Impact of climate change on aquatic ecosystems along the Asse River network

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Abstract Intermittent rivers and their ecosystem will have to face climate change during the 21st century, with more frequent and more severe droughts possible, leading to changes in biodiversity. The Asse River (France) basin is one of the tributaries of the Durance River basin experiencing dry conditions. A framework was developed to simulate flows and biodiversity richness of intermittent rivers. The approach involves two rainfall–runoff models with distinct structures and a post-processing technique to simulate zero flow events. Perturbed meteorological forcings (downscaled GCM projections and biased resampled observed time series) are considered to study the biological response and intermittence. Results suggest that, by 2050: (1) zero flow events could be more frequent, (2) durations of zero-flows event are expected to increase, and (3) the consequence could be a loss of approximately two taxa. Sensitivity analysis also demonstrates that this basin is very sensitive to changes in total precipitation between June and November.

Key words intermittence; rivers; Durance River; climate change, hydro-ecology; hydrological modelling

INTRODUCTION

Intermittent rivers (IRs) represent a large proportion of the network and are not restricted to areas under arid climate (e.g. Snelder *et al.*, 2013). Moreover, in the perspective of global change this proportion may increase (Larned *et al.*, 2010). Nevertheless only a few studies concentrate on hydrological modelling of IRs, and knowledge on their biodiversity richness and relationship to river flow regime is still limited, leading to nonexistent management to protect the current ecosystems (Datry *et al.*, 2011). The Asse River is located in southern France, which experiences intermittent flow in the downstream part. This basin is considered as representative of the Mediterranean IRs within the Durance River basin and has been monitored since 2008 to analyse IR biodiversity and its controls.

The objective of this study is to capitalize on previous studies (Larned *et al.*, 2011; Datry, 2012), to model change in intermittence and to assess potential impacts on biodiversity and ecosystem services for the 2050s for the Asse River. This is one of the main issues addressed by the national research project R^2D^2-2050 (Risk, Water Resources and Sustainable Development within the Durance River Basin in 2050; http://r2d2-2050.cemagref.fr/).

Two rainfall–runoff models, including GR4J (Perrin *et al.*, 2003) and J2000 (Krause & Hanisch, 2009) were applied to simulate discharge time series at the gauging station located at La Clue de Chabrières (LCL). Then, a post-processing procedure was carried out to simulate zero flows downstream to LCL gauging station. An ensemble of perturbed climate conditions was used to study changes in river flow regime. Flow intermittence–biodiversity relationships generated under present-day conditions were then applied to predict possible future changes in biodiversity.

STUDY AREA AND DATA SET

The Asse River basin (660 km^2) is located in southeastern France (Fig. 1(a)). The river flow regime is partly influenced by snowmelt processes in the upper part of the basin due to high elevation (the highest elevation is 2282 m a.s.l) whereas the Mediterranean climate does lead to severe low flow events and drives the seasonal variations of runoff contribution in the alluvial plain (Fig 1(b)).

Observed discharges are available at LCL gauging station (375 km^2) upstream (Fig. 1(c)). In addition 13 cross-sections are regularly gauged (13 spot gauging data during the period

2004–2010). This monitoring system shows losses occur to the underlying aquifer between Section 1 and 7 and downstream to Section 8 before merging with the Durance River. Benthic and hyporheic invertebrates were collected twice a year (in autumn and spring) in addition to point flow measurements from the 13 sites along the alluvial plain. Dates for invertebrate collection were centred on 15 October and 15 April of each year. The samples are representative of conditions before and after observed dry events and therefore characterized the invertebrate richness in spring and in autumn, respectively.

Daily climate time series were extracted from the DuO database (Magand *et al*., 2013) which is a hybrid of two re-analyses: Safran (Vidal *et al*., 2010) and SPAZM (Gottardi *et al*., 2012). The FAO-Penman formulation (Allen *et al*., 1998) was used to compute reference evapotranspiration.

For this study, 300 climate projections derived from the ENSEMBLES Stream2 GCMs under the A1B emissions scenario, downscaled with three statistical procedures (Lafaysse *et al*., 2013), were used.

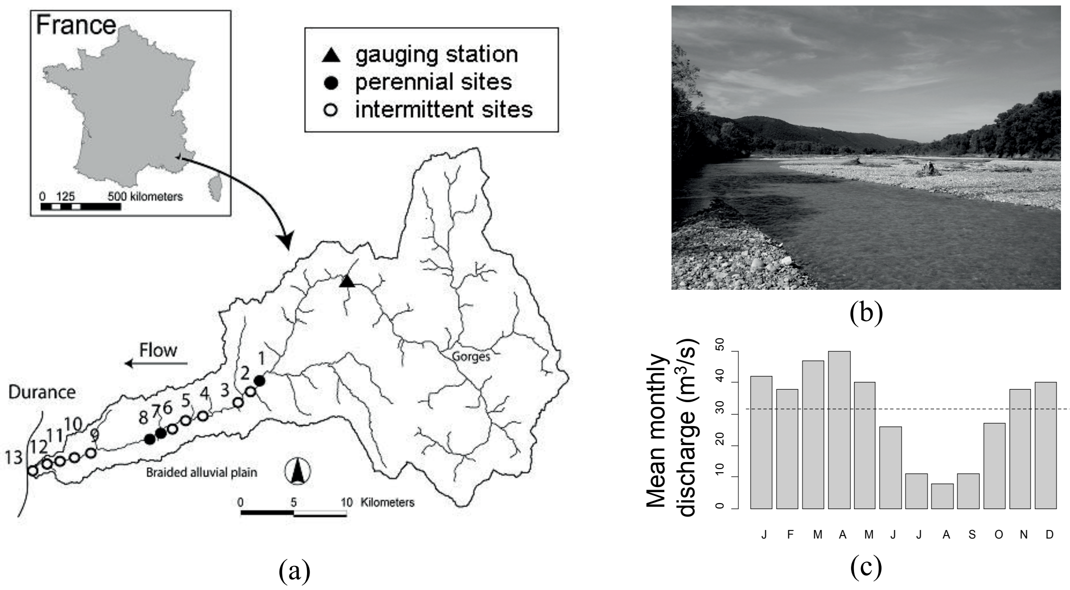


Fig. 1 (a) Location of the monitored sites within the Asse River basin. (b) View of the alluvial plain. (c) Long-term average monthly discharge is displayed at La Clue de Chabrières gauging station (the dotted line refers to the long-term average annual discharge).

MODELLING FRAMEWORK

Two hydrological models were adopted for simulating natural daily discharge at Section 13 and at LCL gauging station where an analysis of performance is possible. The GR4J model is a daily lumped rainfall–runoff model (Perrin *et al*., 2003). The four parameters calibrated against the observed discharges at LCL gauging station were transferred to the downstream cross-section 13 and slightly modified to fit against spot-gauging data. The distributed physically-based model J2000 (Krause & Hanisch, 2009) simulated processes including river flows using the concept of Hydrological Response Units (HRUs). The J2000 model is not calibrated.

Considering the period of records between 1961 and 2009 at LCL gauging station with perennial flows, the Nash–Sutcliffe Efficiency criterion computed on log transformed flows was 0.69 and 0.63 for the GR4J and J2000 models, respectively. A more satisfactory fit between observed and simulated flows was obtained with the GR4J model as no calibration procedure was considered for the J2000 model.

At Section 13 both models failed to reproduce dry river conditions. A post-processing technique of the simulated discharges (quantile mapping approach, e.g. Snover *et al*., 2003) was therefore carried out to simulate zero-flow events (Fig. 2). The procedure was first tested with other strategies on another temporary French river basin, the Albarine River basin (Larned *et al*.,

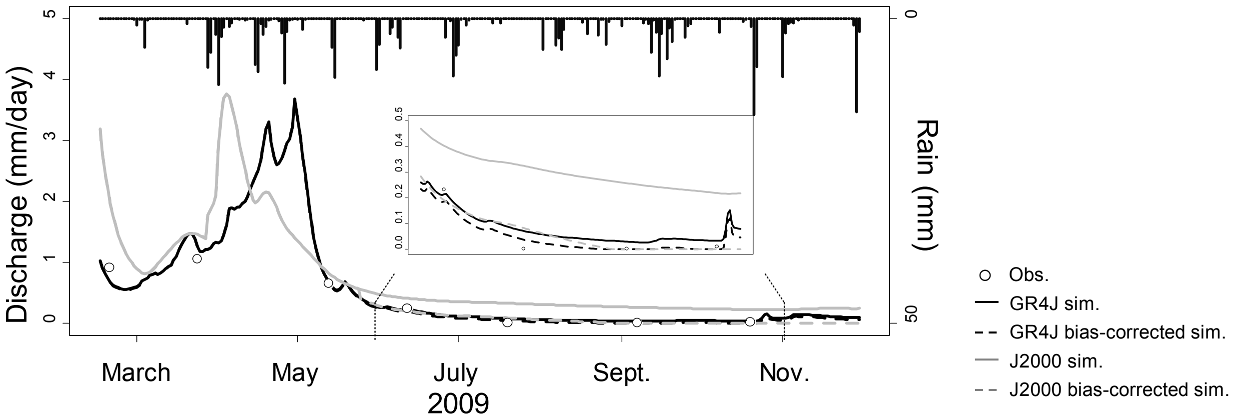


Fig. 2 Simulated and bias-corrected discharge time series at Section 13 for year 2009.

2011) and was found to be the most reliable way to model flow intermittence without modifying the structures of the models.

In addition, discharges at gauged sites were estimated, as a first guess, by linear interpolation along the river network between 2003 and 2010 using the ELFMOD model (Larned *et al.*, 2011).

Flow permanence *Fp*, i.e. the number of flowing days over the period between two successive dates of invertebrate collection (expressed in %), and drying duration *DD*, i.e. the mean number of days with zero-flow observed per event over the period between the two successive dates of invertebrate sampling, were found to be the most explanatory variables for community richness and structure within the collected invertebrate samples. This result is in accordance with other sites (Datry, 2012). The empirical regression shown in Fig. 3 indicates that 2.6 taxa disappear for every 10% decrease in *Fp*.

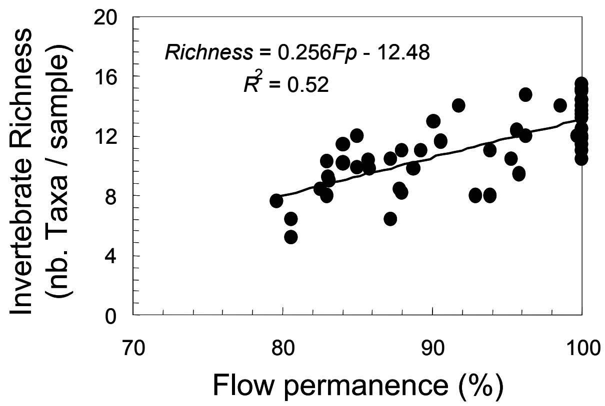
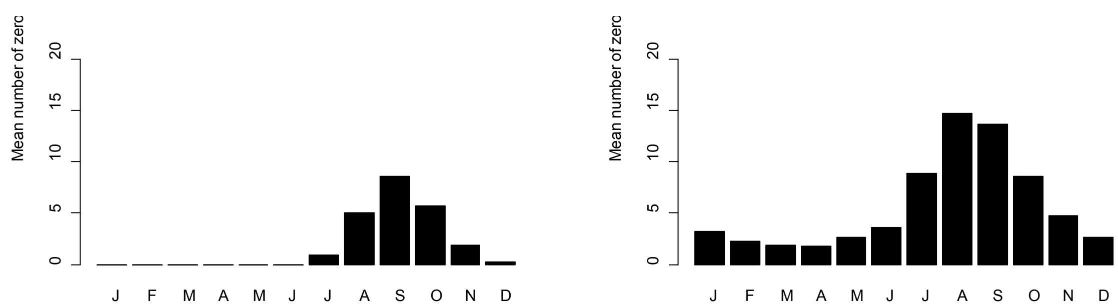


Fig. 3 Biological models relating flow permanence *Fp* to invertebrate *Richness.*



(a) (b)

Fig. 4 Bias-corrected statistics of zero flow events at Section 13 for the period 1961–2009; (a) GR4J; (b) J2000.

The GR4J model suggests less severe low-flow conditions than the J2000 model (Fig. 4) with a mean annual *Fp* of 0.92 and 0.74 for GR4J and J2000, respectively. No flow was observed at Section 13 for 3 of the 13 measuring campaigns. Hence if the gauged conditions are supposed to be representative of the river flow regime, the mean annual *Fp* is 0.77 (=1–3/13), which is an intermediate value between the two estimations.

PROJECTED CHANGES AND SENSITIVITY TO CLIMATE VARIATIONS

Only results obtained by the GR4J model are shown here. The GR4J model was forced by 300 climate projections derived from the ENSEMBLES Stream2 GCMs under the A1B emissions scenario, downscaled with three statistical procedures (Lafaysse *et al.*, 2013). Changes were examined for model runs under perturbed climate data between the control period (1980–2009) and the future period (2036–2065).

Under current day conditions, in the majority of cases, zero-flow events occur between June and November. There is a weak auto-correlation within the discharge time series at Section 13 (partial autocorrelation is less than 0.07 for lag time higher than 4 days) explaining why the analysis of climate change focuses on temperature *T* and total precipitation *P* during the June–November period.

All of the projections suggest an increase in air temperature *dT* between +0.9 and +3.3°C on average during the June–November period. There is less consistency on total precipitation *P* during the June–November period with *dP* between –25% and +12%.

Most of the scenarios lead to changes in *DD* between –10 and +18 days (mean: +1.5 days) and in annual *Fp* between –14 and +7% (mean: –3.5%) (Fig. 5). A consistent pattern was observed in Fig. 5 for *Fp*: changes in *Fp* seem correlated with changes in *P*. No structure of correlation is evident for *DD*.

More significant changes were observed when flow permanence *Fp* is computed between 15 April and 15 October (min: –23%, mean: –5%, max: +11%). Consequently, after the zero flow period, in autumn, assuming that the empirical regression shown in Fig. 3 is still valid. Change in *Richness* is given by:

$$dRichness = 0.256 dFp \qquad (1)$$

and all other things being equal *Richness* is expected to decrease with, on average, a loss of 1.3 taxa with $dFp = –5\%$.

Climate expected by 2050 is significantly different from climate from the recent past. This may question the stationarity of the hydrological processes operating in the rainfall–runoff

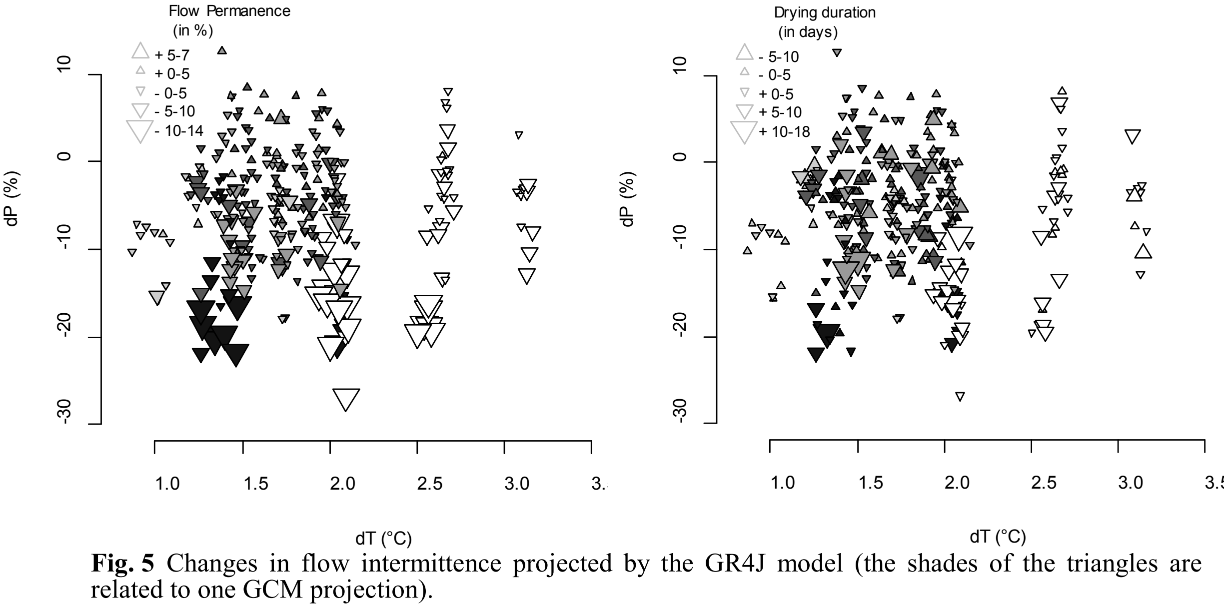


Fig. 5 Changes in flow intermittence projected by the GR4J model (the shades of the triangles are related to one GCM projection).

transformation. This hypothesis may not hold because land and vegetation cover will adapt in response to altered climatic conditions and considering parameters for the GR4J model constant over time is arguable. Therefore, a sensitivity analysis to climate variations around the current-day conditions (Fronzek *et al*., 2010) was performed to complement the climate change impact study. Perturbed climates were derived from observations by applying the modified KNN resampling technique (Hendrickx & Sauquet, 2013). The KNN scenarios were used as inputs of GR4J. Changes in annual *Fp* are estimated by a quadratic polynomial with the two variables *dP* and *dT* fitted to the set of simulated *Fp* ($r^2 = 0.96$):

$$dFp = 2.38(dP/10) - 0.722dT - 0.246(dP/10)^2 \qquad (2)$$

A similar relationship ($r^2 = 0.93$) was fitted to predict changes in *Fp* between 15 April and 15 October:

$$dFp = 2.95(dP/10) - 1.348dT - 0.272(dP/10)^2 \qquad (3)$$

Figure 6 shows that changes in *Fp* for this basin were more related to changes in rainfall regime than to changes in air temperature and results partly confirm those obtained with climate change scenarios (Fig. 5). Black dots indicate results for a given KNN climate. Anomalies for specific years are indicated by grey dots (year and its related *Fp* are indicated above and below the dots, respectively). All other things being equal 1.8 taxa may disappear as result of a 20% decrease in total precipitation during the June–November period.

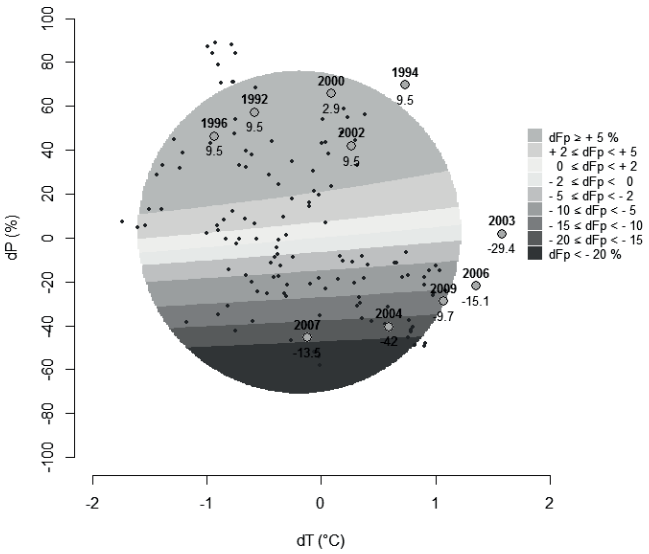


Fig. 6 Sensitivity analysis of *Fp* calculated between 15 April and 15 October to climate anomalies from June to November (• KNN scenario; ● observed year).

DISCUSSION

The results obtained with the two models show that modelling flow intermittence is a difficult task for hydrologists. The two rainfall–runoff models were not easily adapted to simulate dry conditions and zero-flow events, and an additional post-processing requiring days with observed zero flow is necessary.

The mean air temperature is likely to increase over future decades for the Asse River basin. Projected changes in flow permanency may lead to the decrease in species richness, due to increasing zero-flow events. The sensitivity analysis to climate variations performed with the GR4J model showed that, for this basin, *Fp* is more sensitive to rainfall regime than to air temperature.

To date, the effects of climate change on freshwater biodiversity have been assessed mostly through the responses of communities to increasing water temperature (e.g. Heino *et al*. 2009; Ormerod, 2009). To our knowledge, this study is the first to attempt predicting the effects of increasing flow intermittence on river biodiversity. Our results indicate that from 1 to 2 species may be lost from invertebrate communities due to increasing flow intermittence around 2050 in the Asse River. Yet, this exercise has some limitations. Firstly, some invasive species could take advantage of this increasing harshness to colonize the river and out-compete some present-day species. However, integrating this aspect is out of the scope of the present study. Secondly, changes in community diversity do not necessarily reflect changes in community function (Bonada *et al*., 2007). Some species may be lost without resulting in severe changes in ecosystem functions, thanks to species redundancy (Lawton & Brown, 1993). In contrast, some key species loss may lead to irreversible and dramatic changes in ecosystem functions. Therefore, our analysis needs to be refined in the future to identify which species would most likely disappear from river communities. Moreover, such a modelling exercise would benefit from being applied in other river basins, notably in those with different spatio-temporal pattern and magnitude in flow intermittence than the Asse River (e.g. Larned *et al*., 2011; Datry, 2012). One perspective of this future study will consist of transferring this framework into different basins on several continents to have a broader view of biodiversity changes related to increasing flow intermittence. This is one goal of the recently started IRBAS international project (www.irbas.fr).

Uncertainty related to hydrological modelling under current climatic conditions is high (e.g. the noticeable difference between long-term average *Fp* estimated by the two models). The next step will be to confirm the results of the sensitivity analysis applying J2000.

Acknowledgement This study is one of the issues addressed by the national project R^2D^2-2050 Risk, Water Resources and Sustainable Development within the Durance River Basin in 2050 (https://r2d2-2050.cemagref.fr/). The project R^2D^2-2050 is partly supported by funding from the GICC programme of the French Ministry for Ecology.

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