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Role of Land Use and Seasonal Factors in Water Quality Degradations

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Abstract Surface water and groundwater are the most important water sources in the natural environment. Land use and seasonal factors play an important role in influencing the quality of these water sources. An in-depth understanding of the role of these two influential factors can help to implement an effective catchment management strategy for the protection of these water sources. This paper discusses the outcomes of an extensive research study which investigated the role of land use and seasonal factors on surface water and groundwater pollution in a mixed land use coastal catchment. The study confirmed that the influence exerted on the water environment by seasonal factors is secondary to that of land use. Furthermore, the influence of land use and seasonal factors on surface water and groundwater quality varies with the pollutant species. This highlights the need to specifically take into consideration the targeted pollutants and the key influential factors for the effective protection of vulnerable receiving water environments.

Keywords Surface water quality · Groundwater quality · Land use · Stormwater quality · Stormwater pollutant processes · Multivariate analysis

1 Introduction

The pollution of coastal waterways is of prime concern as these resources are widely used for aquaculture and recreational activities. Additionally, polluted surface water and groundwater can pose a risk to human health as well as to the estuarine environment and local watercourses (Kim 2010; Liu et al. 2012a). In order to undertake effective strategies for protecting the water

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environment, it is important to understand the factors that influence the quality of surface and groundwater resources. Past researchers have noted that land use and seasonal factors play an important role in relation to water quality (for example Tong and Chen 2002; Ouyang et al. 2006; Goonetilleke et al. 2005). Consequently, this gives rise to two important questions: (a) is the influence exerted by these two factors similar or different for surface water and groundwater quality? and (b) does the influence exerted vary with the pollutant species due to the different generation, accumulation and transport characteristics of different pollutant types as noted by researchers such as Miguntanna et al. (2013) and Liu et al. (2012b)?

In order to provide answers to these two research questions and thereby derive an in-depth understanding of how land use and seasonal factors influence surface water and groundwater quality, this paper discusses a comprehensive research study undertaken in a mixed land use coastal catchment. The new knowledge created in the context of these two questions is expected to contribute to strengthening catchment management strategies for protecting vulnerable receiving water environments.

2 Materials and Methods

2.1 Study Area

The study area was the Ningi Creek catchment, located in the Caboolture region in Queensland, Australia. The catchment area is 47.1 km^2 and drains into the Pumicestone Passage and eventually into Moreton Bay Marine Park which is internationally recognised for its ecosystem values (Pantus and Dennison 2005). The catchment consists of a variety of land uses including: urban residential development relying on on-site wastewater treatment systems (OWTS), particularly septic tanks; agricultural areas mostly consisting of livestock production; small areas of pineapple farming; aquaculture; and large areas of plantation and natural forest in the upper catchment (see Fig. 1).

2.2 Sample Collection and Testing

Twelve surface water sampling (SW1-SW12) and ten groundwater sampling (GW1-GW10) stations were established along the Ningi Creek to encompass the different land uses in the catchment as shown in Fig. 1. Due to the presence of OWTS creating the potential for groundwater pollution, the urban residential area was of interest for groundwater monitoring (GW1-GW5 were located in urban residential area while GW6-GW10 were located in non-urban land use). The catchment is tidally influenced up to monitoring sites SW8 and GW8.

In order to investigate the seasonal variation of pollutant inputs, surface water and groundwater sampling was undertaken at the monitoring locations at monthly intervals during both, base flow conditions and after rainfall events covering the dry (rainfall< 30 mm), moderate (30 mm<rainfall<100 mm) and wet periods (rainfall>100 mm). Details of the sampling episodes are given in Table 1. Accordingly, a total of 94 surface water samples and 71 groundwater samples were collected.

The samples collected were tested for nitrate (NO_3^-), phosphate (PO_4^{3-}), iron (Fe), total inorganic carbon (TIC) and total organic carbon (TOC). These are the primary parameters which have a significant impact on water resources. Nutrient excess can lead to eutrophication of water bodies (Lewitus et al. 2008). The presence of elevated concentrations of metals such as iron is able to sustain algal blooms longer in conjunction with various abiotic factors (Watkinson et al. 2005; Roelfsema et al. 2006). Inorganic and organic carbon can influence

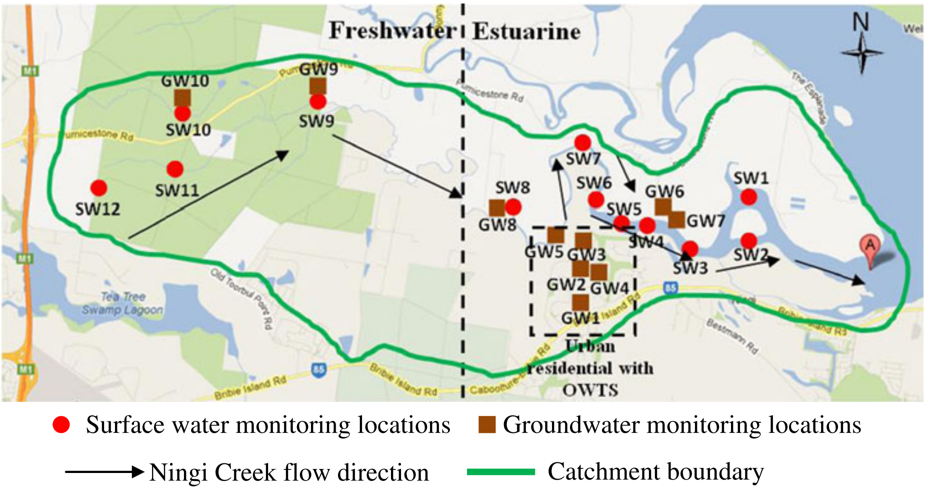

Fig. 1 Surface water and groundwater monitoring locations. (SW1, SW2 – close to river mouth; SW3 – prawn farm; SW4 to SW7 – residential; SW8–cattle grazing; SW9 to SW11–forestry; SW12–agriculture-pineapple farming; GW1 to GW3-grass swale; GW4-outlet of grass swale; GW5-residential; GW6 to GW7-rural; GW8-cattle grazing; GW9 to GW10-forestry; Groundwater was sampled from the shallow aquifer and the sampling depths were: GW1-3.86 m; GW2-1.99 m; GW3-1.52 m; GW4-2.67 m; GW5-1.61 m; GW6-2.91 m; GW7-3.35 m; GW8-1.23 m; GW9-3.83 m; GW10-14.22 m)

the solubility of other pollutants such as metals and consequently, enhance their bioavailability (Warren et al. 2003). Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA 2005) with appropriate QA and QC procedures in place. Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS 1998).

3 Results and Discussion

3.1 Comparison of Surface Water and Groundwater Quality

Initially, the results from the surface water and groundwater quality sampling were compared based on mean concentrations and coefficients of variation (CV). Table 2 clearly shows that

Table 1 Sampling episodes

Sampling episodes	Rainfall depth for the month prior (mm)	Humidity	Season
1	22	Dry	Spring
2	120	Wet	Spring
3	180	Wet	Summer
4	0	Dry	Summer
5	42	Moderate	Autumn
6	31	Moderate	Autumn
7	68	Moderate	Autumn
8	147	Wet	Winter

Table 2 Comparison of surface water and groundwater qualities

Category	Parameter	TIC	TOC	NO_3^-	PO_4^{3-}	Fe
Surface water	Mean (mg/L)	16.20	8.38	0.67	0.16	0.27
	CV[a] (%)	61.34	96.19	280.81	189.52	313.50
Ground water	Mean (mg/L)	23.62	11.99	1.69	0.23	38.88
	CV (%)	101.10	62.03	151.42	70.19	249.24

[a] coefficient of variation

groundwater is more polluted than surface water. The higher pollutant concentrations in groundwater are attributed to contributions from the soil. Additionally, both surface water and groundwater have high CV values regardless of the pollutant species. According to Hamburg (1994), a data set with CV greater than 10 % is considered as having a high variability. As the data was collected from different land uses and seasonal conditions, the high variability suggests that water quality is being significantly influenced by external factors such as land use and seasons.

Therefore, in order to further investigate how water quality is influenced by these factors, surface water and groundwater data were analysed separately employing the multi criteria decision making method, PROMETHEE (Preference Ranking Organisation method for Enrichment Evaluations) using Decision Lab software (Decision Lab 2000). PROMETHEE is a non parametric method which ranks a number of actions in a data matrix based on a range of criteria. This method was used due to its ability to identify relationships between criteria and actions while GAIA visually displays the results of the PROMETHEE analysis using a principal component analysis (PCA) biplot. A detailed explanation of this method can be found in Keller et al. (1991) and Khalil et al. (2004).

The surface water data matrix used for PROMETHEE analysis was 94×5 (94 samples with variables TOC, NO_3^-, PO_4^{3-}, Fe and TIC), while the matrix for groundwater was 71×5 (71 samples with variables TOC, NO_3^-, PO_4^{3-}, Fe and TIC). The GAIA biplots derived for these two matrices are shown in Fig. 2.

3.1.1 Influence of Land use

In terms of surface water (Fig. 2a), most samples projected on the positive PC1 axis are from the freshwater environment (SW9-SW12), while most of the samples projected on the negative PC1 axis are from the estuarine environment (SW1-SW8). Additionally, the estuarine samples cluster together along with the TIC vector while freshwater samples along with other pollutants (NO_3^-, PO_4^{3-}, Fe and TOC) are relatively widely scattered. This indicates that the estuarine environment tends to produce higher inorganic carbon whilst the freshwater area is signified by higher concentrations of nutrients, iron, and organic carbon. The monitoring locations in the estuarine area were primarily in urban residential areas and near aquaculture farms. Evidently, these areas generate inorganic carbon due to microbial activity (Dunn et al. 2006). The land uses in freshwater monitoring locations were agriculture and forestry. This results in inputs of nutrients into the surface water due to the application of fertiliser and degradation of leaf litter.

These conclusions indicate that land use results in inputs of different pollutant species to surface water. In turn, this implies that the diversity of surface water pollutant sources including, both, natural areas (forestry) and areas which are subject to anthropogenic influence (such as agriculture) play important roles. Additionally, in terms of anthropogenic activities, the role of agricultural land use in introducing surface water pollutants such as nutrients appears to be more significant than urban development.

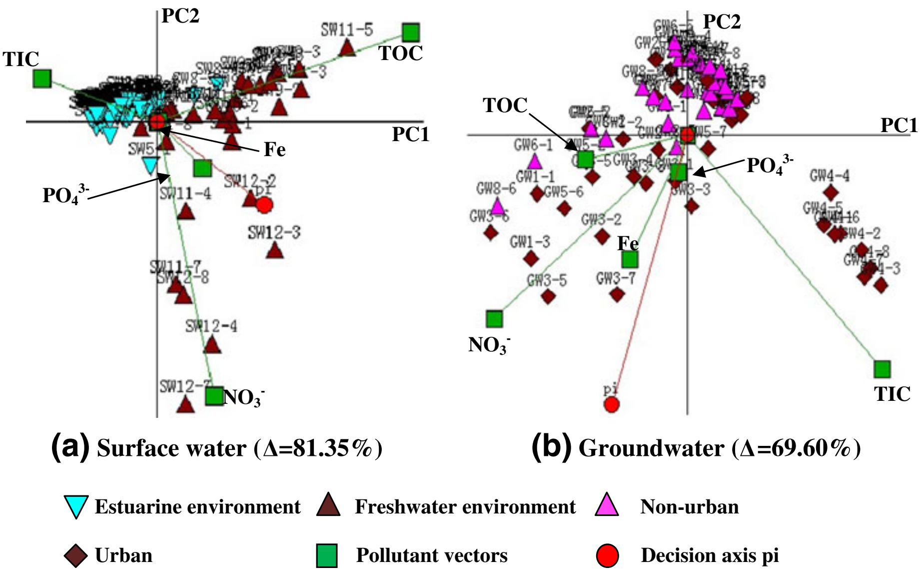

Fig. 2 GAIA biplots for surface water and groundwater quality. (Δ = the variance of original data matrix explained by GAIA biplot; pi = decision axis; SW = surface water; GW = groundwater; the first numeral indicates monitoring location while the second numeral indicates sampling episode, e.g. SW12-1 indicates the surface water sample collected at monitoring location 12 in Episode 1)

In the case of groundwater (Fig. 2b), the samples are separated based on the PC2 axis. Interestingly, most samples projected on the positive PC2 axis are from non-urban areas (GW6-GW10). Additionally, it is evident that all pollutant vectors point in the same direction as the urban samples. This points to the fact that urban areas, in comparison to non-urban areas, contribute more pollutants to groundwater. This is attributed to the anthropogenic influence in urban areas. Due to the high density of OWTS in the urban area, the groundwater could be polluted by the effluent from OWTS (Carroll and Goonetilleke 2005), thus an important pollutant source to groundwater. Additionally, the use of fertiliser in residential gardens could also contribute to groundwater pollution.

3.1.2 Influence of Seasonal Factors

It can be also noted from Fig. 2a that most of the samples strongly associated with nutrient inputs were those collected during the wet and moderately wet episodes (such as SW12-2, 120 mm in Episode 2; SW12-3, 180 mm in Episode 3; SW11-7, 68 mm in Episode 7 and SW12-8, 147 mm in Episode 8), while the samples strongly associated with TOC and Fe were from wet, moderate and dry season episodes (such as SW11-3, 180 mm in Episode 3; SW11-5, 42 mm in Episode 5 and SW10-4, 0 mm in Episode 4). This highlights the important role seasonal factors played in influencing pollutant inputs (particularly nutrients) and the key role played by stormwater runoff. This also implies that the dominant pollutant sources can alter during the wet and dry periods, thus creating a continuous source of pollutants to the waterway. For example, the downstream area could be the primary pollutant source due to tidal flushing in the dry season. During the wet periods, the upstream land uses would become the primary pollutant contributor. Furthermore, the relatively high concentrations of TOC and Fe irrespective of the season suggest that these pollutant inputs occur continuously and could further increase after rainfall. This indicates that surface water pollutant inputs would occur even over the dry periods, rather than being just episodic after rainfall.

In the case of groundwater, the fact that samples with high concentrations are from different sampling episodes means that seasonal variations did not have a significant impact on the groundwater quality. This could be because a prominent swale located in the urban area is allowing effective drainage of stormwater away from the development and not allowing adequate time for recharge of the shallow aquifer.

3.2 Variability of Water Quality with Influential Factors

According to the discussion above, surface water and groundwater quality in the catchment vary with land use and seasonal conditions. However, it is noteworthy that the degree of influence of these factors is different and varies with the pollutant species. In order to further investigate the influence exerted by these factors, the dataset was re-arranged based on CV values calculated for each set encompassing different monitoring locations, but within the same episode (such as CV value for 12 surface water monitoring locations SW1-SW12 within Episode 1) and each set encompassing different sampling episodes but within the same monitoring location (such as CV value for 8 episodes from the groundwater monitoring location GW1). Accordingly, a CV dataset (38×5) was submitted to PROMETHEE. Figure 3 shows the resulting GAIA biplot.

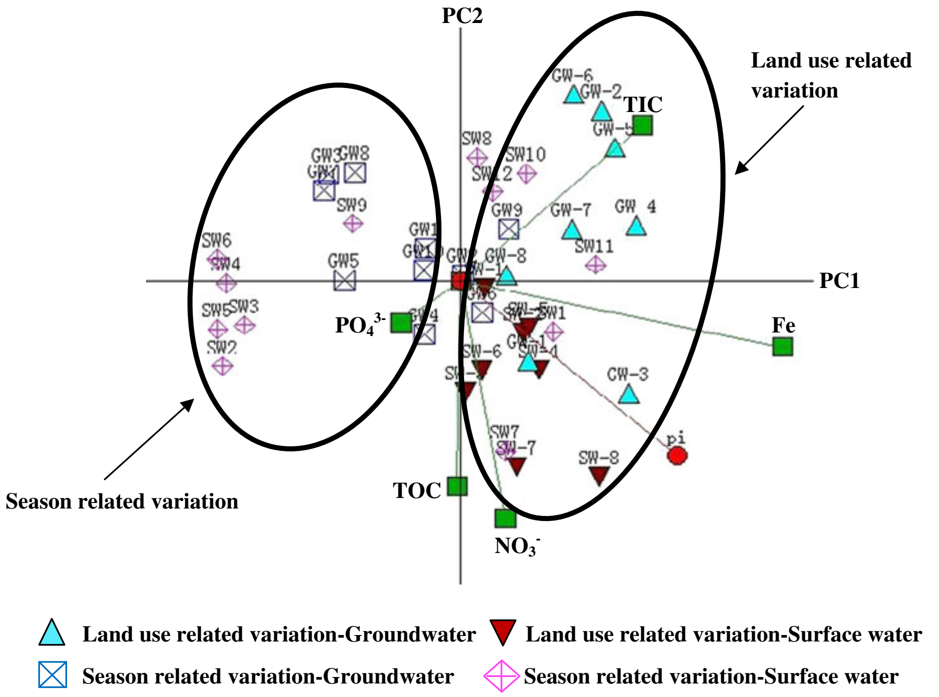

Fig. 3 CV GAIA biplot (Δ = 64.60 %). (SW = surface water; GW = groundwater; hyphen followed by numeral indicates land use related variation; no hyphen followed by numeral indicates seasonal related variation. e.g. GW-6 indicates the CV value for groundwater samples collected at all monitoring locations in Episode 6; SW6 indicates the CV value for surface water samples collected from all episodes at monitoring location 6; for other legends refer to Fig. 2)

It can be noted that all land use related variation regardless of the water resource are projected on the positive PC1 axis while most of the seasonal variation are projected on the negative PC1 axis. Additionally, all vectors indicating pollutant CV values except for PO_4^{3-} are also projected on the positive PC1 axis. This means that independent of the water resource, the influence exerted by seasonal conditions on surface water and groundwater quality is secondary to the influence exerted by land use for most investigated pollutants.

Additionally, the variability of water quality is also closely related to the pollutant species. Phosphorus tends to be influenced by seasonal condition as the PO_4^{3-} vector points to seasonal variation (negative PC1) while other pollutants are more land use influenced since TIC, TOC, NO_3^- and Fe vectors have the same direction as land use related variation. This is attributed to the different processes inherent to different pollutant species. For example, Miguntanna et al. (2013) noted that phosphorus transport by stormwater runoff is transport limiting, where high-intensity rainfall can wash-off a relatively higher concentration of phosphorus while nitrogen is source limiting, where nitrogen wash-off depends on the initial availability. Consequently, phosphorus could be more influenced by seasonal factors such as rainfall while nitrogen would be influenced by land use since land use influences pollutant generation and accumulation (Liu et al. 2012b). In this context, it is hypothesised that TIC, TOC and Fe could also be source limiting, since these pollutants are primarily influenced by land use.

These outcomes confirm that pollutant input processes to surface water and groundwater are complex and multifaceted and influenced by land use, seasonal factors as well as pollutant characteristics. Land use plays the primary role in influencing pollutant inputs such as organic carbon, inorganic carbon, nitrogen and iron, while seasonal variation has a significant impact on phosphorus input to water bodies.

4 Conclusions

This study analysed surface water and groundwater quality characteristics in a mixed land use coastal catchment. Land use and seasonal factors were found to have a significant influence on the water quality characteristics. Furthermore, the degree of influence exerted on the different water resources can be different. The influence of seasonal factors is secondary to that of land use regardless of the type of water resource. Furthermore, the influence of land use and seasonal condition on surface water and groundwater quality also varies with the pollutant species. This highlights the need to take into consideration the targeted pollutants and the key influential factors in the development of management strategies for the protection of vulnerable water resources.

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