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Hydrological indices for quantifying ecologically relevant flow conditions in intermittent alluvial plain rivers

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Abstract Many alluvial plain river systems are under pressure from human impacts, including land-use changes, channel modifications, and hydrological alterations. Flow variation in alluvial plain rivers is influenced by groundwater–surface water exchange, changes of channel form, climatic variation, and water abstraction. Consequently, these rivers often have complex spatial and temporal flow patterns. The natural hydro-geomorphic complexity along intermittent alluvial plain rivers poses a challenge for: (i) developing relationships between recharge and river flows, (ii) predicting effects of water resource developments, and (iii) understanding hydrological effects on ecological systems. Hydrological models that can reconstruct historic flows and/or predict future flows are required for assessing potential hydrological impacts of changing water use, land use, or climate change. If strong flow–ecology relationships exist, these models can also be used to infer potential ecological effects related to the impact in question. In this paper we present a model that accounts for spatial and temporal flow variation in intermittent alluvial plain rivers, and we describe a suite of hydrological indices that can be used to examine flow–ecology relationships. The model we developed, the Empirical Longitudinal Flow MODel (ELFMOD), reconstructs longitudinal and temporal flow patterns along river sections using measured flows at sites along the section and other predictor variables (e.g. groundwater levels, rainfall). Spatio-temporal flow matrices simulated by ELFMOD are used to generate a large range of hydrological indices that describe flow states and flow changes in space and time. Interpretation of these indices increases our understanding of complex flow regimes and hydrological controls of ecological processes and can aid river management.

Key words alluvial plain river; intermittent; ephemeral; ecohydrology; surface water / groundwater interactions; New Zealand

INTRODUCTION

Alluvial plain rivers are frequently under intense pressure from human impacts, including land-use changes, channel modifications, and man-made hydrological alterations (e.g. dams and water abstraction (Larned *et al.*, 2008). Flow variations along alluvial plain rivers can be influenced by variations in groundwater–surface water exchange, changes of channel planform, climatic variations, and abstractions. Consequently, alluvial plain rivers often have complex spatial and temporal flow patterns. Many of the organisms that inhabit alluvial plains rivers are sensitive to natural and anthropogenic alterations in hydrology and geomorphology. Here, we focus on intermittent alluvial plains rivers, which cease to flow over part or all of their length. Ecologically relevant flow conditions in perennial rivers have been identified using a broad range of hydrological indices (e.g. Clausen & Biggs, 2000) and these indices have been used to identify and conserve particular hydrograph components in managed rivers to protect physical habitats and flora and fauna that require those flow components (e.g. minimum flows, flushing flows, flood flows, etc.). In contrast to the diversity of perennial flow indices, very few indices have been commonly used for describing flow intermittence (Arscott *et al.*, 2009). Here, we aim to narrow that information gap by developing a framework for describing the hydrology of intermittent alluvial plain rivers. We present a model that accounts for spatial and temporal flow variations along intermittent alluvial plains rivers, and describe a suite of hydrological indices that can be used to identify flow–ecology relationships for these rivers.

The study area we use to illustrate our approach is the Selwyn River in Canterbury, New Zealand (Fig. 1). The Selwyn River is characterized by longitudinal flow gains and losses at multiple spatial scales caused by aquifer exchange and tributary inflows (Larned *et al.*, 2008). An upstream catchment (above Whitecliffs flow recorder, river km 0, Fig. 1) drains the Canterbury foothills. The river flows from the foothills onto the Canterbury Plains, where river water is lost to

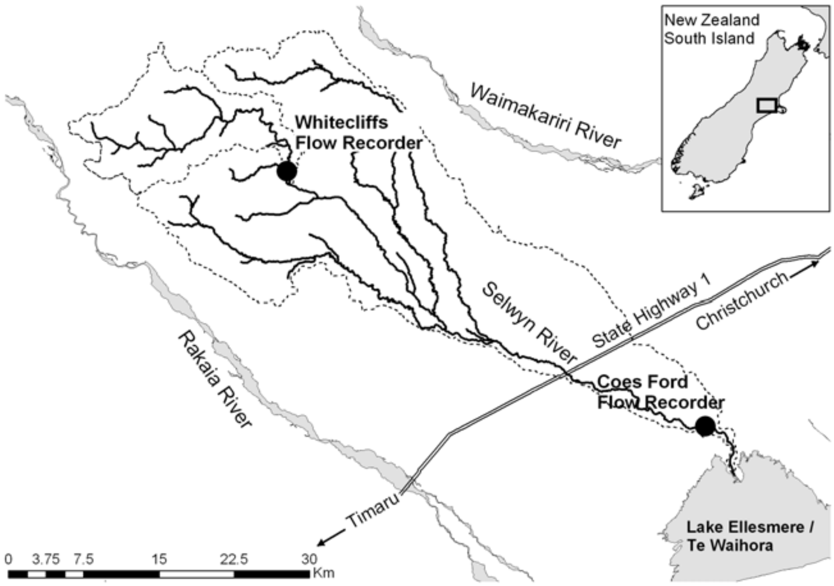

Fig. 1 Selwyn catchment in Canterbury, New Zealand.

groundwater aquifers through the permeable glacio-fluvial gravels. In its lower reach close to the Coes Ford flow recorder (river km 60, Fig. 1) the river gains water from upwelling groundwater again. Over the last few decades, low flows in the lower Selwyn River have decreased in association with decreasing rainfall-recharge and increasing groundwater abstraction for irrigation (McKerchar & Schmidt, 2007).

Construction of spatio-temporal river flows in hydrologically complex rivers

We used an empirical model to estimate spatio-temporal river flows with high spatial resolution (>100 m intervals). In the current example, we derive daily flows estimates along a 60 km river section at 100 m intervals from an Empirical Longitudinal Flow MODel (ELFMOD, see Rupp *et al.*, 2008, for a detailed description). This spatio-temporal flow matrix can be used to derive hydrological indices that characterise the ecohydrology of the modelled river domain in high detail (see next section). ELFMOD constructs flows along a selected river reach using measured flows at sites along the reach and other, optional, predictor variables (e.g. groundwater levels, rainfall). River flows are calculated using a three-step process. First, time series of river flow at the gauging sites are estimated using regression models with continuous records from flow (or other) recorders. Second, flow gains or losses between gauging sites are estimated as a function of upstream and downstream flows. Third, the flow time-series are compiled and a matrix of flows in space (equally spaced points longitudinally along the selected river section) and time (e.g. daily mean flow) is constructed. Figure 2 shows a 20-year matrix of river flows along the Selwyn River (Rupp *et al.*, 2008).

Hydrological indices for intermittent rivers

Hydrological indices used to describe river flow include moment statistics, ratios (e.g. baseflow indices), and flow thresholds. These indices can be generated using river flow time series, but are only applicable in close proximity to the gauging sites corresponding to the time series. The ELFMOD output can be used to estimate the same indices at user-controlled spatial intervals along a river (within the model domain). By compiling values of “traditional” or single-site indices (e.g. mean flood duration) at intervals along a river, a new series of indices can be generated that express longitudinal changes in flow patterns over a reach or an entire model domain. In addition to length-specific indices, whole-river (i.e. whole-domain) indices such as the number and total length of losing, gaining and dry reaches, and point indices such as the distance from a dry point to the nearest flowing reach can be computed.

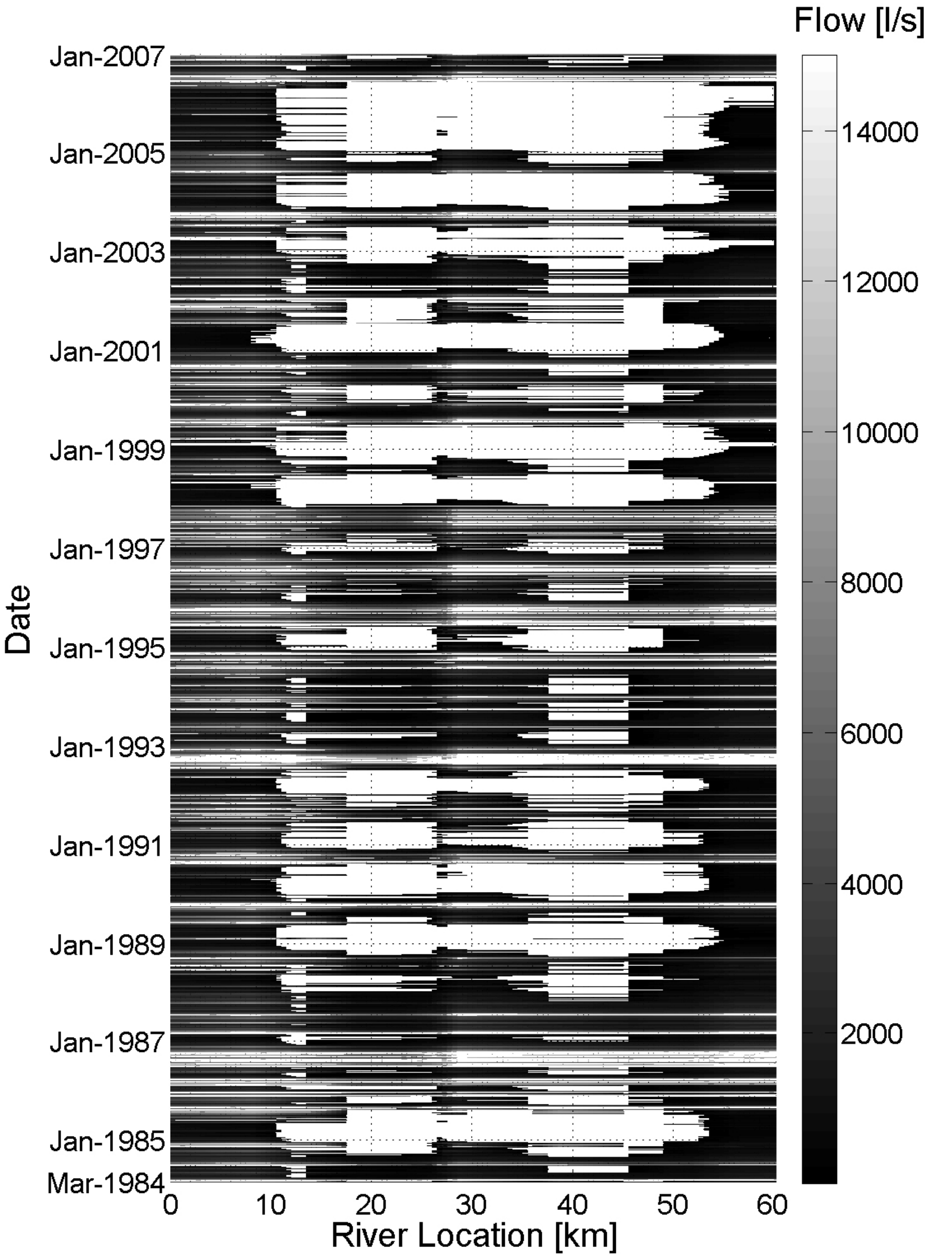

Fig. 2 Spatio-temporal flow matrix for the Selwyn River, New Zealand, shown as daily mean flows at 100-m intervals along the river for the time period March 1984–December 2006. River km 0 corresponds to the upstream flow recorder at Whiteciffs, and river km 60 to the downstream flow recorder at Coes Ford (Fig. 1). White spaces indicate areas and periods where the river is dry.

We organize the many hydrological indices generated with ELFMOD output using flow categories and sampling domains. We use three broad flow categories: (1) indices that summarize flow at each spatial interval and each time step in the model domain (e.g. average flow for all spatial intervals for given day, month, year); (2) intermittence indices that describe the flow state (wet/dry) in space at each spatial interval and each time step (e.g. mean annual flow permanence, days flowing or days dry, distance to wetted edge, length of dry channel at a time step); (3) flood indices (e.g. number of flood days per year at a location). We use two sampling domains: (1) the spatio-temporal flow matrix collapsed in time to provide flow statistics for each point in the spatial domain (each interval along the river reach) for the entire time period or specified time periods (e.g. annual values, monthly, or seasonal values); (2) the spatio-temporal flow matrix collapsed in space to provide flow characteristics for each modelled day over the entire modelled reach or specified subreaches. Flow statistics can be calculated for each time step (e.g. total amount of water in the river) as well as intermittence parameters (e.g. extent of dry reach for each day). In the following discussion a selection of hydrological indices calculated for the Selwyn River are used to illustrate potential applications of ELFMOD in river hydrology and ecology.

Gradients in flow frequency and flow permanence

Figure 3 shows flow values for different flow exceedence percentiles as a longitudinal profile along the Selwyn River. The probability of higher flows decreases in the middle section of the river, where the river falls regularly dry (Fig. 2). The large longitudinal gradients in flow magnitude and frequency lead to changes in ecological conditions that limit the diversity and distribution of both aquatic and terrestrial communities (e.g. Datry *et al.*, 2007; Davey *et al.*, 2007; Larned *et al.*, 2007; Arscott *et al.*, 2009).

The flow matrix in Fig. 2 indicates complex spatial and temporal patterns in intermittence in the Selwyn River. Dry reaches expand and contract seasonally, and coalesce to form long dry reaches during periods of very low flow. During periods of very high flow, dry reaches do not form. Long-term flow permanence (the proportion of time that water is present) varies widely down the length of the river, and ranges from 100% in the perennial reaches at the top and bottom of the mainstem, to 40% in the central reach where flow loss rates are highest (Fig. 4). On average, flow permanence is highest in Austral spring (September–November) and lowest in late summer and early autumn (January–March).

Flood frequency gradients

Floods and their frequencies are an important factor in determining habitat extent and habitat dynamics in a river. Sagar (1983) found that a flow of three times the median flow in the Rakaia River (20 km south of the Selwyn River) was sufficient to reset the invertebrate (and presumably

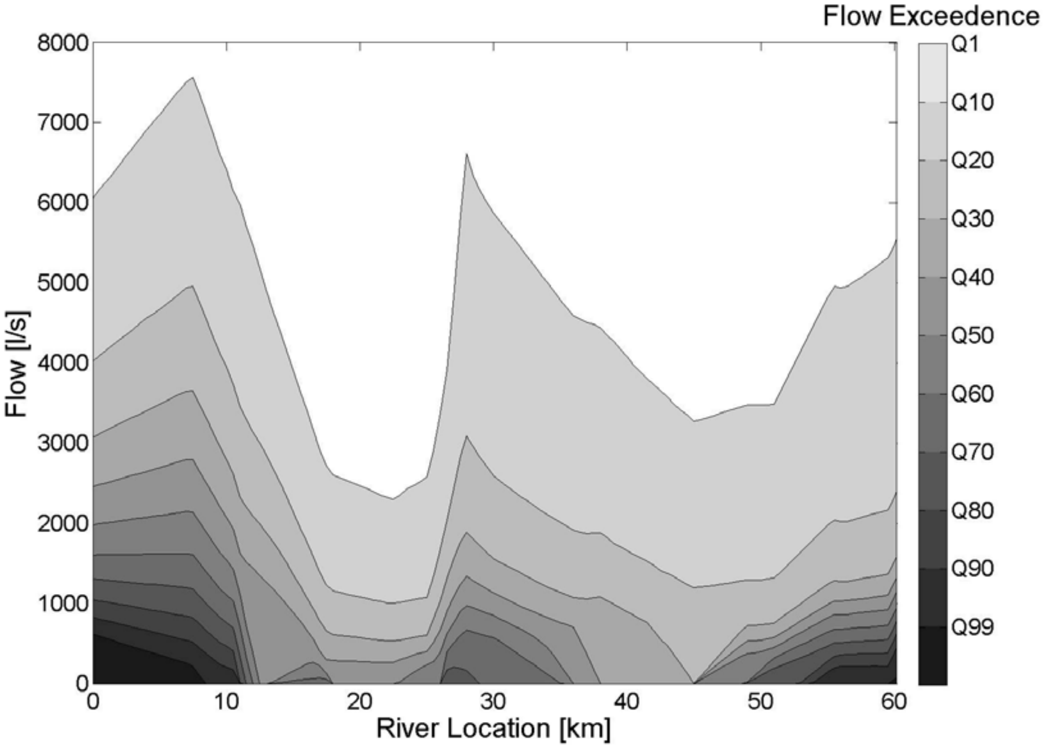

Fig. 3 Gradients in flow exceedence percentiles (percent of time flows exceed shown level, Qx equivalent to x exceedence percentile) along the Selwyn River.

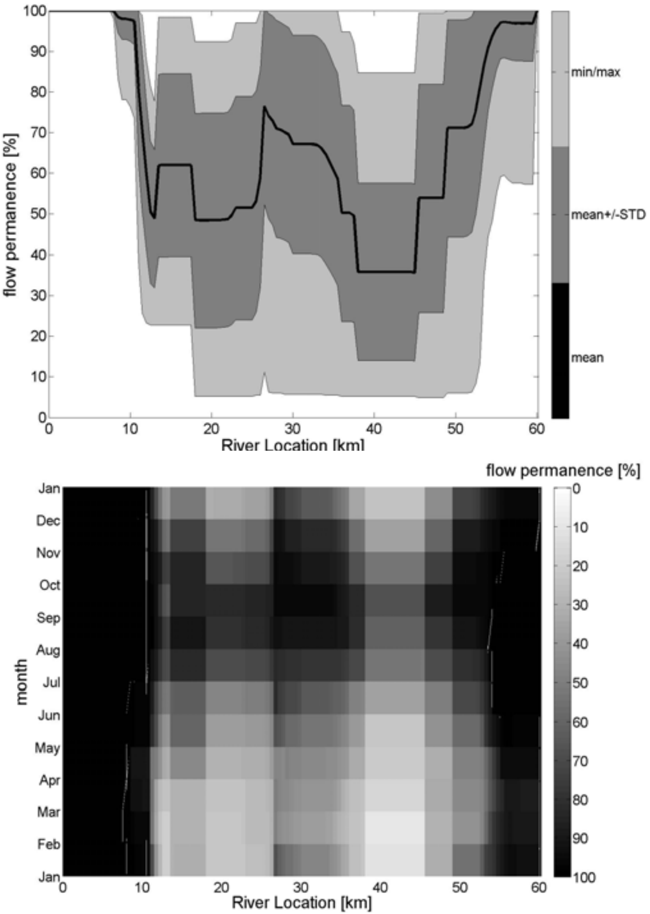

Fig. 4 Flow permanence profiles along the Selwyn River. Average annual figures and monthly variations of flow permanence (fraction of the time that the river is flowing at a location) are shown as longitudinal profiles.

periphyton) communities. Figure 5 shows the total number of events that the Selwyn River is in flood for each month of the year (using 3 × median flow as the flood threshold) and river location. The number of flood events changes markedly with river location. Floods produced during winter months in the upper catchment often do not show up in terms of flood statistics in the middle and lower Selwyn reaches; the number of flood events decrease dramatically around river km 10 due to transmission losses. Around river km 27, where the Hororata River joins the Selwyn (Fig. 1) and in the lower gaining sections around km 40, the number of flood events increase again. However, one might argue that the flood statistics produced for the perennial, intermittent, and ephemeral river reaches are hard to compare due to differences in their flow frequency profiles.

Intermittence profiles

A drying trend is apparent in the flow matrix shown in Fig. 2, with longer dry periods and more extended dry areas (as indicated by white patches in Fig. 2) in the last 10 years. Data in Fig. 6 quantify this temporal change in length and duration of intermittent reaches along the Selwyn River. Specifically, the length of dry river is increasing with time. Rupp *et al.* (2008) quantified the trend with an increase of 0.5 km of the average length of dry reaches per year on average. The potential ecological consequence of increasing intermittence along the Selwyn, for fish, invertebrates and other aquatic life forms has been discussed previously (Davey *et al.*, 2007; Datry & Larned, 2008; Arcsott *et al.*, 2009). Briefly, the abundance, diversity and distribution of fish and invertebrates are restricted by the duration and frequency of intermittent periods and the average proportion of time that a reach is dry. If intermittence continues to increase in severity, we predict that population densities will decline, and some species may be excluded from the river.

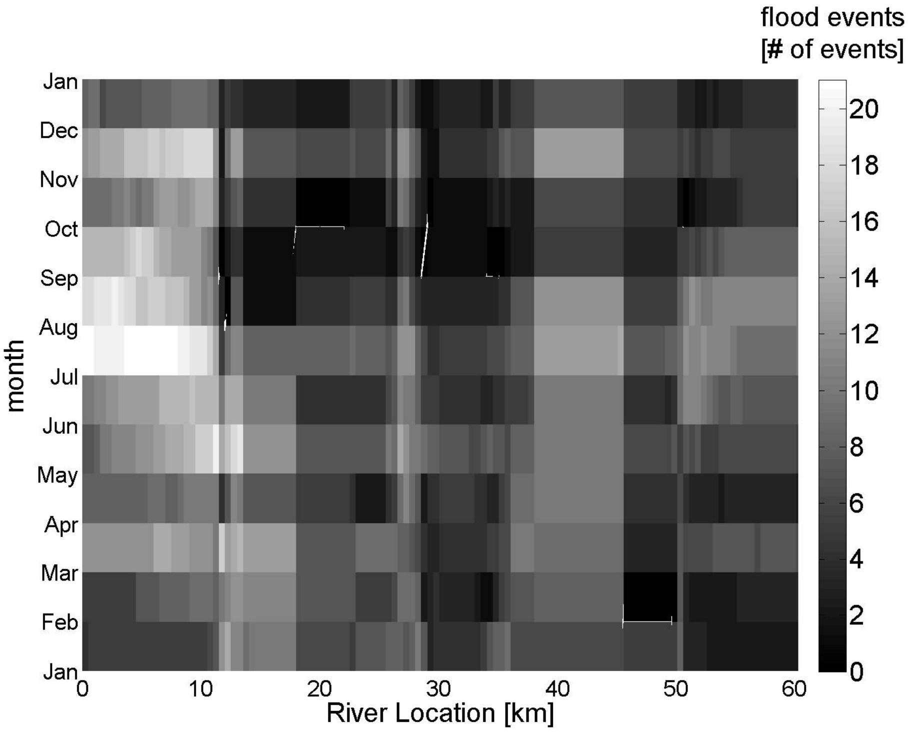

Fig. 5 Flood frequency statistics for the Selwyn River expressed as the total number of flood events (flood = flow exceeds 3× median flow) per calendar month as longitudinal profile along the Selwyn River.

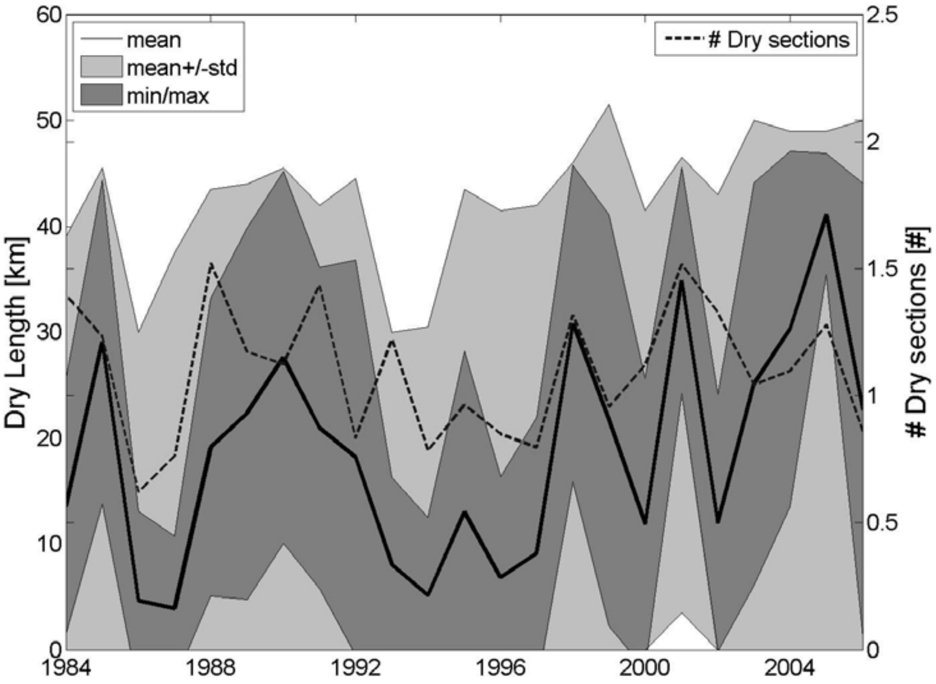

Fig. 6 Temporal development of longitudinal intermittence statistics in the .Selwyn river. The dry river length and number of dry sections are displayed against time. An increasing temporal trend in dry section length is visible (see text).

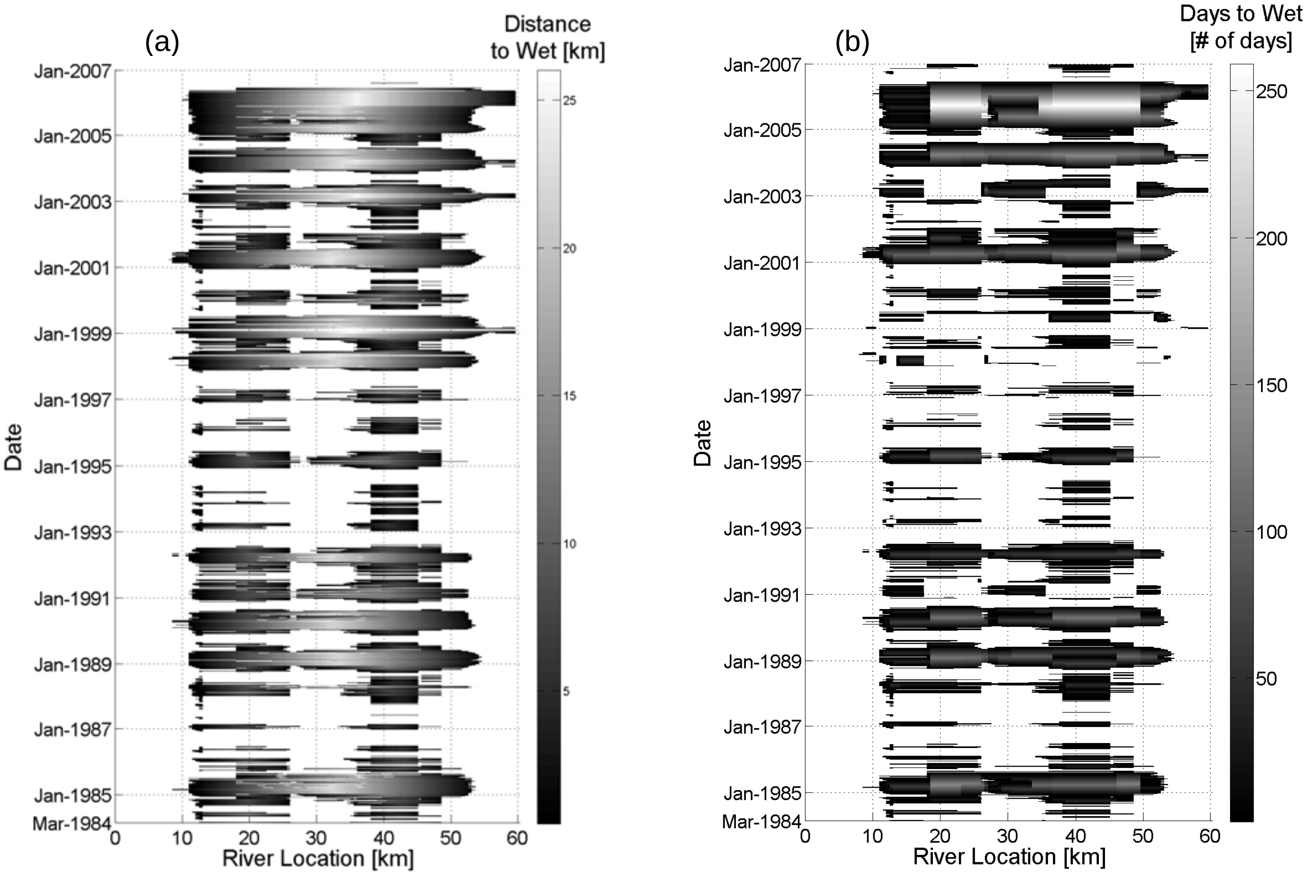

Fig. 7 Intermittence statistics in space and time for the Selwyn River: (a) the minimum distance ("Distance to Wet [km]") and (b) the time period ("Days to Wet [# of days]") to a wet part of the river, for parts of the river which are dry, are displayed.

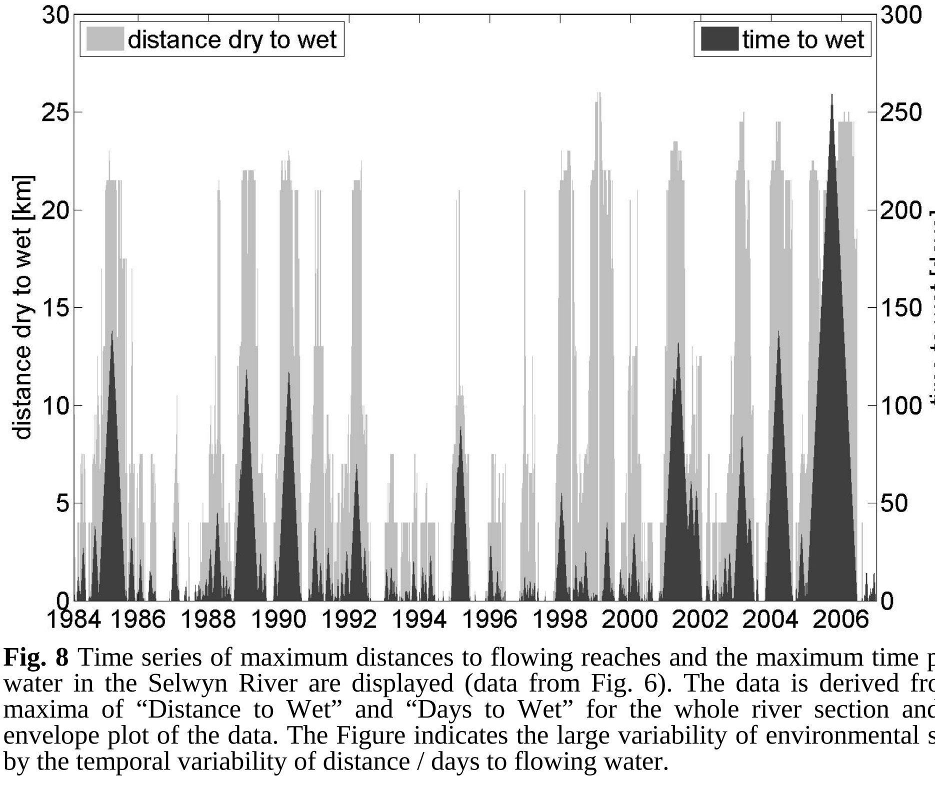

Fig. 8 Time series of maximum distances to flowing reaches and the maximum time period to flowing water in the Selwyn River are displayed (data from Fig. 6). The data is derived from Fig. 7 as the maxima of "Distance to Wet" and "Days to Wet" for the whole river section and thereby are an envelope plot of the data. The Figure indicates the large variability of environmental stresses indicated by the temporal variability of distance / days to flowing water.

For invertebrates and fish in intermittent rivers, distances from dry reaches to flow reaches partly determine mortality risks in intermittent rivers (Gotelli & Taylor, 1999; Labbe & Fausch, 2000). ELFMOD output was used to estimate distances from dry points in the Selwyn River to the nearest flowing water, and the duration of dry periods at each point in the river (Fig. 7). Figure 7(a) illustrates the distance to the closest flowing reach for each river km that is dry during the temporal domain of the model. Likewise, for the temporal dimension of the model, Fig. 7(b) illustrates the minimum number of days until wet (either forward or backward in time) for each river km for the entire temporal domain of the model. In Fig. 8, the data are rearranged to show a time series of maximum distances to flowing water. Together, these figures identify potential risks of desiccation for aquatic biota at any given spatial interval for any given point in time along the Selwyn River. Long periods of relatively short distances to flowing water occurred from 1992 to 1998, after which distances to flowing water and dry durations generally increased. Figure 8 also indicates that there was a potential shift in the river flow regime in about 2000, with increasingly longer distances and longer durations to wet river patches. Furthermore, a particularly severe dry period is evident in 2005–2006, when there was no flow in the central section of the river for about 18 months (Fig. 2).

DISCUSSION AND CONCLUSIONS

Uncertainty of these estimated flow matrices (and therefore the hydrological indices) using the empirical model depends on:

- uncertainties of the input data (flow time series and gauging data),
- uncertainties of the regression models produced by the model, and
- uncertainties in the concept, underlying the empirical model, i.e. how well a complex river system is described by simple linear equations. This uncertainty is related to the spatial and temporal sampling intensity of spot gaugings. Of particular importance is how well the sampling intensity reflects or captures spatial variations in surface water gains and losses.

In our implementation we can quantify impacts of two sources of uncertainty on the results: uncertainty in input data, and model uncertainty. The input data sets can be prescribed with a nominal error of measurement and the model will be run with upper and lower values (measurement ± error) to produce two alternative output scenarios. Model uncertainty is quantified by the 95% confidence intervals from the regression equations, which can be applied to the data set to produce a minimum and a maximum output scenario. This of course does not answer the third question – how well can we quantify surface water flows in space and in time in a hydrologically complex river? Our ongoing efforts are focused on understanding surface water–groundwater interactions in alluvial plain river systems to develop mechanistic models capable of higher predictive power and lower uncertainty. However, mechanistic approaches for modelling longitudinal flows in hydrologically-complex alluvial rivers are at an early developmental stage, and many simplifying assumptions are needed (Konrad, 2006). In the absence of mechanistic models that are both widely-applicable and comprehensive, simple empirical models – like the one presented here – are useful tools for a larger-scale assessment along rivers, and in particular for comparing river systems and identifying regional and long-term trends in river flow and intermittence patterns.

ELFMOD and its predecessors (Davey & Kelly, 2007; Rupp *et al.*, 2008) have been used to develop flow-ecology relationships for the Selwyn River, with an emphasis on flow intermittence. These relationships indicate that fish and benthic (surficial) and hyporheic (shallow subsurface) invertebrate communities along the Selwyn Rivers respond to variation in flow permanence, flow duration, dry duration, drying frequency, and distance to perennial reaches (Datry *et al.*, 2007; Davey & Kelly 2007; Larned *et al.*, 2007; Arscott *et al.*, 2009). The relationships with the greatest predictive power were for annual average flow permanence and for flowing and dry period durations prior to sampling. Coefficients from these intermittence–ecology relationships can be used to estimate the incremental effects of spatial or temporal changes in intermittence. It is part of our ongoing research to test hydrological indices, like the ones described in this paper, with regards to their predictive capability for stream biota, with the ultimate goal to provide supportive tools to identify ecological limits that may be useful for guiding management of intermittent alluvial plains rivers.

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