Assessing catchment water quality: The “Snapshot Study”

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Abstract

Monitoring catchment water quality is typically based on monthly/weekly grab sampling at-a-site over a given length of time. Interpretation of water quality data is then usually based on threshold criteria (ANZECC/ARMCANZ, 2000) and the catchment response evaluated relative to these values. However, monitoring programs of this nature rarely capture all catchment processes operating at the time of sampling and therefore evaluation of catchment response is limited. A recent approach to characterising catchment water quality has been the “Snapshot Study”. The Snapshot Study is based on three fundamental criteria including categorising catchment landuse, designing a sampling/analysis strategy based on catchment hydrology and knowledge of the climatic conditions before and during the time of sampling. Results from various source-tracking techniques are then used to compare relative contaminant contributions from mixed landuses. The snapshot study allows numerous sites within a catchment to be sampled and results can be interpreted in the context of the hydrological processes at the time. This provides a water quality “fingerprint” of catchment waterways, whilst allowing an improved evaluation of potential contaminant sources and subsequent waterway health. However, the interpretation of contaminant contributions using different source-tracking techniques resulted in contradiction in several sub-catchments. This was considered an important outcome between sub-catchments and ultimately characterised sub-catchment water quality. The monitoring approach is novel and this paper discusses the main outcomes from two snapshot studies undertaken, whilst highlighting the complex relationships between landuse and catchment/sub-catchment water quality.

Introduction

Over the past decade, increasing urban development in catchments near sensitive estuarine environments has resulted in elevated microbial and nutrient loads in natural waterways (Beal et al., 2003 Vaelia et al., 1997; Wieskel and Howes, 1991). The research has described an important relationship between activities on land, the quality of runoff from different land uses and the contamination of receiving waters.

Many coastal urban areas are experiencing population growth and increased development. In many instances, water quality in adjacent and downstream of waterways has been compromised due to contaminant export from various landuses within respective catchments. Methods undertaken to monitor water quality typically utilise monthly sampling over a given period. Results are usually interpreted with respect to threshold values in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ARMCANZ, 2000) to evaluate the potential impact on natural waterways and ecosystems. However this approach means that the collected data may not reflect the catchment processes operating at the time, which is an important aspect of evaluating catchment response and particularly in creating an effective catchment water quality management plan.

A recent approach to characterising catchment water quality has been the “Snapshot Study”. The Snapshot Study is based on three fundamental criteria including categorising catchment landuse and designing a sampling/analysis strategy based on catchment hydrology and knowledge of the climatic conditions before and during the time of sampling. Results from various source-tracking techniques are then used to compare the likelihood of contaminant contributions from different landuses. The benefit of this holistic approach is that water quality data from all major hydrological pathways (that reflect different landuses) can be obtained and interpreted in the context of the climatic conditions at the time. The usefulness of this approach is improved if several “snapshots” are taken over a range of climatic conditions and hydrological settings. Outcomes from two snapshot studies are presented and discussed during this paper.

Background

For microbial and nutrient contamination to be a problem there needs to be a source that can be mobilised and transported to a specific location where adverse effects are expressed. The likely sources of the contamination in a catchment are often highly contentious and many sources are usually identified as having the potential to contribute to poor runoff water quality. Possible sources of contamination potentially include failing septic tank/absorption trench systems in unsewered areas, urban stormwater runoff from directly routed drainage networks, runoff from fertilised agricultural lands containing livestock, waterway users such as boating marinas (wastewater pump-outs) and sewerage treatment plant discharges.

As a result, water quality monitoring programs aim to detect exceedances in threshold guidelines which in turn trigger the catchment management response. Contaminant export in some catchments has been linked to threshold rainfall events, thus monitoring programs focus on monitoring water quality after rain events. For example, the NSW Shellfish Quality Assurance Program (SQAP) monitors water quality in shellfish harvesting areas after wet weather. In these catchments, surface runoff from surrounding areas usually contains elevated faecal coliform concentrations, which may trigger the closure of some areas if concentrations are believed to be a risk to human health. However, most water quality monitoring programs occur at regular intervals (weeks to months), and whilst many record hydrological conditions at the time it is difficult to extrapolate the influence of sub-catchment flows to actual contaminant loads from the data with any confidence.

So what are the limitations of monitoring programs that occur at regular intervals? Firstly, consider Figure 1 which conceptualises a range of different sub-catchments and landuses within a catchment. A typical monitoring program would sample at point "X" which represents end-of-system water quality. In addition, other samples would possibly be taken near or adjacent to known point sources (such the sewerage treatment plant (STP)). However, even if there was a dominant contaminant source in the catchment, the current monitoring approach would not be able to ascertain the specific source. This poses a fundamental problem in creating an optimal catchment water quality management plan.

Secondly, the conservative/non-conservative nature of the multitude of contaminants present in the catchment would not be reflected in water quality analysis at point "X". For example, dilution during wet weather would most likely mask any significant elevated contaminant concentrations that would indicate a specific contaminant source. This too limits the opportunity to create an optimal catchment water quality management plan.

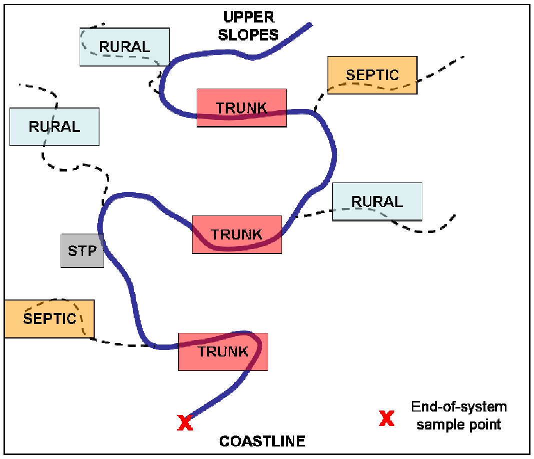


Figure 1: Conceptualised catchment and sub-catchments/landuses

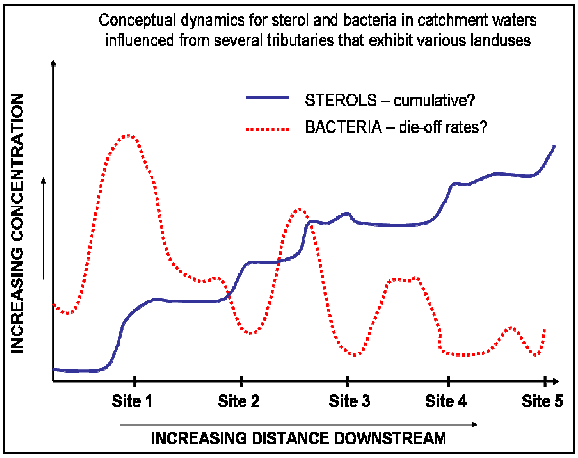


Figure 2: Example of Conservative/non-Conservative contaminants

Most contaminants are likely to behave differently depending on the hydrological setting at the time (wet/dry, high/low flows) and distance downstream from the point/diffuse source. Figure 2 conceptualises this using faecal sterols (cumulative) and bacteria (die-off rates) as examples. Faecal sterols are conservative in sediment and water in the environment (as suggested in Reeve and Patton, 2005) and have the potential to be "flushed-out" with sediment and surface runoff. Faecal sterols are likely to accumulate in catchments waters as they are transported downstream, which may result in a cumulative effect at the end-of-system. The die-off of bacteria is commonly known to occur in natural waters, particularly with increased salinity and/or low nutrient and oxygen levels. Bacteria are likely to be sourced from several sub-catchments/landuses and undergo increases/decreases in populations along different reaches within the catchment. This variability cannot be detected when end-of-system monitoring approaches are implemented.

In addition, Figure 2 highlights the different scenarios open for interpretation when sampling occurs at several downstream sites within the catchment (sites 1 – 5). Bacteria levels exceed sterol levels at site 1, yet the result is reversed at site 2 (sterol concentrations > bacteria concentrations). Sites 3 to 5 then revert to results similar to site 1 (bacteria concentrations > sterols concentrations). It can be seen that end-of-system monitoring would not enable this insight to be observed.

So what makes the "snapshot study" an improved approach to the way monitoring is currently undertaken? Using Figure 1 as a conceptual example, the snapshot study approach would sample waters from each of the sub-catchment/landuse tributaries and several river samples (trunk). The results obtained from many characterised sites during one study allow the contaminant contributions from each sub-catchment/landuse and resultant trunk sample to be evaluated in context of the hydrological setting at the time. Due to the complexity and dynamic nature of catchment processes, producing a detailed snapshot of catchment water quality during several wet/dry periods is likely to provide an improved water quality "fingerprint" based on relative results from source-tracking indicators and bacteria species presence/abundance. Furthermore, the spatial and temporal attributes of data obtained during several snapshot studies is vital for calibrating hydrological models to better understand catchment water quality and implement optimal catchment water quality management plans.

A project involving the analysis of sources of faecal contamination in 14 catchments on the north coast of New South Wales using faecal sterol analysis, antibiotic resistance analysis and bacterial surveys has been reported by Shah et al. (2006a). This research has established that faeces from humans, herbivores, carnivores and birds can be distinguished by their faecal sterol signatures. Concentrations of coprostanol have been found to be highest in samples associated with outfalls from sewage treatment plants (STP) and lowest in samples taken from forested catchments. There did not appear to be a unique biomarker that can be utilised for tracking of human faecal contamination. Nevertheless, high concentrations of coprostanol may indicate the potential for human faecal contamination.

Shah et al., (2006b) established that elevated concentrations of coprostanol and faecal sterols in streams were observed during both wet and dry periods. Average concentrations of coprostanol were highest in catchments with sewage treatment plants and lowest in forested catchments. Average faecal coliform counts were lower in pristine catchments than in catchments subject to human or agricultural contamination. Concentrations of coprostanol and faecal coliforms were higher during dry periods in catchments containing cattle. Coprostanol concentrations can be used to distinguish between forested catchments and catchments subject to faecal contamination from septic, cattle and sewage treatment plants.

Another technique used by researchers to distinguish between contaminant sources is antibiotic resistance analysis (ARA). The higher the resistance of bacteria to selected antibiotics, the higher the likelihood of the presence of human contamination. For example, using selected bacterial species that reflect faecal contamination and are common to both herbivores and humans, the bacteria species in humans will have will show a higher resistance to selected antibiotics than the same bacteria sourced from other sources (e.g. herbivores, birds, dogs, etc).

Interpretation of data obtained using the snapshot approach, as opposed to regular time-based end-point monitoring, is likely to provide greater insight into catchment water quality and highlight likely contributors to contaminant loads in different parts of the catchment. Two case studies are discussed in the following section and while actual results are not presented the major outcomes from the studies are highlighted to show the benefits of the snapshot study approach (compared to time-based monitoring) and the implications for characterising catchment water quality.

Case Studies: Tilligerry Estuary (NSW) and Maroochy (QLD)

Tilligerry Estuary (NSW)

The aims of the snapshot study were (a) to gain insight into the water quality of major surface drains, Tilligerry Creek and of the estuary after a particularly wet event; and (b) to identify the most likely sources of faecal contamination.

The rainfall record showed approximately 200 mm had fallen in the four days prior to the sampling day. In addition to large areas of ponded surface water throughout the catchment, considerable flows were also observed in all surface drains towards the estuary on the sampling day. Sample sites are shown in Figure 3.

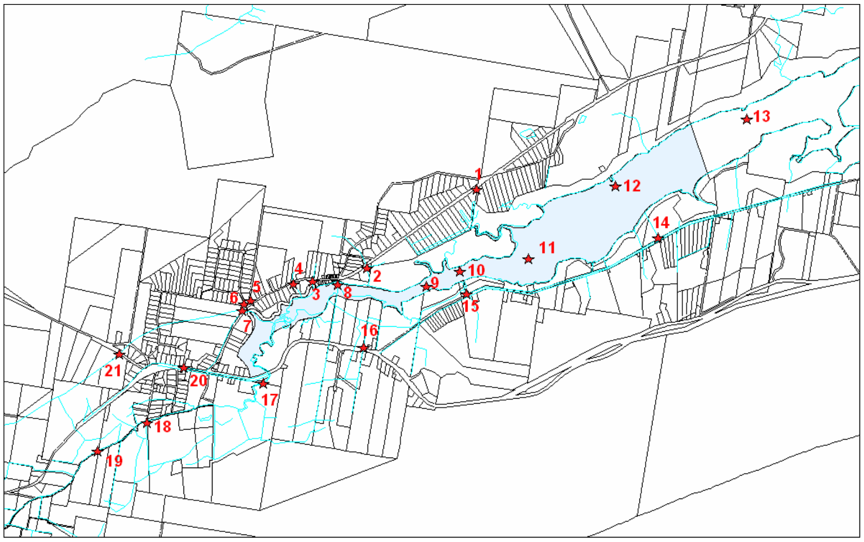


Figure 3: Sample sites for the Tilligerry Estuary snapshot study (Port Stephens, NSW)

Nutrient results at all sites draining to the estuary and within the estuary did not reflect any specific source of faecal contamination. Nitrate (NO_3^-) concentrations did not exceed 0.9 mg/L and thus fell well below the threshold guideline of 10 mg/L for recreational waters (ANZECC/ARMCANZ, 2004). Phosphate (PO_4^{3-}) concentrations however were shown to exceed 0.2 mg/L, the concentration threshold for potential algal blooms in natural waterways.

Of particular interest was the increasing EC gradient from site 8 to 13 (150 – 35,000 µS/cm). These results illustrated the salinity gradient along the terminal reach of the estuary and suggested that oyster leases in this reach (zones 5A and 5B) are effectively subject to little more than water quality indicative of rural stormwater runoff. Furthermore, bacterial and viral die-off are most effective in waters with higher electrical conductivities (i.e. those typical of seawater) (Hoang Pham, N.K., 2006), and the poor mixing of catchment runoff and estuarine waters in the Tilligerry catchment have considerable implications with respect to die-off rates in this reach of the estuary. Bacterial transport and die-off rates within the Tilligerry catchment can only be further clarified by 3-D modelling of hydrological pathways and mixing regimes to and within the estuary.

Sites in the estuary (sites 8, 9, 10, 11, 12, 13) displayed the highest faecal coliform numbers of all locations. The relative high faecal coliform numbers recorded at sites entering the estuary indicated that faecal contamination from most surface drains was likely to contribute to elevated faecal coliform counts in the estuary.

The sites upstream from the main floodgates (sites 17, 18 and 19) generally had relatively higher sterol concentrations when compared to other sample sites draining to the estuary. Since the creek channel is likely to provide the greatest flows to the estuary, then the highest faecal sterol loads to the estuary are also likely to emanate from the main Tilligerry creek channel.

Compared to surface drainage waters, faecal sterol concentrations in the estuary (sites 8 – 13) were amongst the highest recorded in the study and there are two possible explanations. Firstly, faecal sterols may accumulate in the freshwater “tongue” that enters the estuary after heavy rainfall and secondly, faecal sterols accumulated in sediment around the estuary margin are likely to be re-suspended by turbulence from stormwater runoff after heavy rainfall events. Further research is required to improve our understanding of these processes and the potential impact to water quality in Tilligerry estuary.

Maroochy (QLD)

A further study was undertaken to analyse the sources of faecal contamination in streams in the Maroochy Shire. The sampling locations in various streams within the Maroochy Shire were classified in accordance with land use as Rural, Septic, Trunk or Sewage Treatment Plant (STP). Monitoring locations within waterways in the Maroochy region were chosen in conjunction with staff at Maroochy Shire Council. The areas and land uses within water sub-catchments discharging to each of the sampling locations were supplied by Maroochy Shire Council.

The Maroochy snapshot study (Coombes et al., 2007) utilised a wide range of chemical, biochemical and molecular methods to analyse water samples taken from selected locations in waterways within the Maroochy region to identify sources of faecal contamination. Methods included bacterial analysis, surveys of abundance bacterial species using polymerase chain reaction (PCR) methods to extract DNA of bacteria, investigation of the presence of selected bacteria using PCR primers, faecal sterol ratio analysis, antibiotic resistance analysis and elemental tests to produce two snapshots of water quality in streams within the Maroochy Shire. The two snapshots of water quality were taken in a wet and a dry period and are discussed separately in the following sections.

Outcomes from the wet weather survey

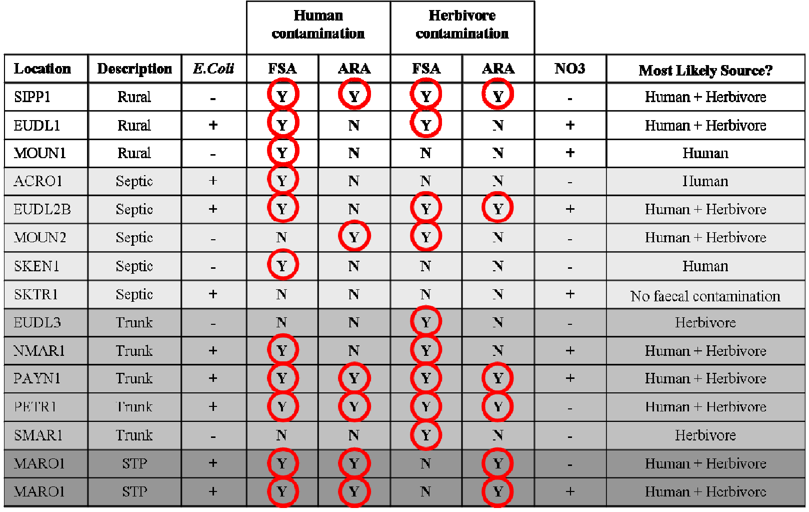
The wet weather sampling mission was completed on 2 March 2006. Over 70 mm of rain fell in the catchments on that day and considerable rainfall was experienced in the two weeks prior to the sampling mission. All of the streams were subject to high stream flows of turbid water indicating that the wet weather involved significant rainfall runoff from land surfaces within the chosen sub-catchments. As a consequence all of the samples, with the exception of ground water samples, taken on this day revealed high counts of total and faecal bacteria.

For *E. coli* and NO_3, the results at each location were compared to average results from the Rural group of sub-catchments (depicted as + or –), and together with results from faecal sterol analysis and antibiotic reaction analysis are used to summarise sources of contamination in Table 1. Within the Rural sub-catchments, “+” and “–” refer to relative differences between locations. “Y” indicates the test was positive for human and/or herbivore contaminant contributions and “N” indicates the test was negative for human and/or herbivore contaminant contributions (for FSA and ARA). Table 1 also shows the likelihood of contamination from human and/or herbivore sources whilst highlighting the increasing degree of ambiguity between source-tracking techniques, particularly in Trunk sub-catchments.

For example, the faecal sterol ratio analysis suggested that all of the Rural sub-catchments (SIPP1, EUDL1 and MOUN1) were subject to human faecal contamination with SIPP1 and EUDL1 also subject to faecal contamination from herbivores. The antibiotic resistance analysis at the SIPP1 sub-catchment also suggested faecal contamination from human and herbivores, but not at EUDL1 and MOUN1. This result, coupled with concentrations of NO_3 and *E. coli* at SIPP1 being less than at the other Rural sub-catchments, indicated that faecal contamination at the SIPP1 sub-catchment was likely. For EUDL1, the faecal sterol ratio analysis and antibiotic resistance analysis results could not validate each other.

The results indicating human faecal contamination at the Rural locations was of interest given that the sites, in particular the SIPP1 sub-catchment, were chosen as reference sites for comparison to the Septic, Trunk and STP sites. Considering that concentrations of *E. coli* at the Rural sub-catchments were significantly less than the Septic sub-catchments and indicates that the Septic sub-catchments may be subject to greater faecal contamination. However, the concentrations of both coprostanol and cholestenol were statistically similar at both sub-catchment groups suggesting that the Rural and Septic sub-catchments were equally likely to have faecal contamination from humans and herbivores.

Table 1: Summary of likely contaminant sources (wet weather)



			Human contamination		Herbivore contamination			
Location	**Description**	***E.Coli***	**FSA**	**ARA**	**FSA**	**ARA**	**NO3**	**Most Likely Source?**
SIPP1	Rural	-	Y	Y	Y	Y	-	Human + Herbivore
EUDL1	Rural	+	Y	N	Y	N	+	Human + Herbivore
MOUN1	Rural	-	Y	N	N	N	+	Human
ACRO1	Septic	+	Y	N	N	N	-	Human
EUDL2B	Septic	+	Y	N	Y	Y	+	Human + Herbivore
MOUN2	Septic	-	N	Y	Y	N	-	Human + Herbivore
SKEN1	Septic	-	Y	N	N	N	-	Human
SKTR1	Septic	+	N	N	N	N	+	No faecal contamination
EUDL3	Trunk	-	N	N	Y	N	-	Herbivore
NMAR1	Trunk	+	Y	N	Y	N	+	Human + Herbivore
PAYN1	Trunk	+	Y	Y	Y	Y	+	Human + Herbivore
PETR1	Trunk	+	Y	Y	Y	Y	-	Human + Herbivore
SMAR1	Trunk	-	N	N	Y	N	-	Herbivore
MARO1	STP	+	Y	Y	N	Y	-	Human + Herbivore
MARO1	STP	+	Y	Y	N	Y	+	Human + Herbivore

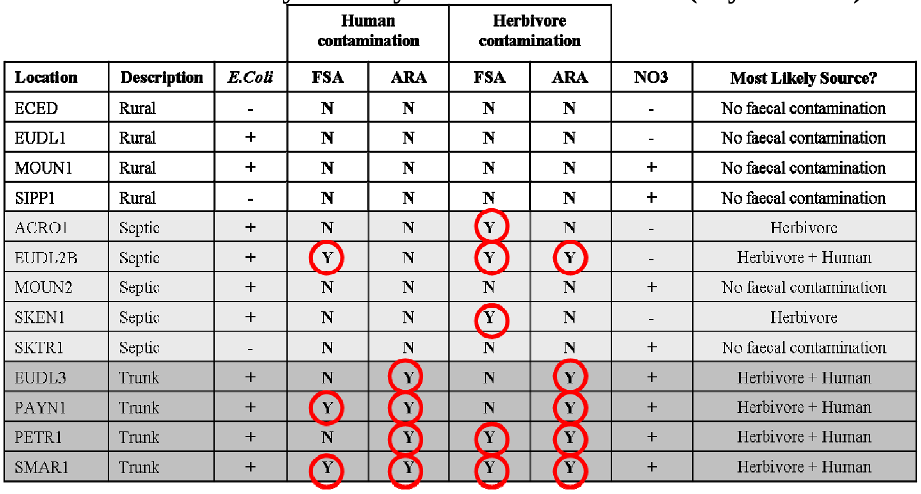
Septic and Trunk catchments also showed contradictions between faecal sterol ratio analysis and antibiotic resistance analysis in determining the likelihood of human/herbivore contaminants. For example, the faecal sterol ratio analysis suggested that the Septic sub-catchments ACRO1, EUDL2B and SKEN1 were subject to faecal contamination from human sources and that the EUDL2B and MOUN2 sub-catchments were also subject to faecal contamination from herbivores. The MOUN2 sub-catchment suggested faecal contamination from humans using antibiotic resistance analysis. For these catchments, the ambiguity of results between source-tracking techniques highlights that no one technique is suitable for determining the presence of potential contaminant source contributions. However, using the snapshot approach has characterised water quality in different sub-catchments.

During wet weather, the use of a number of source-tracking techniques resulted in many contradicting results. For example, faecal sterol ratio analysis and antibiotic resistance analysis were shown not to support each others interpretation on several occasions. While the interpretation of contaminant contributions was different depending on a unique source-tracking technique, the snapshot approach clearly differentiated water quality at each location and between sub-catchments.

Outcomes from the dry weather survey

The second sampling mission was completed on the 13th June 2006 and approximately 25 mm of rain had fallen on the catchment areas in the two weeks prior to the sampling day and little or no rain fell during the day the sampling mission was conducted. The results at each location for *E. coli* and NO_3 were compared to average results from the rural group of sub-catchments, and together with results from faecal sterol analysis and antibiotic resistance analysis were used to summarise sources of contamination in Table 2.

Table 2: Summary of likely contaminant sources (dry weather)



			Human contamination		Herbivore contamination			
Location	**Description**	***E.Coli***	**FSA**	**ARA**	**FSA**	**ARA**	**NO3**	**Most Likely Source?**
ECED	Rural	-	N	N	N	N	-	No faecal contamination
EUDL1	Rural	+	N	N	N	N	-	No faecal contamination
MOUN1	Rural	+	N	N	N	N	+	No faecal contamination
SIPP1	Rural	-	N	N	N	N	+	No faecal contamination
ACRO1	Septic	+	N	N	Y	N	-	Herbivore
EUDL2B	Septic	+	Y	N	Y	Y	-	Herbivore + Human
MOUN2	Septic	+	N	N	N	N	+	No faecal contamination
SKEN1	Septic	+	N	N	Y	N	-	Herbivore
SKTR1	Septic	-	N	N	N	N	+	No faecal contamination
EUDL3	Trunk	+	N	Y	N	Y	+	Herbivore + Human
PAYN1	Trunk	+	Y	Y	N	Y	+	Herbivore + Human
PETR1	Trunk	+	N	Y	Y	Y	+	Herbivore + Human
SMAR1	Trunk	+	Y	Y	Y	Y	+	Herbivore + Human

Table 2 provides an indication of the sources of faecal contamination in each sub-catchment. No faecal contamination was found in any of the Rural sub-catchments using either faecal sterol ratio analysis or antibiotic resistance analysis.

In Septic sub-catchments, the only indicator of human contamination in any of the sub-catchments was faecal sterol ratio analysis at EUDL2B. This was supported by the antibiotic resistance analysis which also indicated contamination from herbivores. In Trunk sub-catchments, antibiotic resistance analysis indicated the likelihood of both herbivore and human contamination. Faecal sterol ratio analysis only supported antibiotic resistance analysis interpretation for SMAR1. However, faecal contamination in Trunk sub-catchments appears equally likely from humans and herbivores.

The general trend observed in Table 2 indicates an increasing likelihood of herbivore and/or human contamination in Septic and Trunk sub-catchments respectively when compared to Rural sub-catchments. This trend is likely to be a result of the Trunk sub-catchments experiencing a greater diversity of contaminant inputs from other landuses within the greater catchment during baseflow conditions.

Overall, the ambiguity of results between locations, sub-catchments and wet/dry conditions was likely to be due to the fact that the hydrological processes for contaminant export were different for each sub-catchment. For example, faecal contaminant sources in Rural sub-catchments (scattered excretions from herbivores) could be considered diffuse and would be transported by surface flow after rainfall (wet conditions). Rural contaminants are likely to be retained on land during dry conditions. Septic catchments are likely to be dominated by point-source contributors (septic tanks), which would exhibit a diurnal pattern of discharge pulses to the environment during wet and dry conditions. Trunk sub-catchments are likely to have a multitude of contaminants contributed from diffuse and point sources from numerous other sub-catchments (wet and dry conditions), which result in a higher degree of ambiguity between source-tracking techniques. However, faecal sterol ratio analysis and antibiotic resistance analysis results in STP sub-catchments were less ambiguous (wet and dry conditions), possibly due to the proximity to the treatment plant discharge and the relatively constant presence of human contamination. Using data obtained during snapshot studies, the influence of these processes provide an improved understanding of catchment water quality which could be further evaluated by 3-D hydrological modelling.

Conclusion

The snapshot study has been shown to be a useful approach in characterising water quality in catchment waters and improving the evaluation of likely contaminant sources. The study by Lucas et al. (2007) highlighted that indicators of human-sourced contaminants could not be distinguished from other predominant landuses in the greater catchment, even though samples were acquired over a range of different hydrological settings. However, the snapshot approach provided further insight into catchment processes that influence contaminant export.

The combined contaminant survey methods used in the Maroochy snapshot study provided a more reliable estimate of contaminant sources at a catchment scale. The study has provided a wide range of data that has enabled a glimpse of total catchment water quality during wet and dry conditions. Further analysis of the data is likely to provide a greater understanding of the sub-catchments in the Maroochy Shire.

Importantly, analysis of concentrations of bacteria, sterols, chemicals and elements to understand the significance of contaminant sources has limited usefulness without a hydrological setting. Incorporation of several “snapshot” results in hydrological models to derive the relative contaminant loads at each sub-catchment during wet and dry weather will provide greater understanding of contributing contaminant processes.

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