Environmental Modelling & Software 63 (2015) 97–108

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Prediction of sediment, particulate nutrient and dissolved nutrient concentrations in a dry tropical river to provide input to a mechanistic coastal water quality model

Barbara J. Robson*, Vincent Dourdet [1]

CSIRO Land and Water Flagship, GPO Box 1666, Canberra, ACT 2601, Australia

ARTICLE INFO

Article history:
Received 22 June 2013
Received in revised form
16 July 2014
Accepted 6 August 2014
Available online

Keywords:
Catchment model
Regression
Watershed
Phosphate
Empirical vs. deterministic modelling

ABSTRACT

A Generalised Additive Modelling (GAM) approach is applied to prediction of both particulate and dissolved nutrient concentrations in a wet-tropical river (the Fitzroy River, Queensland, Australia). In addition to covariant terms considered in previous work (i.e. flow, discounted flow and a rising-falling limb term), we considered several new potential covariates: meteorological and hydrological variables that are routinely monitored, available in near-real time, and were considered to have potential predictive power. Of the additional terms considered, only flows from three tributaries of the Fitzroy River (namely, the Nogoa, Comet and Isaac Rivers) were found to significantly improve the model. Inclusion of one or more of these additional flow terms greatly improved results for dissolved nitrogen and dissolved phosphorus concentrations, which were not otherwise amenable to prediction. In particular, the Nogoa sub-catchment, dominated by pasture for cattle, was found to be important in determining dissolved inorganic nitrogen and phosphorus concentrations reaching the river mouth. This insight may direct further research, including future refinement of processed-based catchment models. The GAMs described here are used to provide near real-time river boundary conditions for a complex coupled hydrodynamic and biogeochemical model of the Great Barrier Reef Lagoon, and can be coupled with a forecasting hydrological model to allow integrated forecasting simulations of the catchment to coast system.

1. Introduction

Sediment and nutrient loads from rivers to estuaries and coastal waters often increase when land use changes, especially as agriculture intensifies and urban development progresses. This is often a concern for environmental managers, as increased sediment and nutrient loads adversely affect water quality and change the trophic status of freshwater and marine systems (Smith, 2003).

In the case of the Great Barrier Reef Lagoon, an environmental asset of internationally recognised importance, increased nutrient loads from catchments over the past 200 years are believed to be the driving force behind the spread of Crown of Thorns Starfish, an invasive species which preys on coral and has been responsible for massive damage to reef ecosystems in recent decades (Brodie et al., 2005; De'ath et al., 2012; Fabricius, 2005). Increased nutrient loads also drive increases in pelagic primary production, which can have a complex range of ecological impacts.

A large project (eReefs) is currently underway to implement a three-dimensional coupled hydrodynamic, sediment dynamic and biogeochemical model for the entire Great Barrier Reef Lagoon (GBRL) (Chen et al., 2011). The marine models are implementations of SHOC (Cetina-Heredia and Connolly, 2011) and EMS (Margvelashvili et al., 2013; Robson et al., 2008; Wild-Allen, 2013). These models operate on small time-steps (typically around 2 min) and require as input daily or sub-daily estimates of concentrations of sediments and nutrients (dissolved and particulate organic and inorganic nitrogen and phosphorus) in each of 22 rivers flowing into the system.

Semi-distributed models that predict average annual loads of sediments, nitrogen and phosphorus in GBR catchments have been implemented in Source Catchments and its predecessors (Armour et al., 2009; Dougall et al., 2006; McCloskey et al., 2011), but have so far not demonstrated the ability to accurately simulate day-to-day variations in the concentrations of nutrients. While more complex, process-based catchment models such as SWAT may (Lai

* Corresponding author. Tel.: +61 2 6246 5614.
E-mail addresses: bjrobson@gmail.com, barbara.robson@csiro.au (B.J. Robson).
[1] Present address: Ecole des Mines d'Ales, France.

http://dx.doi.org/10.1016/j.envsoft.2014.08.009
1364-8152/

et al., 2006; Richards et al., 2003) or may not (Chahinian et al., 2011; Chu et al., 2004) offer the potential to simulate such nutrients on daily timescales, these detailed process models have very large data requirements and heavy implementation costs.

Sediment rating curves, which estimate sediment concentrations using a simple linear regression of sediment load as a function of flow, often produce adequate estimates of loads on yearly or decadal timescales, but produce very large errors when applied to daily concentrations (Horowitz, 2003). More sophisticated statistical techniques such as maximum likelihood estimation (MLE) and adjusted maximum likelihood estimate (AMLE) applied to parameterisation of a linear regression model have been used successfully in a range of applications (Cohn, 2005). AMLE is particularly appropriate for use with datasets that include “below detection limit” results. The LOADEST package, available online from the USGS, provides a user-friendly tool to implement these methods, optionally incorporating sin and cosine terms in the linear regression to account for seasonal patterns (Aulenbach and Hooper, 2006), and has been widely used, particularly within the USA.

Vecchia and Ballerini (1991) and more recent work involving the same author (e.g. Johnson et al., 2009; Milly et al., 2005) have applied autoregressive time series analyses to detect and quantify temporal trends in water quality data, adjusted for expected concentrations given flow. Hirsch et al. (2010) built on this theme, presenting the WRTDS (Weighted Regression on Time, Discharge and Season) model, a linear modelling approach that pays particular attention to changes and trends over time.

More recently, Generalised Additive Models (GAMs) such as LRE (Loads Regression Estimator) have been developed and implemented for several rivers (Kuhnert et al., 2012; Wang et al., 2011). GAMs are generalised regression models which incorporate smoothing functions, $s()$ of covariates. These functions do not have a pre-defined form, and need not be linear, but attempt to capture the main features of the data, using, for instance, a penalised regression spline function that fits a flexible smoothing term to the data. This makes the approach very flexible as it is capable of combining multiple, nonlinear functional responses. GAMs have been demonstrated as a powerful tool for prediction of sediment loads, requiring much less input data and lower computational costs than process-based models. LRE has been extended to estimate total nutrient as well as sediment loads from Great Barrier Reef catchments (Kroon et al., 2012) to provide a firm comparative basis for management.

The LRE model is simply defined as:

$$\log(C)_j = \beta + \sum_{i=1}^{2} \alpha_k X_{kj} + \sum_{i=1}^{2} s_k\left(Z_{kj}\right) + \varepsilon_j. \quad (1)$$

(Kuhnert et al., 2012) where C is the concentration of a constituent at time i, X_{kj} and Z_{kj} are covariates measured at that time, $s()$ represents a smoothing term (described above), and ε_j is a normally distributed error term. x_{1i} to x_{3i} represent linear and quadratic flow terms and a categorical term to indicate whether flow is rising or falling. Smoothed terms (z_{kj}) include discounted flow terms (discussed below). Additional covariates, which may or may not be log terms, are included on a case-by-case basis.

Although LRE achieves good agreement with observed sediment, total nitrogen and total phosphorus concentrations in both the Burdekin River (Kuhnert et al., 2012) and Fitzroy River (our analysis), when the method is applied to prediction of dissolved organic or inorganic nutrients on daily time-steps, LRE does not achieve satisfactory results if driven by flow and discounted flow alone.

In this paper, we build on the basic LRE GAM, applying the approach with a range of additional covariates to the Fitzroy River, one of the largest rivers flowing into the GBRL and demonstrate models that provides good agreement with observational measurements of dissolved inorganic and organic nitrogen and phosphorus as well as sediment and particulate nutrient concentrations in the Fitzroy River.

2. Methods

Regular sediment and nutrient monitoring has been conducted in the Fitzroy River since 1999. Samples are taken at ‘the Gap’, just upstream of the barrage at Rockhampton, to avoid the complicating tidal influences downstream.

The dataset used to develop our model includes 102 Total Suspended Solids (TSS) records and 67 nutrient records, from samples taken under varying flow conditions between 2003 and 2008. An event sampling strategy was followed, so most measurements relate to flow events. Nutrients measured include total phosphorus (TP), total dissolved phosphorus (TDP), particulate phosphorus (PP, measured as the difference between TP and TDP), dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP), total organic phosphorus (TOP), total nitrogen (TN), particulate nitrogen (PN), dissolved organic nitrogen (DON), total organic nitrogen (TON), and dissolved inorganic nitrogen (DIN), comprising ammonia (NH_3) and nitrogen oxides (NOx). In order to arrive at a first-order estimate of particulate organic nutrient concentrations, we assumed that inorganic components of particulate nitrogen and phosphorus were negligible in comparison with Particulate Organic Phosphorus (POP) and Particulate Organic Nitrogen (PON).

Data from a further 127 samples, taken between November 1993 and July 2012, were held back for validation.

Meteorological data were obtained from a Bureau of Meteorology monitoring site at Yeppoon (The Esplanade), the closest available routine meteorological site to the Fitzroy River, located approximately 40 km north of the water sampling site.

In developing GAMs capable of simulating dissolved as well as particulate nutrient concentrations, we considered a range of potential hydrological and meteorological control variables (Table 1). Each of these candidate variables is routinely monitored, available through web services in near real-time, and has a potential influence on sediment and nutrient concentrations. Each is discussed in turn below.

2.1. Flow

Stage height is monitored continuously and converted to an estimate of daily average flow. Flow in the Fitzroy River, as in most tropical rivers, is very peaky, with high flow following storm events in the catchment, falling to a low baseline during the dry season (Fig. 1).

Table 1
Input variables tested for inclusion in the models.

Variable	Symbol	Units
Flow at the Gap	Q, flow	m^3s^{-1}
Flow in Comet Creek	Comet	m^3s^{-1}
Flow in Nogoa River	Nogoa	m^3s^{-1}
Flow in Dawson River	Dawson	m^3s^{-1}
Flow in Connors Creek	Connors	m^3s^{-1}
Flow in Isaac Creek	Isaac	m^3s^{-1}
Flow in Mackenzie River	Mackenzie	m^3s^{-1}
Discounted Flow	DF	m^3s^{-1}
Wind speed	V	m s^{-1}
Air temperature	T_a	°C
Pressure	P	hPa
Water temperature	T_w	°C
Conductivity	σ	μS cm^{-1}