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A review of methods for analysing spatial and temporal patterns in coastal water quality

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ABSTRACT

Coastal environments contain some of the marine world's most important ecosystems and represent significant resources for human industry and recreation. Water quality in the coastal environment is extremely important for a number of reasons from the protection of marine organisms and the well being of marine ecosystems to the health of people in the region and the safety of industries such as aquaculture. As a result it is essential that environmental health in coastal environments is monitored. Traditional monitoring methods include assessment of biological indices or direct measurements of water quality, which are based on *in situ* data collection and hence are often spatially or temporally limited. Remote sensing imagery is increasingly used as a rich source of spatial information, providing more detailed coverage then other methods. But the complexity of information in the imagery requires new analysis techniques that allow us to identify the components and possible causes of spatial and temporal variability.

This paper presents a review of methods to analyse spatial and temporal variations in remote sensing data of coastal water quality and discusses and compares these methods and the outcomes they achieve. Selected techniques are illustrated by using a sample dataset of MODIS chlorophyll-*a* imagery. We consider classification methods (cluster analysis, discriminant analysis) that may be used in exploratory, confirmatory and predictive ways, methods that summarize and identify patterns within complex datasets (factor analysis, principal components analysis, self-organizing maps), and techniques that explicitly analyse spatial relationships (the semivariogram and geographically weighted regression). Each technique has a different purpose and addresses different questions. This review identifies how these methods can be utilized to address water quality variability in order to foster a wider application of such techniques for coastal water quality assessment and monitoring.

1. Introduction

The majority of the world's most productive marine ecosystems are found within coastal environments and owe their productivity, diversity and wealth of life to their terrestrial adjacency. Shelf regions are key areas for biological activity and generate the biological production that supports 90% of the world's fish catches (Pauly et al., 2002). Coastal marine environments also contain greater biodiversity than open ocean regions (Gray, 1997). These productive marine ecosystems are important habitats for many fish and other marine organisms that are not only a significant source of food for human consumption, but are also vital components of marine ecosystems. The proximity of these ecosystems to land often provides nutrients and favourable conditions that support primary producers, which in turn provide nourishment for higher levels of the food chain. However, the threat of rapid and often devastating changes to water quality through both anthropogenic and natural mechanisms is often increased as a result of the connection to the land. Changes in water quality can be potentially catastrophic for marine ecosystems as species are threatened by conditions which are no longer suitable for their survival. These changes in water quality also pose threats to humans through changes in waters utilised for recreation, fishing and industry. It is clear that human reliance on these precious resources requires regulatory interventions and that robust and reliable ecosystem condition indicators are needed for decision making (Pinto et al., 2009).

Coastal environments throughout the world are affected by eutrophication and harmful algal blooms, often as a result of

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anthropogenically driven increases in nutrients (Anderson et al., 2002). Harmful algal blooms can have significant consequences for marine ecosystems and the people dependant upon them (Hallegraeff, 1993; Smayda, 1997; Anderson et al., 2002). Reductions in water quality can also be caused by increases in concentration of pollutants or contaminants like oil, heavy metals, organic compounds etc. (Shahidul Islam and Tanaka, 2004), increases in turbidity (Orpin et al., 2004), and changes in dissolved oxygen (Sanchez et al., 2007), which all have implications for the well-being of marine ecosystems and those reliant upon them.

As a result of the implications variations in water quality can have for both marine ecosystems and human well-being, it is necessary to monitor coastal environments. By monitoring changes in water quality we can observe, assess and correct long term trends in water quality degradation from anthropogenic sources such as industry and coastal development. We can better understand changes in water quality due to natural sources. Finally we can possibly even reach an ability to predict changes in water quality to a point where the negative affects upon natural and economically important environments can be mitigated.

It is recognised that indicators need to be "applicable over a variety of spatial scales and conditions to support global as well as local comparisons" (Rees et al., 2008). But it is inherently difficult to develop and validate indicators, if spatio-temporal pattern are complex. This refers to indirect methods of using biological indicators (e.g. Borja and Dauer, 2008; Weisberg et al., 2008), as well as for direct assessment of chemical and physical water quality properties. Statistical power in any underlying analysis can be improved if temporal and spatial data is used as a covariate or simply to stratify field collection points into similar areas hence allowing data to be pooled. This would reduce stochastic variability and thus act similar to a low pass filter for noisy data. The vast and growing amount of spatial information in the public domain has motivated us to examine the methodological potential for using satellite imagery in coastal marine water quality monitoring and assessment.

The methods of collecting water quality data depend upon the property or parameter to be measured, the scale of the study, and the questions to be addressed. Traditional techniques can include targeted campaigns of *in situ* field sampling, moored instruments, drifting instruments, and ship of opportunity measurements. These techniques often provide accurate and reliable water quality information, but the resultant data is frequently limited in space and time. Recently, the application of satellite and airborne remote sensing imagery to collect water quality information has become more frequent (e.g. Goetz et al., 2008, and references therein). Remote sensing datasets are generally more comprehensive than those collected using other techniques in that they provide greater spatial coverage with finer resolution and often increased temporal frequency and resolution. This makes remote sensing a rich source of data. However, the large amount of data presents challenges for the extraction of meaningful information of water quality parameters.

Several analytical techniques are available to extract spatial and temporal patterns and trends in order to provide enhanced understanding and resolve the full information hidden within water quality data. These techniques can be used to identify regions or periods of time with different water quality characteristics, determine whether significant differences in water quality occur between different regions, and also to indicate the variables responsible for water quality variations. Remote sensing datasets, however, are generally spatially and temporally comprehensive, large in volume, and often contain internal correlation and redundancy: traditional statistical techniques are often inappropriate, but conversely, there is scope for development of new techniques to fully exploit the richness of the data.

The purpose of this paper is to review analytical techniques that can be used to examine spatio-temporal variability in coastal water quality derived via remote sensing data. The differences between techniques, their advantages and limitations, as well as the questions they address and the outcomes they can achieve are reviewed in order to identify the most appropriate techniques for differing circumstances.

Along with reviewing these techniques and summarising some previous applications, several of the techniques will be illustrated with a sample dataset of MODIS imagery. This dataset consists of a one-year series of monthly MODIS chlorophyll-*a* images for 2006 over the coastal areas of South Australia, between 30 and 40°S and 129 and 141°E (Fig. 1). The monthly MODIS images were obtained from the Goddard Space Flight Centre (oceancolor.gsfc.nasa.gov) and analysed in ENVI (RSI, 2006). Along with the MODIS imagery, a set of field-based chlorophyll-*a* measurements collected in Spencer Gulf is also utilised when required.

2. Multivariate analytical techniques

Numerous multivariate methods are available to analyse spatial and temporal trends in water quality datasets. Some techniques are applicable only to more traditional data comprising measurements of discrete samples, while others are transferable to remote sensing data and some are exclusively applied to remote sensing data. These methods vary in the questions they address and the outcomes they reach. Table 1 summarises the techniques to be discussed in this paper, their purposes and relationships to one another. Techniques such as cluster analysis (CA), discriminant analysis (DA), factor analysis (FA) and principal components analysis (PCA) are widely used, not just in marine applications but also in many other areas of science, to explore structure and relationships in multivariate data, and in some cases to predict responses. While many of these statistical methods have been widely used with point sample data, several have found new application to remotely sensed data. Some analyses explicitly address spatial variability and relationships (self-organising maps (SOM), the semivariogram and geographically weighted regression (GWR)) and naturally find most application with remotely sensed data. These techniques are reviewed to provide insight into how they can be utilised to derive conclusions from water quality data.

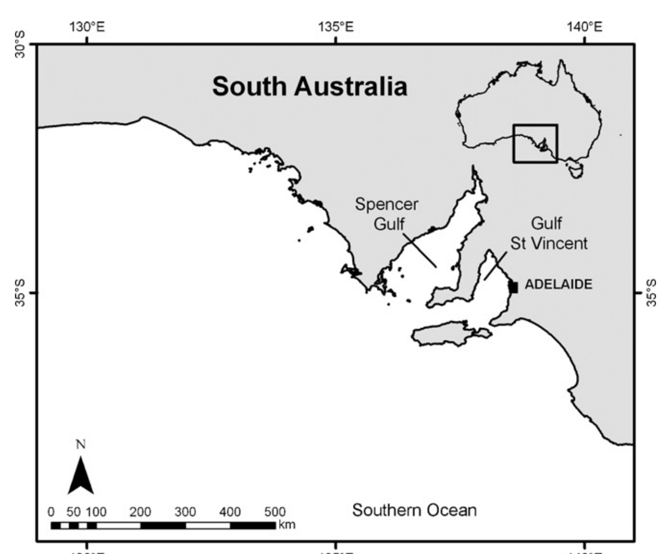

Fig. 1. South Australia.