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Sources and management of urban stormwater pollution in rural catchments, Australia

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Summary This paper assesses the impact and quantifies the relative contribution of stormwater runoff (diffuse pollution sources) and point pollution sources on the quality of receiving water in the urban catchment of Orange. The study results were employed to develop management strategies to control stormwater pollution at the catchment level. The Orange urban catchment has experienced moderate to high levels of pollution in terms of nutrients (P and N), suspended solids (SS), heavy metals, fecal coliforms, and, to a lesser extent, salinity (TDS). Treated sewage effluent (point source) contributed, on average, 5% SS, 29% total nitrogen (TN) and 41% total phosphorous (TP). The nutrient yield per unit area was 2–31-folds higher than those reported for other Australian urban catchments. The overall contribution of the urban sources accounted for 93% and 94% of the TP and TN mass loads, respectively. In contrast, stormwater pollution in coastal urban catchments, that have similar population and land use, is dominated by rural diffuse sources contributing 81–99% of nutrient mass loads. This striking difference is attributed largely to the position of the catchment with respect to the hydrological system. Orange urban catchment is situated at the headwater of its river system and as such rural runoff into the urban part of the catchment was limited. The coastal catchments, on the other hand, are located at the end of their river systems and thus rural inflow into the urban area is substantially higher than those in upland catchments. This comparative assessment may suggest that the relative impact, per capita, of urban stormwater pollution on the receiving water is more significant in the upland catchments than in the coastal catchments. A stormwater management plan (SMP), consisting of structural and non-structural strategies, was developed to control stormwater pollution and enhance the quality of receiving water.

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Introduction

Stormwater pollution is the untreated contaminated water that drains into natural waterways from land uses within an urban catchment. The stormwater runoff can cause hydrological changes in the catchment as well as environmental, social and economic losses (Joliffe, 1995). Introducing urban developments, with paved and impervious surfaces, to rural catchments increases surface runoff that is discharged more quickly to the receiving water (Anon, 1981; O'Loughlin, 1994). Many of the water pollution problems in urban areas are due, in large part, to pollutants that are washed off from land by storms. The stormwater runoff from urbanized lands can change the health of water bodies, impact on aquatic habitats, recreation and aesthetics, or cause algae to grow uncontrollably (NSW-EPA, 1998; Settacharnwit et al., 2003). Contributions to water quality impairment from point sources such as industrial effluent and effluent from sewage treatment plants (STP) can be equal to or even greater than that of stormwater (Cordery, 1976). Pollutant loads discharged through point sources are relatively simple to quantify because the point of entry into the waterways is fixed, and the flow rates and concentrations are generally known. Releases are licensed and pollution must remain within license restrictions (Griffin et al., 1980). On the other hand, stormwater pollution generally has no fixed point of origin, and the flow rates are not as well documented. In addition, diffuse source loads are more temporally and spatially variable than are point source loads because they occur only as a catchment responds to rainfall events (Novotny, 1994). Furthermore, pollution from diffuse sources such as stormwater runoff is more difficult to monitor and control.

Most of the stormwater research in Australia has focused on metropolitan areas (e.g. Argue, 1997; Duncan, 1997). The findings from these studies cannot be directly extrapolated to urban centres in rural catchments due to differences in land use, vegetation cover, proportion of impervious surfaces, traffic densities, population densities and other landscape features. Over the past decade, a number of stormwater studies have been performed in the Orange catchment (Sinclair Knight and partners, 1980; Morse McVey and Associates, 1997; Lyall and Macoun Consulting Engineers, 1997, 1998). However, they did not deal with issues related to stormwater pollution and its impact on the quality of receiving water.

This paper aims to assess ambient water quality and to quantify the impact of stormwater pollution on the receiving water in the urban catchment of Orange. A comparative assessment was conducted to determine the relative impact of urban stormwater pollution in rural and coastal catchments. The study results were used in developing sound management strategies to control stormwater pollution.

Orange urban catchment

Orange is situated approximately 250 km west of Sydney in the Central Tablelands region of New South Wales. The total area of the Orange urban catchment is approximately 58 km^2 (Fig. 1). The rural part of the urban catchment comprises 41% of the total catchment and consists of orchards and light grazing lands with increasing development in viticulture and associated rural tourist activities. The urban area, which covers 59% of the catchment, serves as a regional centre for business, health, community services, education, recreation and government administrative services for the surrounding region. The catchment is dominated by Tertiary basaltic rocks and Ordovician mafic volcanic and sedimentary rocks. The catchment is generally considered very stable in terms of erosion. Almost 95% of the catchment shows no appreciable surface erosion (Pogson and Watkins, 1998). The population of Orange is approximately 40,000 mostly concentrated in the middle of the town. Orange has an extensive stormwater drainage system, which is designed to collect and carry stormwater to the natural drainage ways, the Blackmans Swamp Creek (BSC) and Ploughmans Creek (PC) (Fig. 1). Both Creeks ultimately flow into the Macquarie River, a major tributary of the Murray-Darling Basin. The BSC drains the Central Business District (CBD) through a series of channels and pipes with concrete lining and picks up the treated effluent from the Orange STP (Sewage Treatment Plant) before it joins with Summer Hill Creek downstream of the urban area. Ploughmans Creek drains the northwest and western sides of Orange This creek is an unlined channel and flows north into the Bell River, a tributary of the Macquarie River. Runoff from this portion of the catchment flows via culverts in the embankment to a system of storage dams at Wentworth Golf Course. The Orange catchment is characterised by a temperate climate with cold winters and warm summers. Rainfall data indicate a relatively high level of precipitation with an annual mean of 875 mm (Woodward-Clyde, 1995).

Methods

For the purpose of this study, the urban catchment was divided into six subcatchments and stormwater quality was monitored from November 1998 to October 2000 at six gauging sites (Fig. 1 and 1). Spatial analysis, using geographic information system (GIS), was used to determine areas and boundaries of various land use categories such as urbanised and impervious sites. In situ measurements of water temperature, pH, dissolved oxygen (DO), electrical conductivity (EC_w) and total dissolved salt (TDS) were undertaken at 14 day intervals and after storm events using a multi probe field analyser (Hydrolab®, Austin, USA). The Hydrolab® was calibrated prior to and following each day's sampling event. Stormwater samples from the monitoring sites were collected using ISCO automated samplers. Each sampler was linked to a flow meter and was activated by a data logger to collect 1000 mL of water based on predetermined gauge heights. The method for determining stream water flow is described in Rahman and Al Bakri (2006). Water samples were collected for both dry and wet periods from the monitoring sites using polyethylene containers. Glass bottles were used for hydrocarbon, bacterial and other microbiological pollutant testing.

A total of 246 water samples (100 samples during low flow and 146 during high flow) were analysed for phosphorus (P), nitrogen (N), turbidity and suspended solids (APHA, 1992). Biochemical oxygen demand (BOD_5) from 32 samples, trace metal (78 samples) and fecal coliforms (52 samples)

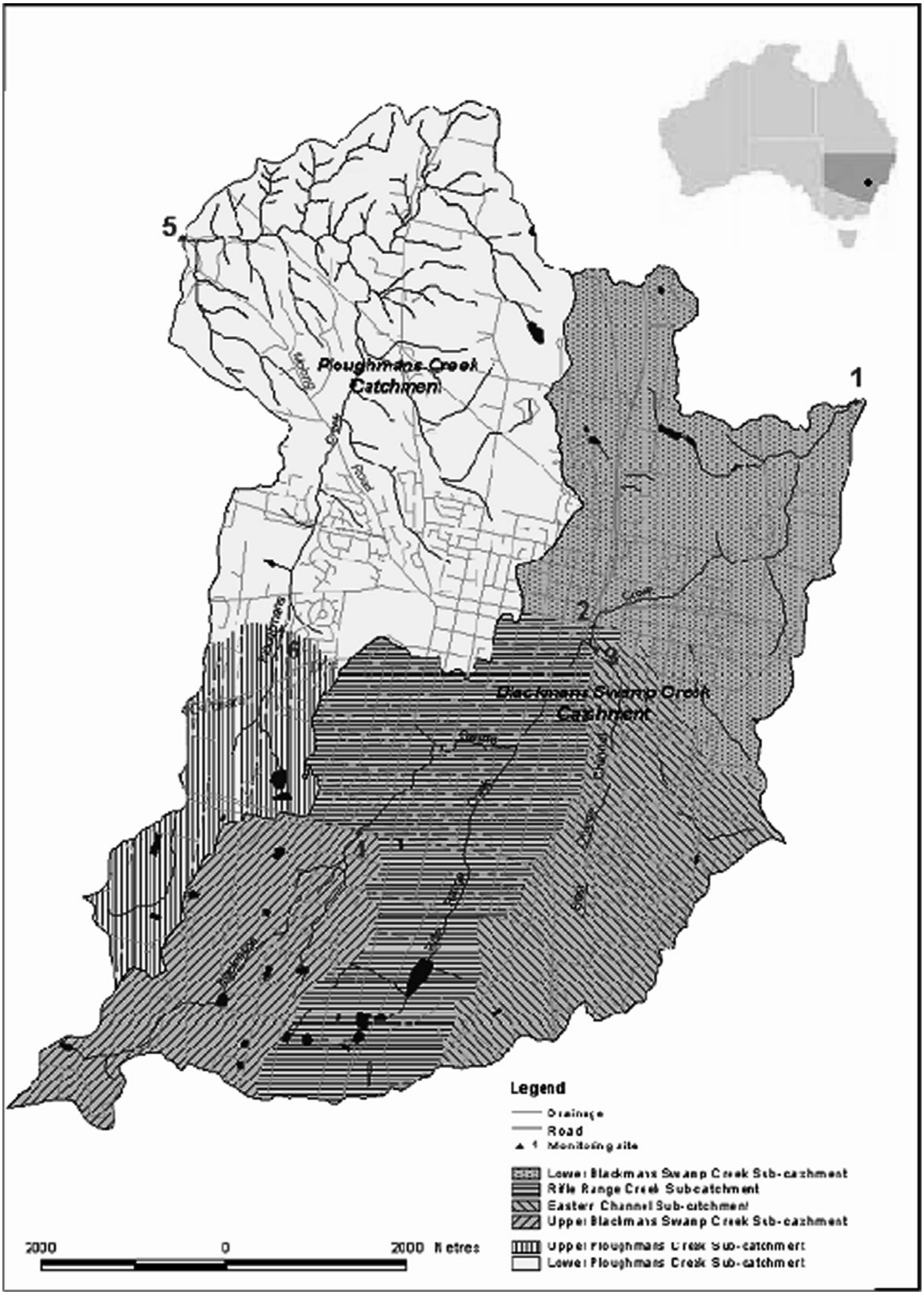

Figure 1 Orange urban catchment and stormwater monitoring sites.

were also analysed following standard methods (APHA, 1992). Samples were usually filtered within 12 h of collection and stored in the dark at 4 °C when not being processed immediately. Nitrogen and phosphorus analyses were completed within 24—48 h of collection. Other tests were completed within a week. Unfiltered samples (50 mL) were used for the determination of total phosphorus (TP) and total nitrogen (TN) concentrations. These samples were digested

Table 1 Blackmans Swamp Creek (BSC) and Ploughmans Creek (PC) catchments and water quality monitoring sites

Catchment (dominant land use)	Catchment area (km^2)	Catchment area (%)	Site number
Lower BSC (residential/rural)	10.7	31	1
Rifle Range Creek (CBD)[a]	10.6	30	2
East Orange Channel (industrial)	7.2	21	3
Upper BSC (rural)	6.0	18	4
Subtotal	34.5	100	
Lower PC (rural-residential)	19.8	81	5
Upper PC (rural)	3.7	19	6
Subtotal	23.5	100	

[a] CBD: Central Business District.

using the potassium persulphate ($K_2S_2O_8$) and sodium hydroxide (NaOH) digestion procedure (Hosomi and Sudo, 1986). After digestion, the TP sample was neutralised and the colour was developed using the ascorbic acid procedure (Kenkel, 1986; APHA, 1992). A filtered sample (100 mL) was used for the determination of ammonium nitrogen (NH_4-N), nitrate—nitrite nitrogen (NO_x-N) and filterable reactive phosphorus (FRP). The ascorbic acid reagent was used for the determination of the FRP. All these tests were performed using a Lambda 20 UV/vis spectrophotometer (Perkin Elmer, USA). Several samples were analysed to determine the heavy metals lead, copper and zinc using an atomic absorption spectrophotometer (AAS) following standard procedures (APHA, 1992). Several samples were also tested for fecal coliforms by the State-certified Central West Regional Laboratory, Orange. The Australian and New Zealand Guidelines for the Protection of Freshwater Aquatic Ecosystems (ANZECC, 2000) were used to define the level of physical and chemical pollution or stressors in the receiving water of the Orange catchment. The guidelines aim to specify appropriate 'trigger values' for selected water quality indicators to protect a range of aquatic systems from degradation and to maintain and enhance the ecological integrity of freshwater ecosystems. Trigger values are concentrations that, if exceeded, would indicate a potential environmental problem, and so 'trigger' some response such as implementation of management or remedial actions (ANZECC, 2000).

The pollutant mass loads were determined using the ratio estimator method (Preston et al., 1989; Kronvang and Bruhn, 1996). The mass loads for the cumulative sites such as Sites 1 and 5 were determined by subtracting the load of the upstream site or sites from the load measured at the downstream site. For instance; mass load at Site 1 = total load measured at Site 1 — load measured at Site 2. Load for low flow periods was based on data obtained from samples collected during dry periods whereas load for high flow periods was determined from samples collected during wet periods where rainfall events produced surface runoff. The pollution load was also expressed in terms of export coefficient (kg/ha/yr) as the annual pollution load over the area of each subcatchment from which pollutant was discharged. The STP pollution load was estimated using data provided by the Sewerage Section of Orange City Council for the study period.

Community input was actively sought during the various stages of the study. Participation and contribution of the Orange community, Orange City Council and NSW-EPA were achieved through three integrated phases. The first phase involved the establishment of a project Advisory committee (PAC) consisting of key stakeholders The PAC role was to oversee the overall direction and implementation of the project and to identify stormwater issues that stakeholders believed to be of importance. The second phase involved holding a one-day public forum to identify and prioritise desired community catchment values, stormwater issues and management objectives. The third phase of this process involved the establishment of the stormwater management committee (SMC), a statutory authority established under State Government legislation to oversee the implementation and monitoring of the proposed SMP. Local media outlets were used throughout the duration of the project to educate the wider community with respect to impacts of stormwater pollution. This consultation process provided significant social, economic and environmental inputs to the development of the stormwater management plan (SMP) for Orange.

Results

Physico-chemical properties

The water temperature in all monitoring sites was within the recommended guidelines for the protection of aquatic ecosystems in Australia (ANZECC, 2000). The mean and median pH values in both catchments were also within the Australian guidelines (6.5—8.0) for upland rivers (ANZECC, 2000) during most of the study period. However, pH values tended to increase marginally as water passed through the urban area. The pH values at the outlets of both creeks (Sites 1 and 5) were consistently higher than those at the corresponding inlets. The industrial area (Site 3) exhibited the highest pH median (8.4). The mean dissolved oxygen (DO) concentration over the study period, ranged between 8.3 and 9.4 m/L, were well above the recommended trigger value (>5 mg/L or >90%) for upland rivers (ANZECC, 2000). It was evident that DO concentration increased as water passed through the urban area, which may be due to increased runoff and turbulence. It was also apparent that the DO level increased progressively during colder months and decreased during warmer months. As expected, the DO concentration in the BSC declined downstream of the STP effluent due to an increase in decomposed organic matter.

Total dissolved salt and electrical conductivity

Salinity was calculated using ANZECC's conventional formula of multiplying the electrical conductivity (EC_w) value (μS/cm) by 0.68 (conversion factor) to obtain total dissolved solids (TDS) concentration in mg/L. According to the ANZECC (2000) guidelines, the salinity level in natural waterways should not exceed 200 mg/L (or 300 μS/cm). The TDS concentrations ranged from 55 to 382 mg/L with an overall mean of 174 mg/L during low flow and 141 mg/L during high flows. In the BSC catchment, Site 1 exhibited the highest TDS values with means of 243 mg/L (low flow) and 207 mg/L (high flow) followed by Site 3 and then Site 2. Site 4 (rural) always had lower TDS values, with means of 76 mg/L during low flows and 85 mg/L during high flows. This pattern demonstrated that salinity levels increased as the creek passed through the urban area and receives stormwater runoff from industrial, commercial and residential sources (Table 2). The salinity level in the PC catchment exhibited a similar pattern (Table 2). The total salt load discharged from the BSC catchment during the study period was 7 710 000kg. Of this, 70% was contributed by the Lower Blackmans Swamp Creek (BSC) and the STP. Of the total TDS load, 67% was delivered during high flow and 23% was contributed by the low flow. Although TDS data for the STP effluent were not available, it appears that this point source is an important contributor to dissolved solids in the BSC catchment. A total TDS mass load of 2 345 000kg went through the PC over the same period (Table 4). Of this, the Lower PC and Upper PC contributed 92% and 8%, respectively. The high flow, which occurred only 10% of the time, provided almost 70% of the total TDS load. The overall salt export coefficient for the BSC catchment was 2235 kg/ha/yr. However, on a spatial basis the export coefficient in this catchment ranged from 386 kg/ha/yr (Site 4) to 5044 kg/ha/yr (Site 1). The export coefficients for the PC catchment varied from 507kg/ha/yr at Site 6 to 1009 kg/ha/yr at Site 5 with an overall value of 998 kg/ha/yr for the whole catchment (Table 5). The above pattern confirmed that salinity increased as the water passed through the urban area in both catchments which indicates the cumulative effect of the urban sources on receiving water.

Turbidity and suspended solids (SS)

Turbidity was relatively low during low flow but was substantially higher during storm events in both catchments due to increased runoff bringing particulate material into the streams. Turbidity in the BSC varied from 2NTU (Nephelometric Turbidity Unit) to 385 NTU and tended to increase as the water passed through the urban area. The median turbidity values were highest at Site 3 (industrial area) and Site 2 (commercial area) followed by Site 1 which may indicate the influence of the industrial and commercial activities. Turbidity in the BSC was approximately 2—3 times higher than that in PC. This is due to the fact that the BSC catchment is highly urbanised with the impervious area representing >50% of the catchment whereas the PC catchment is much more rural with good vegetation cover. With the exception of a few low flow situations, turbidity level in both catchments were above the ANZECC (2000) trigger value (2—15 NTU).

There are no Australian guidelines for SS in fresh water but according to Graham (1989), the desirable concentration should not exceed 25 mg/L. The SS concentration in the BSC ranged from 0.5 mg/L during low flow to 658 mg/L during high flow (Table 3). Again the highest concentration was found at Site 3, followed by Site 1 and the lowest value was at Site 4. The SS concentrations in the PC varied from 0.2 to 268 mg/L during low flow and from 1.5 mg/L to a

Table 2 Summary statistics of the total dissolved solids (TDS) concentrations (mg/L)

	BSC catchment			PC catchment		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Low flow						
No. of samples	16	16	13	13	16	9
Maximum	382	277	343	103	372	114
Minimum	95	58	55	58	94	94
Mean	243	154	211	76	265	105
Median	248	155	216	73	265	107
Std. deviation	86	62	77	11	73	6
High flow						
No. of samples	22	20	22	14	20	12
Maximum	302	154	232	204	295	124
Minimum	95	61	69	60	126	71
Mean	207	108	140	85	179	101
Median	209	107	129	77	181	102
Std. deviation	63	28	46	36	41	14

Table 3 Summary statistics of the suspended solids (SS) concentrations (mg/L)

	BSC catchment			PC catchment		
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Low flow						
No. of samples	21	19	18	15	18	9
Maximum	655	128	658	26	268	7
Minimum	0.5	1.2	2.5	0.8	0.2	3
Mean	118	35	102	10	22	4.3
Median	26	17	16	6.8	1.5	3.5
Std. deviation	179	40	174	6.8	50	1.4
High Flow						
No. of samples	38	25	29	17	24	13
Maximum	209	187	655	110	387	43
Minimum	5	3.5	8	4.2	1.5	2
Mean	64	48	113	31	47	12
Median	43	29	57	17	14	10
Std. deviation	62	52	130	31	89	11

maximum of 387 mg/L during high flow. In both catchments, the median of the SS concentration during low flow was consistently lower than that during high flow (Table 3). The SS concentrations at Sites 1, 2 and 3 of the BSC catchment frequently exceeded Graham's (1989) guidelines particularly during high flow events. The SS level in the PC was significantly lower than that in the BSC catchment and they were frequently within the recommended guidelines during both low and high flow events (Table 3).

The overall SS export coefficient for the BSC catchment was 953 kg/ha/yr. On a subcatchment basis, the SS export coefficient from the urban areas was almost three times higher than that from the rural area. On the other hand, the export coefficient for the PC catchment was 377 kg/ha/yr and it increased as water passed through the urban area due to the cumulative effect of the urban sources. This means that the export coefficient for Site 5 is higher than that for Site 6 (Table 5). A linear regression analysis confirmed a strong correlation ($p < 0.01$) between turbidity and SS concentration with R^2 values ranging between 0.77 and 0.96 (Fig. 2). This suggests that most of the turbidity was caused by the presence of SS and that turbidity can be used to predict SS concentration reliably in this catchment. The regression formulas were developed to facilitate future monitoring of the suspended solids without the need for lengthy field sampling and laboratory analysis that are necessary to determine SS concentrations.

Phosphorus (P)

Total P concentrations in the stormwater of both catchments ranged between 20 and 1970 μg/L and consistently exceeded the trigger value (20 μg/L) for protecting ecosystems in upland streams (ANZECC, 2000). The highest concentration was recorded at Site 1, below the STP, followed by Site 3 (Fig. 3). Total P concentration at Sites 4 and 6 (rural subcatchments) were lower than those at other sites. However, the concentrations at these two sites were still above the trigger value indicating that the two creeks were enriched with TP even before reaching the urban area. The STP effluent appeared to significantly enhance TP concentration at

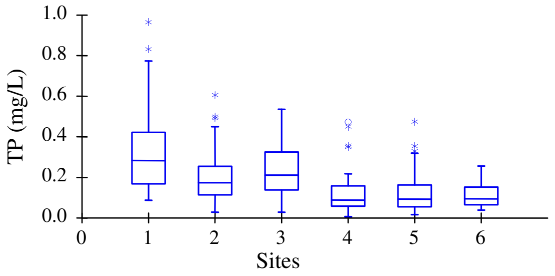

Figure 3 Box plots of TP (mg/L) in the BSC and PC catchments.

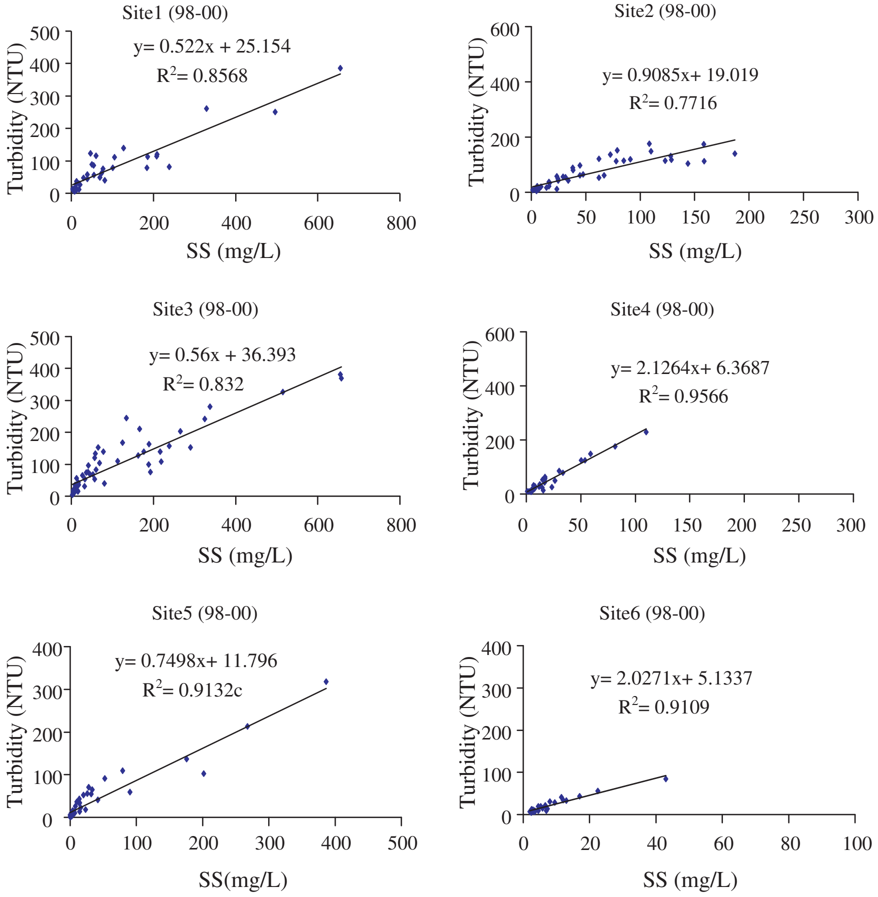

Figure 2 Relationship between turbidity and SPM concentration for the BSC and PC catchments (1998—2000).

Site 1in the BSC. The annual TP load discharged from the BSC catchment (18,040 kg/yr) was derived from diffuse sources (54%) and the STP point source (46%). Of the total TP load (Table 4), 73.5% was delivered during high flow events, which occurred over 30% of the time. The remaining 26.5% was transported by low flow, which occurred in 70% of the study period. During the same period, the annual TP load exported from the PC catchment was 2380 kg/yr (Table 4). Most of this mass load (92%) was delivered during high flow. The TP export coefficient for the BSC catchment, including the STP contribution (2.6 kg/ha/yr), was 5.2 kg/ha/yr. The Lower BSC and Rifle Range Creek subcatchments showed the highest export coefficients. The lowest export coefficient (1.3 kg/ha/yr) occurred at the rural BSC subcatchment. On the other hand, the export coefficient for the PC catchment was 1.0 kg/ha/yr. The Upper PC rural subcatchment yield was almost twice that of the Lower PC urbanised subcatchment (Table 5).

Filterable reactive phosphorus (FRP) is the proportion of the TP that is immediately available for uptake by biological organisms (Wetzel and Likens, 2000). ANZECC (2000) recommended a trigger FRP value of 15 μg/L, above which problems have been known to occur. FRP concentrations in the BSC catchment were found to range from 2 to 317 μg/L during low and high flow, respectively. During the same period, the FRP concentrations in the PC catchment were between 2 and 125 μg/L. Site 1, which includes STP effluent, had the highest concentrations followed by Site 3. Site 4, which is dominated by rural land use, had the lowest median FRP value. It appears that the STP effluent had the greatest single influence on the FRP level in the BSC. On the other hand, the FRP concentration was much lower in the PC, but FRP concentrations in both catchments were frequently above the trigger values (Fig. 4). The FRP concentration pattern was found to correspond closely with that of the TP concentrations in the respective catchments. The total FRP load

Table 4A Average yearly loads of the main pollutants discharged from the Blackmans Swamp Creek (BSC) and the relative contribution of different sources

Source contribution	TDS	SS	TP	TN
Total catchment, including STP contribution (kg)	7,710,000	3,287,050	18,040	254,600
STP (%)	NA	6.5	46	35
Site 1 — Lower BSC (%)	70[a]	51	21.4	35.7
Site 2 — Rifle Range, CBD (%)	18	24	19.7	16.3
Site 3 — East Orange (%)	9	15	8.7	8.8
Site 4 — Upper BSC (%)	3	3.5	4.2	4.2
Total%	100	100	100	100

TDS = total dissolved salt, SS = suspended solids, TP = total phosphorus, TN = total nitrogen, NA = not available.

[a] Including STP contribution.

Table 4B Average yearly loads of the main pollutants discharged from the Ploughmans Creek (PC) and the relative contribution of different sources

Source contribution	TDS	SS	TP	TN
Total catchment (kg)	2,345,000	8,84,975	2380	52,200
Site 5 — Lower PC (%)	92	97	74	83
Site 6 — Upper PC (%)	8	3	26	17
Total%	100	100	100	100

TDS = total dissolved salt, SS = suspended solids, TP = total phosphorus, TN = total nitrogen, NA = not available.

Table 5A Export coefficients for major pollutants in the Blackmans Swamp Creek (BSC) Catchment (kg/ha/yr)

Catchment	TDS	SS	TP	TN
Overall BSC catchment (including STP contribution)	2235	953	5.2	74
STP contribution to the BSC catchment	NA	62	2.4	26
Site 1 — Lower BSC	5044[a]	1567	3.6	86
Site 2 — Rifle Range, CBD	1309	744	3.4	39
Site 3 — East Orange	964	685	2.2	31
Site 4 — Upper BSC	386	192	1.3	18

TDS = total dissolved salt, SS = suspended solids, TP = total phosphorus, TN = total nitrogen, NA = not available.

[a] Including STP contribution.

Table 5B Export coefficients for major pollutants in the Ploughmans Creek (PC) catchment (kg/ha/yr)

Catchment	TDS	SS	TP	TN
Overall PC catchment	998	377	1.0	22.3
Site 5 — Lower PC	1009	434	0.9	21.9
Site 6 — Upper PC	507	69	1.7	23.7

TDS = total dissolved salt, SS = suspended solids, TP = total phosphorus, TN = total nitrogen, NA = not available.

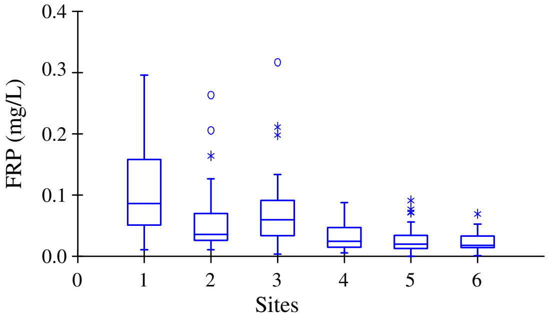

Figure 4 Box plots of FRP concentrations (mg/L) in the BSC and PC catchments.

exported by the BSC catchment, including the STP contribution, was 4950 kg/yr whereas the FRP load contributed by the PC catchment was 367 kg/yr. This means that the bioavailable phosphorus represented 27% and 15% of the TP loads in the BSC and PC catchments, respectively. The FRP export coefficient for the BSC catchment, excluding STP effluent, was 0.3 kg/ha/yr. The combined export coefficient for the Lower BSC and the STP was 0.7 kg/ha/yr. The export coefficient for the PC catchment was 0.1 kg/ha/yr.

Nitrogen (N)

Like P, availability of N is essential for plant growth but when present in excess it can cause growth of obnoxious algae and aquatic plants. The total nitrogen concentration (TN) in most samples analysed from both catchments exceeded the trigger level of 0.25 mg/L (ANZECC, 2000). The highest TN concentrations for both low flow (11.5 mg/L) and high flow (13.96 mg/L) were recorded at Site 1. This was due to the impact of the treated sewage effluent, which was being discharged into the BSC upstream of this monitoring site. The stormwater also picked up N as it passed through the urban area (Fig. 5). The TN the BSC indicated that its concentration was high even before the creek water entered the urban area and it increased progressively as the water passed through the urban area. In the PC catchment, TN varied from a minimum of 0.44 mg/L (Site 5) during low flow to a maximum of 6.18 mg/L (Site 6) during high flow. The median values in this catchment were lower at the outlet (Site 5) than at the inlet (Site 6) during both high and low flow (Fig. 5). This decrease in TN concentration downstream could be due to a dilution effect and denitrification of nitrite and nitrate into gaseous nitrogen. The TN load for both catchments showed a progressive increase with distances downstream. The annual TN load exported by the BSC catchment was 254 600 kg/yr. Of this mass load, diffuse sources contributed 65% and the STP provided 35%. Almost 70% of the TN load was transported through the BSC catchment during high flow. During the same period, the annual TN load transported from the PC catchment was 52,200 kg/yr. Of this only 11% of the load was transported during low flow. The TN export coefficients were 74 kg/ha/yr in the BSC catchment, including the STP contribution, and 22 kg/ha/yr in the PC catchment (Table 5).

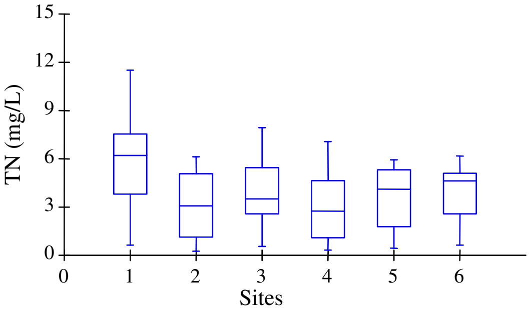

Figure 5 Box plots of total nitrogen (TN) in the BSC and PC catchments.

Nitrate—nitrite N (NO$_x$-N) concentration in the BSC catchment reached a maximum value of 8.45 mg/L at Site 1 which is substantially higher than the trigger value (0.015 mg/L) for environment protection. Again, the STP appears to be the most important contributor to oxidised nitrogen in the BSC catchment. In the PC catchment, oxidised N concentrations were significantly lower with values ranging from 0.01 mg/L (Site 6) to 2.41 mg/L (Site 5). The total annual load discharged by the BSC catchment was 9910 kg/a. Of this, diffuse sources contributed 29% and the STP provided 71%. During the same period, the oxidised N load yielded from the PC catchment was 3400 kg/yr. The oxidised N load accounted for 35% of TN load in the BSC catchment and 7% in the PC catchment. Its export coefficient was 3.8 kg/ha/yr and 0.7 kg/ha/yr in the BSC and PC catchments, respectively. Both annual loads and export coefficients demonstrate that the oxidised N level increased as water passed through the urban area.

The concentration of ammonium-N (NH$_4$-N) in the BSC during low flow (0.18—0.37 mg/L) was substantially higher than that in the PC (0.10—0.14 mg/L). Both creeks were enriched with ammonium-N and frequently exceeded the trigger value of 0.013 mg/L (ANZECC, 2000). The total ammonium-N loads discharged were 10,673 kg from the BSC catchment and 1687 kg from the PC catchment. The NH$_4$-N load represented 3% and 4% of the total TN load in the BSC and PC catchments, respectively. Ammonium-N export coefficients were 1.6 kg/ha/yr in the BSC catchment and 0.4 kg/ha/yr in the PC catchment. Unlike the BSC, the ammonium-N in the PC decreased as water passed through the urban area, possibly due to rapid nitrification to oxidized N.

Heavy metals

During the study period, water samples collected on 13 separate occasions, from each of the six Sites, were tested for lead, zinc and copper. The results indicated that the Zn

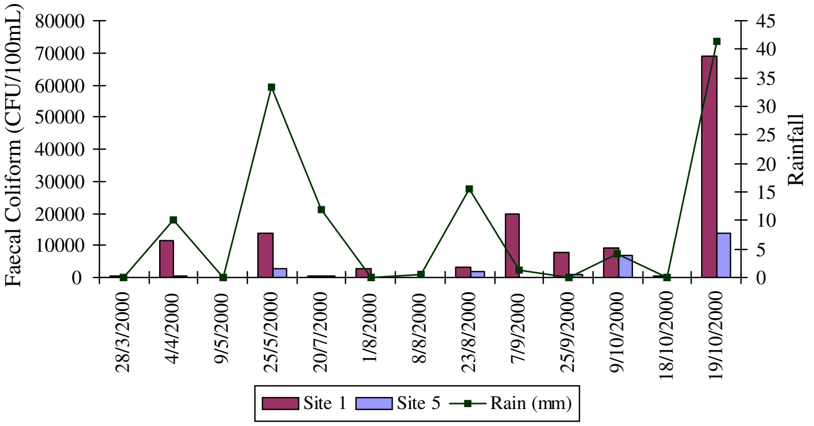

Figure 6 Fecal coliforms at the outlets of the BSC and PC catchments.

concentrations were generally within the recommended guidelines (50 μg/L) for the protection of aquatic ecosystem (ANZECC, 2000) but copper and lead concentrations were almost always above the guidelines (10 and 25 μg/L, respectively). The copper concentration ranged from a minimum 55 μg/L (Site 1) to a maximum 140 μg/L (Site 4). The lead concentration ranged from a minimum 250 μg/L (Site 1) to a maximum 740 μg/L (Site 3).

Biological oxygen demand (BOD$_5$)

Biological oxygen demand is the amount of oxygen required to oxidise the organic matter in water. High BOD means that there is a large amount of organic matter present in water which may cause oxygen depletion due to organic pollution (Harrison, 1990; Chapman, 1996). Graham (1989) stated that the desirable level of BOD in urban stormwater should not be below 2 mg/L. Five-day BOD tests were carried out on 16 different occasions during the study period at Sites 1 and 5, the outlets of the BSC and PC catchments, respectively. The results indicated that BOD varied from 0.6 to 16.9 mg/L at Site 1 and from 2 to 11.3 mg/L at Site 5. With the exception of one sampling occasion (November 1999) the BOD levels in both the BSC and the PC did not meet the criteria for the protection of the ecosystems and indicated a moderate to high organic pollution level in the receiving water. Based on the BOD values, Site 1 exhibited the most polluted water which is most likely caused by the STP effluent discharged upstream of this site.

Fecal coliforms

Fecal coliforms bacteria in water are measured to give an indication of the likely presence of pathogenic microorganisms. The main sources of these bacteria are sewage and domestic wastewater effluent and runoff from abattoirs, feedlots, dairies and hospitals (Chiew et al., 1997). Twenty six water samples, collected during dry and wet periods from Sites 1 and 5, were analyzed in the Central West Regional Laboratory, Orange. The fecal coliform concentrations varied markedly from site to site. The Australian recreational guideline states that the safe level of fecal coliforms for swimming should be less than 150 CFU/100 mL based on the median value from five samples per month (ANZECC, 1992). Fecal coliforms in more than 75% of samples were above the recreational guideline which indicated that the water was unsafe for recreational activities. Mean concentrations of fecal coliforms were also found to be above the secondary contact and livestock drinking water quality criteria (1 000CFU/100 mL) on several occasions at Site 1 (Fig. 7). During high rain periods, fecal coliforms were high at Site 1 reaching a maximum of 69,000 CFU/100 mL. This high value indicated possible sewage overflow, and possibly bird and mammal feces in the stormwater runoff, and inputs from other diffuse urban sources. Generally fecal coliform concentrations were higher in the BSC than in the PC, particularly during storm events (Fig. 6).

Discussion

According to ANZECC (2000) guidelines the impact of stormwater runoff on the quality of the receiving water is negligible in terms of temperature, pH and DO in both the BSC and PC catchments. Although salinity (TDS) levels were also within the recommended guidelines (300 mg/L) for most occasions, the catchment may be at risk of water salinisation in the long-term if current practices are continued. Turbidity level was relatively modest during low flow, but it became much higher during storm events. Both catchments experienced moderate to serious stormwater pollution in terms of TP, FRP, TN, oxidised N, ammonium-N, SS, fecal coliforms and heavy metals during most of the study period. The PC catchment contributed considerably less input to the overall load of the Orange urban catchment than that provided by the BSC catchment. The water quality of the BSC was more seriously degraded than that of the PC. This difference is attributed partly to variation in catchment size, land use and intensity of urbanisation (diffuse sources) and partly to the adverse impact of the point source (STP effluent) on the BSC waterways. Surface runoff and stream flow regime were critical in determining temporal and spatial variation in pollutant concentration and mass load. During wet weather and high runoff, elevated concentrations of SS, TP, FRP, TN, and fecal coliforms were evident. However, nutrient levels exceeded the environment protection guidelines even during low flow conditions. The impact of the STP effluent on the water quality of the BSC catchment varied considerably over time. During periods

Table 6 Comparison of TP and TN export coefficients in the Orange urban catchment and other urban catchments in Australia

Catchment	TP export coefficient (kg/ha/yr)	TN export coefficient (kg/ha/yr)	Source
Various	1.2	6	O'Loughlin et al. (1992)
South East Australia (several)	1.0	6.6	Young et al. (1996)
South East Australia	0.6	6.0	Rosich and Cullen (1982)
Sydney stormwater project	0.6	5.4	Linforth (1995)
Nepean Hawkesbury	1.2	9.3	Linforth (1995)
Various	0.6	NA	Donnelly et al. (1998)
Hawthorn	0.7	4.9	Weeks (1982)
Haslam's Creek	2.1	14.0	Sinclair Knight Merz (1999)
Duck River	0.2	1.7	Sinclair Knight Merz (1999)
Orange urban catchment excluding treated STP effluent	2.1	37.5	This study
Orange urban catchment including treated STP effluent	3.5	52.9	This study

NA = not available.

of low runoff, receiving water quality at Site 1 was dominated by the controlled release of the STP effluent. On the other hand, the impact of this point source was moderated significantly during high stormwater runoff periods. It is evident that stormwater runoff in the urban catchments contributed harmful pollutants to the natural waterways regardless of the influence of the treated STP effluent. However the discharge of sewage effluent was potentially more damaging. Stormwater runoff in the PC catchment was of better quality than that in the BSC catchment due to the absence of significant point sources as well as the absence of intensive industrial and commercial activities in this catchment. In wet weather, the pollutant concentration in the PC also exceeded the environmental protection guidelines. In general, the water quality in the waterways of both catchments declined as water passed through the urban area.

In terms of pollutant mass load discharged from the BSC catchment, the point source (STP effluent) contributed on average 6.5% SS, 35% TN and 46% TP whereas the diffuse

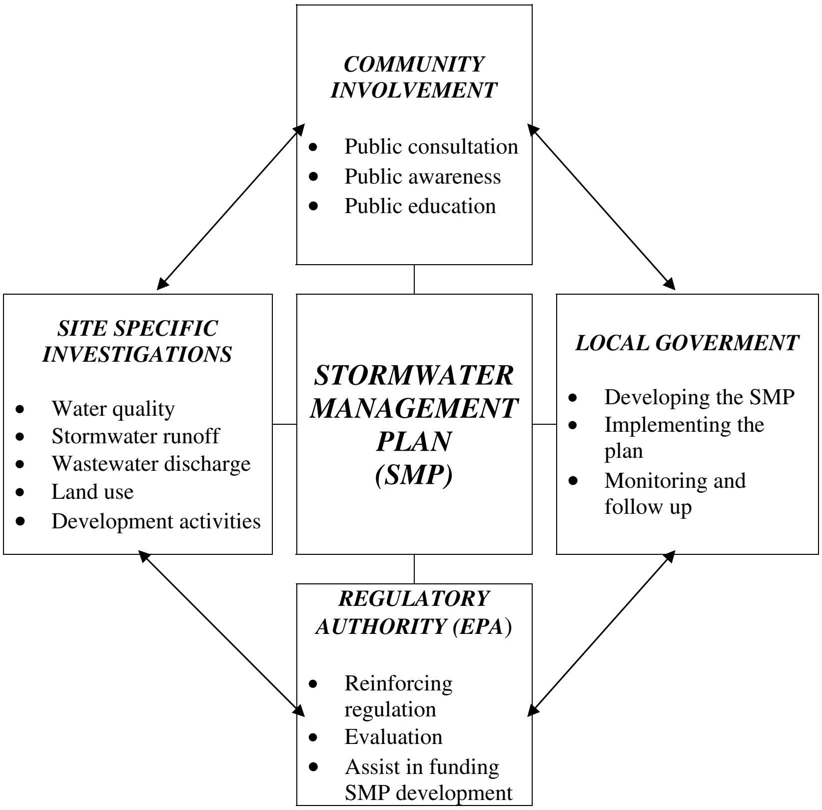

Figure 7 Conceptual model for the development of sustainable stormwater management plan (SMP).

sources (stormwater runoff) accounted for the balance. The pollutant mass loads discharged from the PC catchment were significantly less than those contributed by the BSC catchment and were entirely derived from stormwater runoff (Table 4). The dominance of the BSC catchment to the overall Orange catchment was confirmed by the yield values. The export coefficients of the TDS, SS, TP and TN in the BSC catchment were 3–6 times higher than those produced from the PC catchment (Table 5).

A comparison of the stormwater quality, in terms of export coefficient (Table 6), showed that the TP yield per unit area in the Orange urban catchment (3.5 kg/ha/yr) was considerably higher than the range of TP export coefficients reported in other Australian urban catchments (0.2–2.1 kg/ha/yr). The comparison was even more striking in terms of TN, where the export coefficient in Orange (5 kg/ha/yr) was 4–31 fold higher than those reported for other Australian urban catchments (1.7–14 kg/ha/yr). Even without the contribution of STP effluent, the Orange urban catchment is characterised by relatively high TP and TN export coefficients (2.1 kg/ha/yr and 38 kg/ha/yr, respectively). The nutrient enrichment of the Orange urban waterways (Table 6) is mainly due to the combined effect of the STP effluent (point source) and the diffuse sources from the naturally P-rich basaltic soils dominating the catchment (Al Bakri and Rahman, 2002).

Comparing the Orange urban catchment, which is situated in the upland country of NSW, with coastal urban catchments that are similar in population and land use (Clarence Estuary and Brunswick River catchments) revealed an interesting difference in terms of flow and pollution loads. In the Orange catchment, the contribution from urban sources accounted for 93% and 94% of the TP and TN mass loads, respectively. In contrast, the rural sources in the two coastal catchments were far more dominant than the urban sources. The rural sources contributed 81–99% of nutrient mass loads in those coastal catchments, whereas the urban sources contributed only between 1.0% and 19% (Eyre, 1997, 1998; Mashiah, 2002). This striking difference is attributed largely to the fact that the Orange catchment is situated in the headwater of its river system and as such the rural runoff into the urban part of the catchment was limited (<10% of the catchment flow). The coastal catchments, on the other hand, are located at the end of their river systems and thus rural inflow into the urban area is substantially more than those in the upland catchments. This comparative assessment may indicate that the relative impact, per capita, of urban stormwater pollution on natural river systems is more serious in the upland urban catchments than in the coastal urban catchments. This contrast should be taken into consideration when developing stormwater management strategies at the regional and national level.

Conclusions

The study has revealed that receiving water in the Orange urban catchment has expressed moderate to high levels of pollution during most of the study period in terms of P, N, SS, heavy metals, fecal coliforms, and, to a lesser extent, TDS. Some of those pollutants, particularly nutrients and SS, increased as the stormwater passed through urban areas. However, rural stormwater runoff also showed relatively high concentrations of nutrients even before reaching the urban part of the catchment. As a result, the water discharged from this catchment degrades the water quality and disrupts the aquatic ecosystems in receiving environments. It is evident therefore that the current level of effort and practices concerning stormwater management in Orange fall short of meeting regulatory requirements particularly in terms of the nutrients P and N in the natural waterways of the catchment.

To mitigate the impact of stormwater runoff, a stormwater management plan (SMP) that took into consideration environmental, social and economic dimensions was developed. The conceptual model used to define the key factors and relationships that were considered in the development of the SMP is shown in Fig. 7. The site specific study here provided a relevant and reliable database on the physical, chemical and biological characteristics and land use of the

Table 7A Short-term implementation strategy of stormwater management options (2003–2006)

Management option	Ranking
Establish council working party	1
Implement existing community awareness programs	2
Implement community education programs	3
Sweep roads and car parks regularly	3
Collect autumn leaves	3
Conduct data gathering and monitoring	4
Establish catchment Care Committee	5
Conduct education and training programs for staff, builders and developers	6
Drain stencilling	8
Install sand and aggregate filters at construction sites	9
Review of council policies	10
Restoration of riparian vegetation	11
Construct GPT at corner of Bathurst Road and Allenby Road	11
Streambank stabilisation	14

Table 7B Long-term implementation strategy of stormwater management options (2007–2025)

Management option	Ranking
Low maintenance gardens	7
Install energy dissipaters	9
Install additional rubbish bins	11
Implement salinity control measures	12
Install GPT at Dalton Street	13
Provide public access to waterways	14
Construct artificial wetlands at Ploughmans Creek	15
Construct artificial wetlands at Blackmans Swamp Creek	16
Construct additional detention basins	17

catchment and its waterways. The second important component of the model was community involvement as people are the main contributors to stormwater pollution and their attitudes and actions influence the health of waterways (Dietz et al., 2004).This model assumes that the local authority, in this instance Orange City Council, must take proactive initiatives to develop, implement and monitor effective management strategies. The regulatory authority (NSW-EPA) contribution involved issuing and reinforcing regulations to guide the local authority regarding implementation and monitoring of the management plan.

The SMP in Orange consisted of a combination of structural and non-structural management options aimed at preventing stormwater pollution from existing and new developments, improving public awareness of stormwater issues, eliminating improper discharges into stormwater systems and controlling stormwater impact on the receiving water (Al Bakri and Rahman, 2002). Structural options aim to reduce stormwater pollution by using existing or new infrastructure or natural resources and typically address the immediate and often visible stormwater problems (NSW-EPA, 1998). Non-structural options aim to reduce the amount of pollution entering the waterways that is preventing pollution through human behavioural changes. Table 7 shows the short-term and long-term implementation strategies ranked by the public forum participants taking into consideration the relationship between stormwater issues, values and objectives as well as benefit-cost assessment. The implementation strategy is intended to ensure that the management options are carried out according to the vision and aspirations of the community and stakeholders (Rahman and Al Bakri, 2001).

In addition to the management options listed in Table 7, Orange City Council issued permission to a local mine (Cadia Gold Mine) to divert a significant portion of the STP effluent for reuse at the mine site, which is located outside the Orange urban catchment. A follow up study is recommended to evaluate the effectiveness of this and other implemented management strategies on the water quality in the Blackmans Swamp Creek.

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References

Al Bakri, D., Rahman, S., 2002. Stormwater pollution in inland centres: Orange urban catchment. In: Stormwater Industry Association 2002 Conference on Urban Stormwater Management, Orange, NSW, 23—24 April.

Anon, 1981. Characterisation of pollution in urban stormwater runoff. Technical Paper No. 60. Australian Water Resources Council and Department of National Development and Energy, Canberra.

ANZECC, 1992. Australian Water Quality Guidelines for Fresh and Marine Waters. Australian and New Zealand Environment and Conservation Council, Canberra.

ANZECC, 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, vol. 1, The Guidelines, Canberra, Australia.

APHA, 1992. Standard Methods for the Examination of Water and Wastewater, 19th ed., American Public Health Association, Washington, DC, 1992.

Argue, J., 1997. Stormwater management and ESD: water sensitive urban design in Stormwater in the next millennium: exportable innovations in stormwater management. The Levels, University of South Australia, October 23, Hydrological Society of South Australia, South Australia, pp. 21—26.

Chapman, D., 1996. Water Quality Assessment: A Guide to the use of Biota, Sediments and Water in Environmental Monitoring, second ed. E and FN Spon, UK.

Chiew, F.H.S., Mudgway, L.B., Duncan, H.P., McMahon, T.A., 1997. Urban stormwater pollution, Industry Report 97/5. Cooperative Research Centre for Catchment Hydrology, Clayton, Victoria, Australia.

Cordery, I., 1976. Some effects of urbanisation on streams, Civil Engineering Transactions, Institution of Engineers, Australia, 18, 7—11.

Dietz, M.E., Clausen, J.C., Filchak, K.K., 2004. Education and changes in residential nonpoint source pollution. Environmental Management 34 (5), 684—690.

Donnelly, T.H., Barnes, C.J., Wasson, R.J., Murray, A.S., Short, D.L., 1998. Catchment phosphorous sources and algal bloom — an interpretive review, Technical Report 18/98, CSIRO Land and Water, Canberra, p. 62.

Duncan, H.P., 1997. Urban stormwater treatment by storage: a Statistical overview, Report 97/1. Cooperative Research Centre for Catchment hydrology, Victoria.

Eyre, B., 1997. Contribution of sewage effluent to the Brunswick Estuary Nutrient Budget. Report for Byron Shire Council, November 1997.

Eyre, B., 1998. Water quality in the Clarence Estuary, in Clarence River estuary process study (Appendix C). Manly Hydraulic Laboratory Draft Report MHL 971, Sydney.

Graham, R.A., 1989. Urban stormwater quality improvement in a detention pond and wetland system. Doctor of Philosophy thesis, University of Melbourne, p. 103.

Griffin Jr., D.M., Gizzard, T.J., Randall, C.W., Hessle, D.R., Hartigan, J.P., 1980. Analysis of non-point pollution export from Small Catchments. Journal WPCF 52, 780—790.

Harrison, R.M., 1990. Pollution: Causes, Effects, and Control, second ed. The Royal Society of Chemistry, Cambridge.

Hosomi, M., Sudo, R., 1986. Simultaneous determination of total nitrogen and total phosphorus in freshwater samples using persulphate digestion. Journal of Environmental Studies 27, 267—275.

Joliffe, I.B., 1995. Hydrological cycle and impacts of urbanisation. In: Sharpin, M.G. (Ed.), Environmental Aspects of Urban Drainage, Concord Function Centre, Sydney, 22 August, Stormwater Industry Association, Sydney, pp. 1—20/2.

Kenkel, J., 1986. Analytical Chemistry for Technicians. Lewis Publisher, Boca Raton, Florida, USA, pp. 1—541.

Kronvang, B., Bruhn, A.J., 1996. Choice of sampling strategy and estimation method for calculating nitrogen and phosphorus transport in small lowland streams. Hydrological Process 10, 1483—1501.

Linforth, S., 1995. Estimating diffuse source loads and sewer overflows in urban environments. In: The Second International Symposium on Urban Stormwater Management, Melbourne, Australia, 11—13 July 1995. The Institution of Engineers, Australia Preprints of Papers, National Conference Publication No. 95/03, 223—228.

Lyall and Macoun Consulting Engineers, 1997. Orange Stormwater Drainage Study, vol. 1, Main Report, Sydney.

Lyall and Macoun Consulting Engineers, 1998. Constructed wetland at Ploughmans Lane, Orange, Investigation and Concept Design Report, Lyall and Macoun Consulting Engineers, Chatswood, Sydney.

Mashiah, G., 2002. Rural pollution loads in urban stormwater environments. In: Proceedings of the Sixth Regional Conference on Urban Stormwater Exploding The Myths-Stormwater Driving The Water Cycle Balance, Stormwater Industry Association, 23—24 April, Sydney (7 pages).

Morse McVey and Associates, 1997. Feasibility study for the construction of wetlands at nine locations in the City of Orange, Sydney.

NSW-EPA, 1998. Managing Urban Stormwater: Council Handbook, Environment Protection Authority, Chatswood, Sydney.

Novotny, V., 1994. Diverse solutions for diffuse pollution. Water Quality International, International Association for Water Quality 1, 24—31.

O'Loughlin, G., 1994. Pollution prevention and politics — The recent experience in Sydney. Water Science and Technology, IAWQ 30, 13—22.

O'Loughlin, E.M., Young, W.J., Molloy, J.D., 1992. Urban stormwater: impacts on the environment, a report from CSIRO to the Honourable Ros Kelly, Minister for Arts, Sport, the Environment and Territories, Consultancy Report No. 92/29, Canberra.

Pogson, D.S., Watkins, J.J., 1998. Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory notes, Geological Survey of New South Wales, Sydney.

Preston, S.D., Bierman, V.J.J., Sillimanman, S.E., 1989. An evaluation method for the estimation of tributary mass loads. Water Resources Research 25, 1379—1389.

Rahman, S., Al Bakri, D., 2001. Impact of point sources and diffuse sources on stormwater quality in Orange, NSW, Australia. In: Brebbia, C.A., Anagnostopoulos, P., Katsifarakis, K., Cheng, A.H-D. (Eds.), Water Resources Management. WIT Press, Southampton, Boston, pp. 195—204.

Rahman, S., Al Bakri, D., 2006. Urban stormwater hydrology in rural catchments. Water Journal, AWWA (May), 38—43.

Rosich, R.S., Cullen, P., 1982. Nutrient runoff. In: Hart, B.T. (Ed.), Water Quality Management: Monitoring Programs and Diffuse Runoff. Water Studies Centre, Chisholm Institute of Technology and Australian Society of Limnology, Melbourne, pp. 103—119.

Settacharnwit, S., Buckney, R.T., Lim, R.P., 2003. The nutrient status of Nong Han, a shallow tropical lake in north-eastern Thailand: spatial and temporal variations. Lakes and Reservoirs: Research and Management 8, 189—200.

Sinclair Knight and Partners, 1980. Orange drainage study, Orange City Council and Bathurst-Orange Development Corporation, Sydney.

Sinclair Knight Merz Pty. Ltd, 1999. Duck River stormwater management plan, Final, St Leonards, NSW.

Weeks, C.R., 1982. Pollution in urban runoff. In: Hart, B.T. (Ed.), Water Quality Management Monitoring Programs and Diffuse Runoff. Water Studies Centre, Chisholm Institute of Technology and Australian Society of Limnology, Melbourne, pp. 121—140.

Wetzel, R.G., Likens, G., 2000. Limnological Analyses, third ed. Springer-Verlag, Inc., New York.

Woodward-Clyde, 1995. Cadia Gold Mine Environmental Impact Statement. AGC Woodward-Clyde, Sydney, vol. 2, Appendices.

Young, W.J., Marston, F.M., Davis, J.R., 1996. Nutrient exports and land use in Australian catchments. Journal of Environmental Management 47, 165—184.