. According to the Sweetwater TDS criterion all the stormwater should be allowed to enter the reservoir.

**Storm events—nutrients**

Analysis of nitrogen contributors showed that TKN and nitrate are the most important forms of nitrogen in the runoff. Nitrite and ammonium concentrations are considerably lower. Because TKN is composed of ammonium and organic nitrogen, this implies that organic nitrogen is a major nitrogen form. Total nitrogen levels taken by summing N contributed by nitrate, nitrite and total Kjeldahl nitrogen (TKN) were calculated for the forebays for all five storms. Soluble phosphorus was also determined. Figure 4 shows the typical relative levels of N and P levels in runoff as seen in the runoff of Storm 1 at Alacena Forebay 1. A general decrease of total N occurred during a storm.
Due to low levels of nitrite and ammonia in storm runoff from the second year, only EMCs for total N and soluble P were calculated for the storms and displayed in Figure 5. No clear pattern can be seen among the three sampling sites. Total nitrogen in Gumtree Forebay is twice that of the Alacena Forebays for Storm 3 only. Differences in total N at the two Alacena Forebays decrease in year two during Storms 3, 4 and 5. Soluble P data was not collected during Storm 2, but during Storm 3 the levels at Gumtree are as for N much higher than at the Alacena Forebays.

Variations between forebays across wet seasons exist. For example, during Year 2, levels of nitrite and ammonia were below the method detection limit of 0.05 mg/L for many of the samples. A summary of ranges for the contributors of nitrogen, soluble phosphorus and DOC is presented in Table 1.

Nutrient concentrations among the sites during the five sampled storms varied widely. Nutrient concentration patterns were also not similar to EC. As flow decreases, EC should increase along with nutrient concentration. This pattern was not seen for all the storms monitored. As an example, EC was plotted with total N and soluble P concentrations for Alacena Forebay 1 during Storm 1 in Figure 6. As EC increases at the end of the storm, nitrogen concentration drops while P concentration remains relatively stable. P concentration is generally rate limiting for

Table 1 | Summary of soluble phosphorus and nitrogen contributors (mg/L) and DOC (ppm)

<table>
<thead>
<tr>
<th></th>
<th>NO₂-N</th>
<th>NH₄-N</th>
<th>NO₃-N</th>
<th>TKN</th>
<th>Total N</th>
<th>Soluble P</th>
<th>DOC</th>
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<tr>
<td>Storm 1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>AFB 1</td>
<td>0.14–0.38</td>
<td>0.16–0.85</td>
<td>2.07–3.07</td>
<td>2.4–4.4</td>
<td>4.91–7.85</td>
<td>0.68–1.05</td>
<td>19.4–32.1</td>
</tr>
<tr>
<td>AFB 2</td>
<td>0.08–0.12</td>
<td>0.20–0.59</td>
<td>1.11–2.53</td>
<td>0.9–3.1</td>
<td>2.13–5.75</td>
<td>0.38–1.00</td>
<td>16.3–29.24</td>
</tr>
<tr>
<td>GT</td>
<td></td>
<td>NS</td>
<td>NS</td>
<td></td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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<tr>
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<tr>
<td>AFB 1</td>
<td>&lt;0.05†</td>
<td>0.14*</td>
<td>0.75–2.26</td>
<td>0.7–2.7</td>
<td>1.55–4.77</td>
<td>NS</td>
<td>12.7–16.7</td>
</tr>
<tr>
<td>AFB 2</td>
<td>&lt;0.05†</td>
<td>&lt;0.05†</td>
<td>1.10–1.43</td>
<td>0.1–0.8</td>
<td>1.20–2.23</td>
<td>NS</td>
<td>7.7–10.1</td>
</tr>
<tr>
<td>GT</td>
<td>&lt;0.05†</td>
<td>&lt;0.05†</td>
<td>1.37–1.88</td>
<td>0.5–1.2</td>
<td>1.87–2.99</td>
<td>NS</td>
<td>16.9–19.6</td>
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<tr>
<td>Storm 3</td>
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<tr>
<td>AFB 1</td>
<td>0.07–1.16</td>
<td>0.10–1.22*</td>
<td>0.11–2.67</td>
<td>1.2–5.2</td>
<td>3.01–5.88</td>
<td>0.12–0.64</td>
<td>11.7–69.2</td>
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<tr>
<td>AFB 2</td>
<td>0.08–1.15</td>
<td>0.76–5.16*</td>
<td>0.14–5.33*</td>
<td>2.8–12.7</td>
<td>3.55–12.7</td>
<td>0.53–1.28</td>
<td>21.6–101.4</td>
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<tr>
<td>GT</td>
<td>0.06–1.78</td>
<td>0.86–3.28</td>
<td>0.21–2.39*</td>
<td>4.5–8.0</td>
<td>5.80–8.87</td>
<td>0.99–1.72</td>
<td>25.3–69.2</td>
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<td>Storm 4</td>
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<td>AFB 1</td>
<td>0.05–0.25</td>
<td>0.09–0.18</td>
<td>0.31–2.40</td>
<td>0.8–1.8</td>
<td>1.30–4.45</td>
<td>0.11–0.48</td>
<td>6.2–15.9</td>
</tr>
<tr>
<td>AFB 2</td>
<td>0.07–0.32</td>
<td>0.07–0.27</td>
<td>0.21–4.11</td>
<td>0.6–1.5</td>
<td>0.88–5.81</td>
<td>0.20–0.60</td>
<td>6.4–14.1</td>
</tr>
<tr>
<td>GT</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td></td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Storm 5</td>
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<tr>
<td>AFB 1</td>
<td>0.07–0.16*</td>
<td>0.13*</td>
<td>0.79–1.26</td>
<td>0.6–0.9</td>
<td>1.48–2.05</td>
<td>0.21–0.65</td>
<td>4.0–7.3</td>
</tr>
<tr>
<td>AFB 2</td>
<td>&lt;0.05†</td>
<td>0.11–5.53*</td>
<td>0.11–1.11</td>
<td>0.4–6.7</td>
<td>1.49–6.92</td>
<td>0.12–1.27</td>
<td>3.6–18.9</td>
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<tr>
<td>GT</td>
<td>0.06*</td>
<td>0.05–0.11*</td>
<td>0.07–0.56</td>
<td>0.6–0.8</td>
<td>0.71–1.46</td>
<td>0.18–0.30</td>
<td>5.0–18.7</td>
</tr>
</tbody>
</table>

NS = not sampled.
†Samples below method detection limit (0.05 mg/L for NO₂-N, NH₄-N and NO₃-N; 0.1 mg/L for TKN) are omitted.
‡All samples below method detection limit.
eutrophication in freshwater environments. The EPA recommended limit of 0.1 mg/L for total phosphorus to control eutrophication \cite{USEPA1986} was exceeded by samples in both years of the study. The specific EMCs of total soluble $P$ were $> 0.1$ mg/L for all storms and all samples, Table 1 and Figure 5. This data indicates no water should be allowed into the reservoir directly. However, the TDS data shows all the water should be allowed into the reservoir. Therefore, there is no relationship observed between EC or TDS and soluble P levels.

Storm events – DOC

Table 1 shows that DOC was higher for the first storm at all sites for both years and decreased over subsequent storms within a season. The DOC concentration for the first storm of year 2 (Storm 3) is higher than the first storm of year 1 (Storm 1). During year one, DOC concentration ranged from 16–32 mg/L for storm one and dropped to 8–20 mg/L for storm two. During year two, DOC was significantly higher with concentrations ranging from 12–105 mg/L for storm one and dropping to 4–19 mg/L by the third storm. For both years DOC did not relate to EC or TDS.

The stormwater runoff was significantly greater than reservoir levels of 6–8.5 mg C/L DOC except for Storm 5.

Storm events – bacteria

Samples were collected and analysed for the presence of faecal indicator bacteria. Coliform bacteria are generally considered harmless themselves, but their presence may indicate harmful bacteria such as $E.~coli$. Coliform count was reported as most probably number (MPN) per 100 mL of water. The lower limit of detection was 10 MPN and the upper limit of detection was 240,000. Bacterial counts above this limit were reported as too numerous to count (TNC). Results are summarised in Table 2. Coliform counts at all sites exceeded the maximum MPN during the second storm season. Both Alacena forebays exceeded the maximum MPN count 75% of the time during the first storm season, but Gumtree forebay exceeded the maximum count only 14% of the time. EPA standards for total coliform count in drinking water limits coliform-positive tests to 5% of all samples per month \cite{USEPA2002}. All samples tested for this study were coliform-positive.

Pond study

Runoff gathered in the retention ponds was examined for 5 weeks following the first storm of both seasons to give insight into the behaviour of nutrients over time. Analysis revealed that overall N concentration during Year 1 of the pond study declined during the first three weeks and showed little change thereafter, resulting in 86% N removal to 0.7 mg/L total N. Soluble P concentrations remained low and decreased 81% by the end of the study to 0.08 mg/L and could be allowed into the reservoir. The TDS level of the

| Summary of total coliform counts for all forebays during both wet seasons |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                             | Alacena 1 Year 1 | Alacena 2 Year 1 | Alacena 1 Year 2 | Alacena 2 Year 2 | Gumtree Year 1 | Gumtree Year 2 |
| Total samples               | 11            | 18            | 15            | 15            | 7             | 4             |
| Samples > max. MPN (%)      | 73            | 100           | 75            | 100           | 14            | 100           |
| MPN range                   | 130,000-TNC * | TNC *         | 33,000-TNC * | TNC *         | 4,020-TNC *   | TNC *         |

*TNC designates MPN $> 240,000$. 
URDS did not go below 1,000 mg/L and thus does not predict P levels in the URDS.

Pond study results from the 2004–2005 samples showed similar trending for nitrogen, but the concentration of nutrients in the Year 2 samples were lower. Dissolved N from ammonia, nitrate, nitrite from the second year pond study was below the detection limit for half the samples leading to lower total dissolved N for Year 2 of the pond study. A 68% removal of total N to 0.9 mg/L was achieved in Year 2. Figure 7 shows that dissolved P was so low that only one measurement above the detection limit of 0.05 mg/L was reported among the 5 weekly samples. Therefore, the URDS water could be sent to the reservoir. TDS was also monitored during the pond study to assess the levels of soluble salts over time and remained fairly steady over the 5 weeks above the Sweetwater criterion of 1,000 mg/L. Thus TDS does not predict the P levels in the URDS.

Pond study results from the 2004–2005 samples showed a similar trend for DOC, but the concentration of DOC in the Year 2 samples were lower. Both years showed a decrease of 1.6–2.3 mg C/L over the first 3 weeks and then an increase of 1.4–3.8 mg C/L over the next 2 weeks. The DOC appears much more resistant to biodegradation to CO₂ as compared to N and P uptake.

**Forebay inlet vs. outlet**

The question of whether the forebays themselves play a role in the retention of nutrients from incoming runoff was also examined. In year 2 of the study, samples were taken from the inlet of each forebay to assess the ability of the forebay to function as a location for runoff settling and nutrient uptake by plants prior to diversion into the ponds. Incoming runoff from the inlet was then compared to outgoing runoff flowing to the retention ponds. For the first two storms of Year 1 the inlet levels of analytes are lower than outlet levels. No difference was seen during the third storm. EC and TDS analysis indicated that runoff leaving the forebay is higher in dissolved salts than runoff entering the forebay. EC is, on average, 2–25% higher at the outlet than inlet samples while TDS is 5–27% higher at the outlet. Figure 8(a) shows inlet vs. outlet EC/TDS for the first storm of Year 2 at Alacena Forebay 1 as an example.
Incoming levels of nutrients from the inlet are also lower than outgoing levels of nutrients for the first two storms of Year 2. Outlet sample concentrations for total N were 3–43% higher than the inlet across the sampling sites. Soluble P concentration during the same period was 17–59% higher at the outlet than inlet at the sampling sites. Inlet vs. outlet concentrations for total N and soluble P were comparable during the third storm. Figure 8(b) shows inlet vs. outlet total N/soluble P for the first storm of Year 2 at Alacena Forebay 1. Year 2 samples with concentrations below the method detection limit of 0.05 mg/L for soluble P were omitted from the graph. DOC increased across the forebays from 13–39 mg C/L for the first storm of the second year and decreased with successive storms to influent equaling effluent concentrations. This apparently is caused by decomposing vegetation within the forebays during the dry season.

**DISCUSSION**

The Sweetwater Authority currently uses electrical conductivity as their main indicator of water quality. Runoff is used to recharge the reservoir if TDS levels are below 1,000 mg/L, even if it is above the 500 mg/L secondary drinking water standard. However, runoff with low TDS levels may contain high nutrient levels. Data gathered from the various drainage areas over the past two years show that overall water quality cannot be determined simply by examining TDS because it varies from storm to storm. While TDS and EC increase at the end of a storm when flow is low, other factors that also affect water quality, such as bacterial content and nutrient levels, did not correlate to EC and TDS according to this study.

N, P and DOC tend to decrease over subsequent storms within a rainy season. Phosphorus is generally the limiting nutrient for freshwater systems. Soluble P, and therefore total P, concentrations exceeded the EPA recommended limit of 0.1 mg/L both years (USEPA 1986). Average concentration in the reservoir water is approximately 0.03 mg/L for total phosphorus and 0.04 mg/L for nitrate (Sweetwater Authority 2005). Recharge of the reservoir with runoff from the first storm events of a wet season will result in increased nutrients supporting algal blooms that affect taste and odour of drinking water. The URDS consisting of vegetated retention ponds have been shown to decrease nitrogen and, to a lesser extent, phosphorus during two 5-week studies after the initial storm event of a season. Both years showed a decrease of DOC over the first 3 weeks and then an increase over the next 2 weeks. The DOC appears much more resistant to biodegradation to CO₂ as compared to N and P uptake.

Water at the forebay outlet is higher in TDS and nutrient concentration. The forebays are also vegetated and cement-lined. Decayed vegetation could contribute to increased TDS, N, P and DOC concentrations. The lining prevents standing water from seeping through. Consequently, the water remaining in the depression of the forebay after a storm will evaporate during the dry season and leave an accumulation of solids and salts that will be resuspended during the initial storms of the next rainy season. This may be the reason behind the higher TDS and nutrient concentrations seen at the forebay outlets during the first two storms of a season.

**CONCLUSION**

Runoff from the first substantial rain event of the wet season may contain high levels of N, P and C. If this water were recharged to the reservoir, it would increase the possibility of algal growth which can cause eutrophication contributing to taste and odour problems in drinking water. High levels of nutrients also cause eutrophication and contribute to taste and odour problems. This can be troubling to municipalities where drinking water reservoirs are directly receiving this type of inflow.

EC and TDS cannot be used as the sole parameters to determine whether or not runoff should be used to recharge reservoir stock. These parameters differ within a storm and between seasons at a particular location. EC and TDS have not been shown to relate to nutrient concentration. Runoff from the initial storm event of a season may have low EC and TDS, but high nutrient concentrations. The observed heavy nutrient loading from the initial storm of a wet season can be used as a guideline to divert runoff to a retention system such as the URDS. It is recommended that the runoff from at least the first significant storm event of a wet season...
be retained by the URDS for removal of nutrients prior to reservoir recharge. Runoff from later storms, containing lower nutrient levels than earlier storms, may be used to recharge the reservoir directly. Regardless of the choice, monitoring of the nutrients themselves is essential for decisions. Using only EC and TDS are insufficient.

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