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Estimation of the environmental risk of regulated river flow

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SUMMARY

A commonly accepted paradigm in environmental flow management is that a regulated river flow regime should mimic the natural hydrological regime to sustain the key attributes of freshwater ecosystems. Estimation of the environmental risk arising from flow regulation needs to consider all aspects of the flow regime when applied to water allocation decisions. We present a holistic, dynamic and robust approach that is based on a statistical analysis of the entire flow regime and accounts for flow stress indicators to produce an environmental risk time series based on the consequence of departures from the optimum flow range of a river or reach. When applied to a catchment, (Campaspe River, southern Australia) the model produced a dynamic and robust environmental risk time series that clearly showed that when the observed river flow is drawn away from the optimum range of environmental flow demand, the environmental risk increased. In addition, the model produced risk time series showing that the Campaspe River has reversed seasonal patterns of river flow due to water releases during summer periods, which altered the flow nature of the river. Hence, this resulted in higher environmental risk occurring during summer but lower in winter periods. Furthermore, we found that the vulnerability and coefficient of variation indices have the highest contributions to consequence in comparison to other indices used to calculate environmental risk.

1. Introduction

1.1. Flow regime and environmental risk

The natural flow regime is commonly considered as the main organising variable of healthy fluvial ecosystems (Bunn and Arthington, 2002; Walker et al., 1995). Environmental risk to rivers can be defined as a deviation from natural conditions (Horne et al., 2010) and this change from natural flow affects habitat and biota of a river system over time (Walker et al., 1995). A commonly accepted paradigm in environmental flow management is that the regulated river flow regime should mimic the natural hydrological regimes to sustain the key attributes of freshwater ecosystems (Ladson et al., 1999; Poff and Allan, 1997).

Because the timing and quantity of river flow are critical factors of water supply, water quality and the ecological integrity of a river system, the flow regime is strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity (Poff and Allan, 1997). Flow regulation alters nearly all components of the flow regime with consequent environmental effects. For example, storages and water diversions reduce the magnitude and frequency of high flows and can result in increased deposition of fine sediments in gravels that reduce macroinvertebrate habitat (Poff and Allan, 1997). Conversely, irrigation releases during the summer period significantly change the seasonality of flow in rivers naturally dominated by winter-spring flow and can affect the seasonal cues for aquatic biota, such as fish (Bunn and Arthington, 2002; Rolls and Arthington, 2014). The clear relationships and strong linkages between a flow regime and the environmental assets in both natural and regulated rivers are increasingly recognized (King et al., 2003; Ladson et al., 1999; Poff and Allan, 1997; Poff et al., 2010).

1.2. Approaches to estimating environmental risk

Early approaches to estimating environmental risk for regulated river flow typically did not consider the effects of the entire flow regime on all environmental assets within a river system but instead focused on the ecological responses to alterations to a particular flow component (see review by Poff and Zimmerman (2010)). As a result, environmental risks are often estimated based on individual or multiple stressors, such as drought indices that use a combination of one or more hydrological variables

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(Steinemann and Cavalcanti, 2006; Sun et al., 2012). These methods used to estimate environmental flow requirements for rivers focus primary on one or few species that live in the wetted river channel (Poff and Allan, 1997). The use of arbitrary minimum environmental flows is inadequate, because the structure and function of a riverine ecosystem and the many adaptations of its biota are dictated by the pattern of temporal variation in river flows, reflecting the natural flow regime paradigm (Arthington et al., 2006; Richter, 2010; Tharme, 2003). Single stressor focused approaches have limited application for estimating environmental risk in a water allocation model, which must consider the entire flow regime of a river basin, e.g. from cease to flow to overbank flow (Ladson et al., 1999; Poff and Allan, 1997).

Reviews of recent approaches to estimating environmental risk show a paradigm shift towards considering changes across the entire flow regime (Arthington et al., 2006; Poff and Allan, 1997; Poff and Zimmerman, 2010). Arthington et al. (2006) proposed an empirical approach that holistically incorporates essential aspects of natural flow variability across the flow regime and shared across particular classes of rivers, with these aspects being calibrated against empirical biological and hydrological data. That approach has the advantage of addressing flow requirements of many ecosystem components and assessing the ecological consequences of change in each relevant flow variable. However, the approach is only applicable in a regional context where a large number of impacted rivers are considered in order to produce the reference condition for the same class of rivers and it integrates all past behaviour into a single score rather than a historical time series of risk. As such, it has limited application to the water allocation of a single river. Richter (2010) proposed the notion of a "sustainability boundary approach" (SBA) as a means for setting measurable goals relevant to environmental flow protection that address the water quality and environmental flows required to support water-dependent ecosystem benefits. This approach defines the degree to which human uses of water and land within a catchment can alter natural or baseline hydrologic conditions without impairing flow-dependent ecosystem benefits. The SBA method fosters a precautionary approach that requires only the determination of the magnitude of flow rather than relying on current scientific knowledge to define every aspect of the flow regime and the associated characteristics of the natural flow paradigm, therefore greatly reducing scientific uncertainties (Richter, 2010). However, the SBA approach does not address the cumulative risk due to important flow variables being outside the optimum range for long periods of time.

1.3. Aims

We further develop the approach advocated by Richter (2010) by positing that if the optimum range of the environmental flow demand of a river or reach is defined, then risk can be measured by the magnitude of the deviation from that range. While river health has a number of other aspects besides river flow, the use of river flow to estimate consequences of water allocation policy allows the direct linkage between river flow and the potential negative effects of water allocation. We use statistical analysis to estimate environmental risk based on the hydrological indices from the index of stream condition (Ladson et al., 1999; Merabtene et al., 2002). Our approach makes no attempt to link the magnitude of flow alterations and ecological responses.

2. Study area

The study area is the lower reaches of the Campaspe River catchment in southern Australia (Fig. 1). The study area has a total catchment area of 2124 km^2 and extends from the downstream end of Lake Eppalock (the main storage in the catchment) to the junction with the Murray River at Echuca. The catchment is relatively flat in the downstream northern half with increased higher terrain towards Lake Eppalock (Chiew et al., 1995). The climate is fairly uniform with hot summers experienced particularly in the north. The annual average rainfall is 450 mm (Chiew et al., 1995) and 69 mm average annual runoff (CSIRO, 2008). The rainfall occurs throughout the year, with the winter and early spring being the wettest period and January–February being the driest months (Chiew et al., 1995). The areal potential evapotranspiration is estimated to be 1211 mm (Potter and Chiew, 2009).

The study area has been divided into three reaches defined by major demand centres and four major hydrological structures: Lake Eppalock, Campaspe Weir, Campaspe Siphon and the outlet to Murray River in Echuca (Fig. 1). In Reach 1, the major water demand is from private diversion with little irrigation compared to Reach 2 and 3. In Reach 2, demand consists of the Campaspe Irrigation Areas (East and West). The Rochester Irrigation Areas (East and West) are located in Reach 3, although they divert water from the Waranga Western Channel (marked by the boundary of Reach 2 and 3) which carries water from the Goulburn River, a neighbouring catchment to the east. Within Reach 3, the main demand from the river is by private diversions. Each reach contains a gauging station at the downstream end where the observed flows were obtained: Reach 1 – 406201, Reach 2 – 406202 and Reach 3 – 406265. Because the levels of water demand are different for each reach, the environmental risk must be individually determined.

3. Method

The estimation of Environmental Risk (ER) is based on two key objectives. Firstly, the approach should produce quantitative, dynamic and robust time series of environmental risk that take into account the cumulative effects of past environmental risk. Secondly, it must accounts for risks that arise over the entire flow regime (cease to flow to overbank flow), thus accounting for most environmental flow related consequences. In order to satisfy these two objectives, we propose a method that involves five key steps as summarised in Fig. 2.

3.1. Estimation of the EFD from natural flow

The Environmental Flow Demand (EFD) of a regulated river can be defined as the specified flow magnitude required to maintain the health of the river (Ladson et al., 1999). In this study, it has been estimated using recommendations by ecologists and expert panels based on a 'flow method' assessment (Sharpe, 2006). Typically, these recommended values are in aggregate form and the flow requirement does not specify the timing when the flow should be applied in relation to the level of the Regulated Flow (RF). Instead, only the frequency, duration and magnitude of flow required within a time frame is defined without a clear link to the level of the RF in the river. For this reason, the flow requirement must be disaggregated into a time series of EFD to enable water authorities to adequately provide environmental flow to the river. This disaggregation has been done using the method developed by Neal et al. (2005) that involves the derivation of environmental flow requirements from modelled daily Natural Flow (NF) at a site. This approach assumes that most environmental flows are only provided if these flows would have occurred naturally (Neal et al., 2005). It allows automated decision making for the provision of seasonal flows of a given magnitude at a given annual frequency, and it assumes independence between events and rates of rising and falling hydrograph limbs. Each component of the recommended flow is progressively added until a time series