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Applying econometric techniques to hydrological problems in a large basin: Quantifying the rainfall–discharge relationship in the Burdekin, Queensland, Australia

Diane Jarvis [a,*], Natalie Stoeckl [b], Taha Chaiechi [a]

[a] James Cook University, P.O. Box 6811, Cairns, Queensland 4870, Australia
[b] James Cook University, Townsville, Queensland 4811, Australia

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SUMMARY

This study seeks to explore the relationship between rainfall and river discharge within a large river basin flowing into the waters surrounding the Great Barrier Reef (GBR), and to investigate the best method of measuring the relationship. This aim is addressed by focusing on three specific research questions: (A) Has there been any evidence that global climate change has impacted on either rainfall or river discharge resulting in any change to the relationship between these variables over time? (B) What is the best measure of rainfall to be used to quantify the rainfall–discharge relationship, including the optimal number of rain stations to be included in the sample? (C) What is the optimal temporal scale for measuring the relationship (ranging from fine scale monthly data, medium scale quarterly data, and coarse scale annual data)?

Modern econometric time series techniques are utilised, and compared with results using an alternate technique developed by researchers from the bio-physical sciences; the widely used Thiessen Polygon method.

Firstly, stationarity testing, using econometric unit root tests, did not find evidence to suggest that the data are non-stationary. Evidently, climate change has not had a measurable impact on rainfall or river discharge in the region during the period covered by this study.

Secondly, the analysis shows that the when dealing with fairly simple models with a fairly small number of explanatory variables, those which best represent the river–discharge relationship are those using the coarser scales (both geographic and temporal). In other words, stronger and more robust results are derived from models using fewer rain stations, and annual data (rather than quarterly or monthly data). This approach provides a viable alternative that may be very useful in data-poor environments when it is not possible to use other more data-hungry modelling approaches. The econometric models provided a better explanation of the relationship than the Thiessen Polygon approach, whilst utilising data from a smaller number of rain stations. The most appropriate functional form was that using the natural logs of discharge as the dependent variable, and the relationship appears to be a fairly simple one, with the inclusion of lagged data from previous years not significantly improving the explanation provided by current year models. The approach demonstrates that simple time series models can be enriched by the incorporation of additional variables beyond rainfall levels; both temperatures and rainfall concentration were considered with the inclusion of a rainfall concentration index proving to significantly improve the explanatory power of the model for this study region.

1. Introduction

River discharge can be a source of significant sediment flows resulting in wide ranging impacts on reefs, fish and other life in the oceans, therefore it is important to develop good quality hydrological models to allow us to better understand the discharge and potentially mitigate problems resulting from this. There have been many hydrological studies considering the relationship between rainfall and river discharge, including a variety of approaches to measuring the variables included within the model. However the measurement of the key variables remains a complex exercise, as there is no unambiguously “best” way to measure areal rainfall; similarly, there does not appear to be an unambiguously “best” geographic or temporal scale to adopt. The term areal rainfall, for

* Corresponding author. Tel.: +61 (0) 488453060; fax: +61 (7) 40421300.
E-mail address: diane.jarvis1@jcu.edu.au (D. Jarvis).

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example, describes the amount of precipitation received over a specified area within a specified time period, and comprises the key independent factor within the rainfall–river discharge model (Balascio, 2001). But obtaining values for areal rainfall requires decisions to be made on a range of questions, including how many, and which rain stations to use, how to weight observations from different rain stations (Anctil et al., 2006; Seed and Austin, 1990), and what time scale to use when aggregating observations (Duncan et al., 1993). Moreover, understanding relationships between the key variables is hard in the presence of climate change; the researcher has to consider how to control for possible changes to climate variables and relationships over time (Vaze et al., 2010), whilst still seeking to identify the impact of a range of physical and socioeconomic factors.

A significant number of studies have considered the highly complex processes and relationships involved in river basin systems. The majority of researchers have approached this topic from a biophysical science perspective – developing catchment-wide models to measure the rainfall–stream flow relationship rather than using statistical time series techniques. Importantly, different techniques have different data requirements, with regression models often having the least and simplest data requirements. In this paper, we focus on regression analysis as a method of exploring the stream-flow–rainfall relationship. Although relatively 'unusual', this method has been used before (Alibert et al., 2003; Lough et al., 1998; Nu-Fang et al., 2011; Nadal-Romero et al., 2008; Chang et al., 2011; Troutman, 1983). This approach has been found to perform better than alternative physical based models despite the need for minimal information (Loague and Freeze, 1985) and clearly has the capacity to generate reasonably good models of this relationship.

Importantly, there are numerous analytical techniques from the financial econometrics literature that allow one to control for other problems (such as extreme events and/or climate change) that are likely to confront those interested in the rainfall–stream flow relationship, and the primary aim of this paper is to demonstrate the efficacy of some of these techniques. Whilst not attempting to comprehensively apply econometric techniques to all issues relevant to the modelling of the rainfall–discharge–sediment relationship, this paper aims to demonstrate methods of dealing with some of the perplexing problems, such as: which temporal scale is 'best', which measure of rainfall is 'best' and how does one control for the (potential) impact of climate change in such investigations?

The region selected for this study is the Burdekin River catchment area in Queensland, Australia. The catchment (see Fig. 1) is the second largest in the Great Barrier Reef catchment area, and covers an area of approximately 130,000 km^2 with a population of approximately 23,000 people. To place this in an international context, the catchment is of a similar land area to England with a population of around 51 million. Thus the Burdekin is a very large but scarcely populated region.

The climate of the Burdekin is tropical with summer monsoons contrasting dry winters. Tropical cyclones and El Nino Southern Oscillation events also have a significant effect on the climate of Queensland in general and on the rainfall levels specifically (McBride and Nicholls, 1983). The Burdekin catchment area has been identified as a source of significant sediment flows to the reef (Isdale, 1984; Alibert et al., 2003; McKergow et al., 2005; O'Reagain et al., 2005). Indeed, some researchers have found it to be the largest single source of fine sediment into the GBR lagoon delivering on average 3.77 m tonnes each year (O'Reagain et al., 2005) and often in excess of 10 m tonnes in single run off events (McCulloch et al., 2003). Hence the importance of developing good quality hydrological models in this region: the more we understand the system, the better chance we have of identifying, and potentially helping to mitigate key problems.

This study thus explores the relationship between rainfall and river discharge in the Burdekin Catchment whilst considering both temporal scale and geographic scale. The rainfall–discharge relationship is modelled using monthly, quarterly and annual data to determine the optimal temporal scale. Different methods of aggregating data from across the entire watershed are also considered, acknowledging that conditions (rainfall levels and other features) are unlikely to be consistent across an entire watershed. This is done by comparing models that select and weight rain-stations using statistical techniques, with those that use the widely known Thiessen Polygons method (Section 2.2 provides a review of relevant literature of common approaches, justifying our selection of these two for comparison). Our choice of methods was restricted to those relying on the use of measurements from rain stations as radar data is not available in the study region; thus these methods could not be considered despite research indicating that radar can outperform the Thiessen method (Damant et al., 1983).

Finally, modern econometric techniques are also used to test for stationarity within the data since the use of regression techniques on non-stationary data can produce spurious results. An added benefit of this is that the stationarity tests provide important insights into the impact of climate change since, by definition, a (statistically significant) changing climate is one where climatic variables will not display a constant mean and variance over time (i.e. one where key variables are non-stationary).[1]

As such, this paper focuses attention on three important issues relevant to those interested in using historical, time-series data in hydrological models:

1. *Stationarity testing and climate change*. This study demonstrates the use of stationarity tests on climate data, simultaneously ensuring that regression results will not produce spurious results while also conducting rigorous statistical test for the impact of climate change on key variables in this part of Northern Australia.
2. *Selection and weighting of rain-stations when measuring areal rainfall*. This study compares two different approaches to measuring rainfall across a geographic region for use in rainfall–discharge models.
3. *Selection of temporal scale – and methods for controlling for seasonality if not working with annual data*. This study compares models that use three different temporal scales (monthly, quarterly and annual).

Importantly, these issues are explored using data from a river basin that is significantly larger than the majority of those considered in other studies – as such, the results are likely to be particularly useful to those working on large catchments.

2. Materials and methods

Researchers studying rainfall–discharge relationships rarely consider ONLY rainfall and discharge – other variables are frequently included. As such, this project investigates the relationship between river discharge, rainfall, and 'other variables'. Sections 2.1, 2.2 and 2.3 thus describes how those variables were selected, and measured; Section 2.4 describes how the relationship between those variable was modelled.

[1] Stationarity within the data can be tested for using a range of tests; in this paper we use the Augmented Dickey–Fuller (ADF) test and the Phillips–Peron (PP) test whereby the null hypothesis of non-stationarity can be rejected by finding a statistically significant result, and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test where the null hypothesis is that the data is stationarity with this hypothesis being rejected by finding a statistically significant result Stern, D.I., Kaufmann, R.K., 1999. Econometric analysis of global climate change. Environmental Modelling and Software 14(6), 597–605.