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Hydrological processes controlling flow generation in a Mediterranean urbanized catchment

REMI LOMBARD-LATUNE[1], NANEE CHAHINIAN[1], JEAN-LOUIS PERRIN[1], LAHCEN BENAABIDATE[2] & ABDERRAHIM LAHRACH[2]

1 *IRD-UMR HydroSciences Montpellier, Université Montpellier 2, Case courrier MSE, Place Eugène Bataillon, F-34095 Montpellier Cedex 5. France*
remi.lombard-latune@ird.fr

2 *Département de Géologie. Faculté des Sciences et Techniques. Université Sidi Ben Abdellah. BP 2202, Route d'Imouzzer, Fez, Morocco*

Abstract In the southern Mediterranean many rivers are characterized by an alternation of long dry periods interrupted by short floods. In this context, understanding the catchment's hydrological behaviour, especially during flood generation is essential to quantifying pollutant fluxes. This situation is observed in all the Maghreb countries, of which the famous city of Fez is a perfect illustration. The hydrological behaviour of Oued Fez was assessed through a coupled approach based on field observations and modelling. The analysis of rainfall–runoff events showed that flood generation is mostly caused by urban runoff over the large impervious zones of the city of Fez. A mathematical model based on the unit hydrograph method was used to synthesize the hydrological behaviour of Oued Fez. The model's two parameters were estimated by trial and error. The results indicated that a single set of parameters can accurately reproduce most of the observed flood events.

Key words rainfall–runoff; intermittent rivers; Nash cascade; Oued Fez; Morocco

INTRODUCTION

Intermittent rivers have a specific hydrological behaviour resulting in long drought periods interrupted by floods of high intensity and short duration. This behaviour influences water quality dynamics, as during low flow periods pollutants accumulate in the river bed and are flushed away by the first floods (Walling *et al.*, 2003). These rivers often constitute the only available water resource in semi-arid countries and hence are vulnerable to diffuse and point source pollution.

Some research programmes have investigated the hydrological and pollution transfer mechanisms of intermittent rivers located on the northern shores of the Mediterranean Sea. However, little information is available on their southern counterparts and in the absence of hydrological data, efficient water management schemes cannot be established. Oued Fez, an intermittent river located in central Morocco, is a perfect illustration of this situation. The river flows through the city of Fez, the third biggest city in the country, where in the absence of wastewater treatment plants, all effluents spill into the watercourse. The river's contamination has been established since the mid-1990s (Hmama *et al.*, 1993). However, to this date its hydrological functioning remains poorly documented.

The main objective of this work is to give a first assessment of the hydrological behaviour of the Oued Fez river through a coupled approach based on new field observations and modelling of the flood events recorded during the 2008–2009 hydrological year. This paper serves as a general introduction to the companion paper on the water quality dynamics of Oued Fez.

MATERIALS AND METHODS

The study site

Oued Fez is the main water body crossing the city of Fez in Morocco. It is a tributary of the Sebou River, the biggest river system in Morocco, with a catchment of 40 000 km^2 (Fig. 1). The river flows in an easterly direction from the springs of "Ras el Ma" in the upper Sebou (elevation = 420 m.a.s.l) through the Fez Medina and into the Sebou 4 km downstream of the city of Fez (elevation = 210 m.a.s.l). Its main course has a length of 33 km and its catchment area is reported to be 615 km^2.

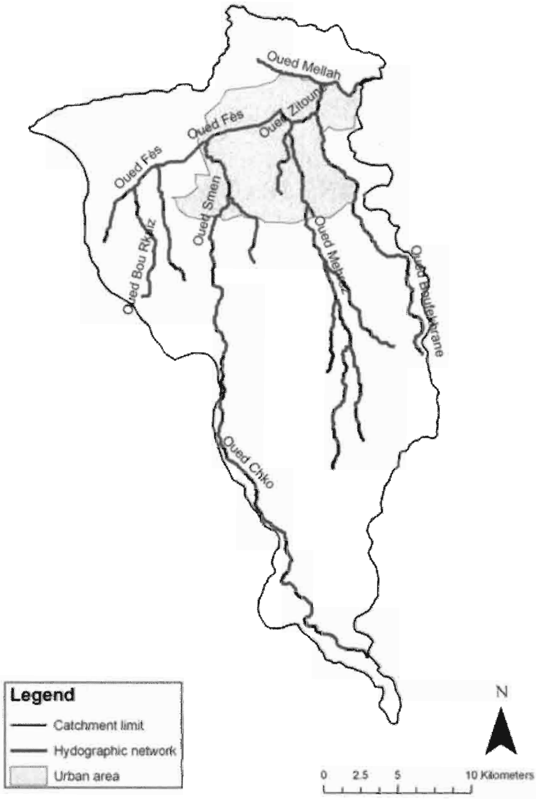

Fig. 1 The Oued Fez catchment.

Oued Fez is located on two groundwater systems: (1) A deep triassic aquifer used for the water supply of Fez, (2) the shallow unconfined Saiss aquifer mostly used by the private sector. Both aquifers are over-exploited and falling piezometric levels have been reported for both (ABHS *et al.*, 2005).

Oued Fez is an urban catchment as >10% of its area lies within the city of Fez. Fez's medina (old city) is densely populated and is the city's craft centre. Fez represents 40% of the total water quality impact on Oued Sebou (ABHS, 2006): all of Fez's sewage (200 000 m^3 per day in 2004; Koukkal *et al.*, 2004) is flushed directly into nearby watercourses.

The catchment has a continental semi-arid climate with cold winters and hot summers. The mean monthly temperature recorded at the ABHS station over the 1978–2008 period is 16.8°C and is similar to the values calculated at Fez airport for 1961–2003 (ABHS *et al.*, 2005). Precipitation data recorded at ABHS station shows a high inter- and intra-annual variation of rainfall, a feature typical of semi-arid climates.

High variations are also observed for the potential evapotranspiration data (PET) recorded at Fez-Saiss airport for 1980–2003 using the Colorado sunken pan method. PET can reach 163 mm during July and drop to 25 mm in January (ABHS *et al.*, 2005). The high PET combined with low or null precipitation yields water stress throughout the summer months.

EXPERIMENTAL SETTING

Since September 2008 a gauging station has been installed at the outlet of Oued Fez, upstream of the National Electricity Office's water intake (Fig. 1). Water level measurements are recorded at

5-min intervals by a pressure-transducer and converted to discharge through a rating curve. The station is operated by the IRD-FST team of researchers. Rainfall data is available for this catchment through a tipping-bucket raingauge installed on the FST roof by the University's Physics department. Until February 2009, data was recorded at 12-min intervals. Currently only hourly rainfall data is available. An additional rainfall gauge has been installed on the catchment in spring 2010.

The rainfall and runoff data collected on the catchment to this date is used to attain a first assessment of the main hydrological processes on the Oued Fez catchment and to model it.

HYDROLOGICAL MODELLING

The rainfall–runoff events were modelled using the Nash cascade model (Nash, 1957) in which the catchment is represented by a series of identical linear reservoirs having the same storage constant *k* (equation (1)). It can be considered as a particular form of the unit hydrograph expressed as:

$$h(t) = \frac{1}{k(N-1)!}\left(\frac{t}{k}\right)^{n-1} e^{-\frac{t}{k}} \tag{1}$$

$$Q(t) = P_e(t).h(t) \tag{2}$$

where Q, flow depth [L.T^{-1}] ; h, unit pulse function [–]; P_e, excess rainfall [L.T^{-1}]; N, number of reservoirs [–]; k, storage constant [T]; t, time [T].

In this application parameters N and k are calibrated by trial-and-error and, for simplicity, only integer values are considered for parameter "N". In this instance $\Gamma = (N-1)!$ corresponds to the gamma probability density function (Chow *et al.*, 1988) and its values can be determined directly. Parameter k is allowed to vary in the range [1; 40] and parameter N in the range [2; 20].

The calibration criteria are the well known Nash & Sutcliffe (1970) efficiency measure (NSE) and the sum of squares (SSQ).

$$NSE = 1 - \left(\frac{\sum_{t=1}^{N} (Q_{sim,t} - Q_{obs,t})^2}{\sum_{t=1}^{N} \left(Q_{obs,t} - \bar{Q}_{obs,t} \right)} \right) \tag{3}$$

$$\mathrm{SSQ} = \sum_{\mathrm{t}=1}^{\mathrm{N}} \left(\mathrm{Q}_{\mathrm{sim}} - \mathrm{Q}_{\mathrm{obs}}\right)^2 \tag{4}$$

where Q_{sim} and Q_{obs} refer to simulated and observed flow depth values.

Excess rainfall is calculated by hydrograph separation using the straight line method (Hewlett & Hibbert, 1964 in Chow *et al.*, 1988).

RESULTS

Figure 2 presents the rainfall data recorded by the FST raingauge during the 2008–2009 hydrological year. By comparison with previous decades, 2008–2009 appears to be an extremely wet year, with an annual rainfall of 842 mm and monthly rainfall values that are systematically higher than the long term averages. 2008–2009 is an exceptional hydrological year in terms of the number of rainfall occurrence days, but not in terms of daily rainfall values. Two distinct rainfall periods can be observed. The first corresponds to the autumn–winter period, with relatively high rainfall values over consecutive days while the second corresponds to the spring showers with sporadic spells of lower intensity.

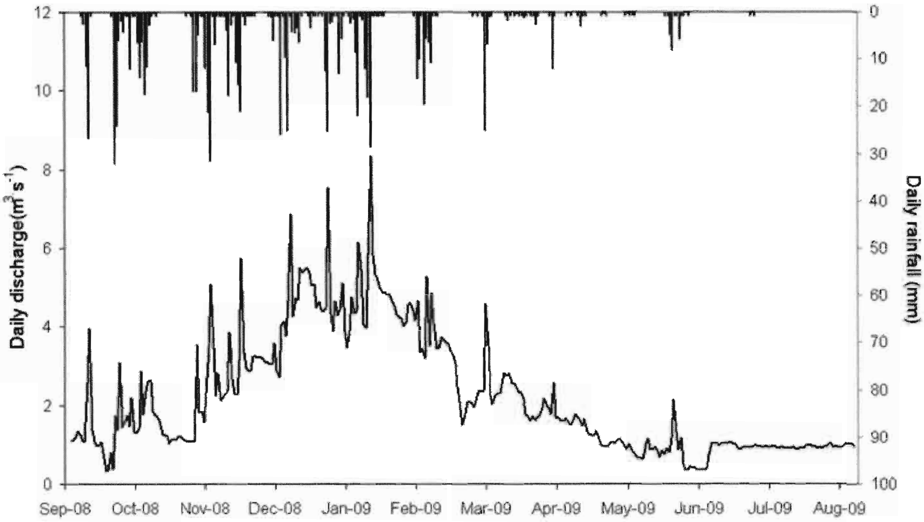

Fig. 2 Daily discharge and rainfall values recorded during the 2008–2009 hydrological year.

The catchment's response to the rainfall spells seems to be in the order of hours rather than days, as each rainfall peak has a corresponding spike on the hydrograph (Fig. 2). The analysis of the hydrograph's shape indicates a high flow period in the river starting in November 2008 and ending in May 2009 when the mean daily discharge settles down to its initial value of 1 m^3 s^{-1}, corresponding to the average base flow value. The general bell-like shape of the hydrograph during the high flow period suggests higher groundwater and subsurface flow contribution. Furthermore, the urban nature of the catchment and the resulting water abstractions can be clearly seen during June–July when part of the river water is diverted to feed a hydroelectric power plant.

For a better understanding of the rainfall–runoff relationship, the individual flood events were analysed. Given the urban nature of the catchment, in order to discriminate between "normal" flow variations and floods, only events where rainfall was continuous and the 12-min discharge values doubled within three consecutive time steps were considered. 34 rainfall–runoff events were recorded on the catchment from September 2008 to August 2009 (Table 1). The minimal time between the end of a flood event and the beginning of a new one is set to 6 h to ensure the independency of flood events.

A scatter-plot of the rainfall–runoff relationship for this catchment is presented in Fig. 3 and shows a linear relationship between the recorded rainfall and runoff depths. A linear regression was used to express runoff depth in terms of rainfall. According to Boyd *et al.* (1993) the slope of the regression line represents the fraction of the catchment which is contributing to runoff; in this instance the percentage corresponds to a 7.2-km^2 area. Contrary to what can be observed on natural Mediterranean catchments (Chahinian *et al.*, 2005), the events having the greatest runoff depth values are those that have the highest rainfall amounts (Fig. 3). This is a classical feature for urban catchments where high runoff coefficients are recorded (Boyd *et al.*, 1993; Rodriguez *et al.*, 2003). Thus no rainfall loss was considered during the modelling phase. The Mediterranean characteristics of the catchment are visible in the wide span of durations (260–2145 min), rainfall values (4.4–40 mm) and intensities (2–12 mm/h).

Because of a change in the rainfall acquisition time step, only the first 25 events were modelled, 13 of which were randomly selected for calibration and 12 for validation (Table 2). The results of the calibration procedure using the two selected criteria (NSE and SSQ) showed the couple $k = 17$ and $N = 5$ to be the best match. The validation phase confirmed the choice of the parameters: the NSE criterion varies from 0.67 to 0.97 for 12 calibration events. Thus, 16 events have a NSE > 0.75 (Table 2).

Table 1 Main characteristics of the rainfall–runoff events recorded during the 2008–2009 hydrological year (for events with an asterix (*) only hourly rainfall data is available).

Beginning of the event	Duration (min)	Time to peak (min)	Max Q ($m^3.s^{-1}$)	Runoff Volume (m^3)	Rainfall (mm)	Maximum hourly rainfall intensity (mm h^{-1})
10/09/2008	590	65	11.95	56611	4.8	4.0
10/10/2008	765	425	16.11	168850	26.8	12.4
10/21/2008	795	85	13.84	155740	32.2	1.8
10/22/2008	1035	570	13.19	207920	23.8	5.2
10/23/2008	625	130	7.24	47126	5.6	2.8
10/28/2008	760	110	5.88	69046	10.2	3.6
11/01/2008	1420	830	6.62	124190	20.2	2.6
11/25/2008	1570	225	8.40	222220	33.4	5.4
11/26/2008	260	105	5.88	18329	4.4	3.6
11/29/2008	1160	595	5.32	80177	10.2	2.4
11/30/2008	840	160	14.73	138030	16.2	6.2
12/01/2008	1515	1005	13.19	310980	33.8	6.2
12/04/2008	605	415	6.17	42579	6.4	1.8
12/09/2008	1295	550	12.15	151260	17.6	3.4
12/12/2008	575	315	9.09	63211	7.6	2.6
12/14/2008	1580	305	14.73	284460	34.0	6.6
12/28/2008	500	90	8.23	53887	6.0	2.6
12/31/2008	1155	600	9.09	150950	26.0	3.4
01/02/2009	530	150	8.06	56980	8.6	3.2
01/03/2009	945	825	13.62	106280	25.2	6.4
01/20/2009	965	600	15.41	246090	33.8	4.8
01/25/2009	1010	625	11.15	75081	10.4	2.2
02/02/2009	1380	670	12.77	201360	22.2	4.6
02/06/2009	1090	320	8.57	118650	15.4	2.2
02/07/2009	1655	310	16.11	357950	40.2	4.8
02/27/2009 *	600	400	14.06	56393	14.2	6.0
02/28/2009 *	600	215	6.93	40325	10.0	2.6
03/02/2009 *	660	215	13.62	115840	18.6	7.0
03/03/2009 *	360	195	14.28	41432	5.2	2.0
03/05/2009 *	2145	115	12.35	133380	14.8	3.4
03/28/2009 *	420	175	14.50	116680	18.8	6.4
04/26/2009 *	660	315	6.47	71530	12.0	4.6
06/16/2009 *	360	135	6.77	23579	8.2	3.8
06/19/2009 *	360	145	8.92	24122	5.8	4.0

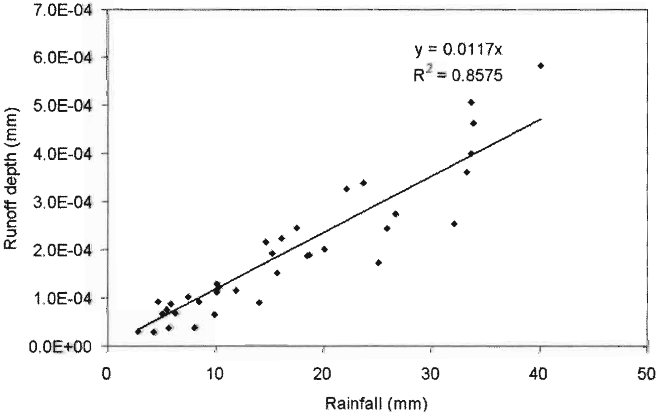

Fig. 3 Rainfall–runoff relationship for the studied events.

Table 2 Modelling results.

Event date	Calibration (C) or Validation (V)	Collective calibration $N = 5$; $k = 17$ min		Individual calibration results		
		Nash criterion (%)	SSQ criterion	k (min)	N	Nash criterion (%)
10/09/2008	C	0.55	118.32	19	3	0.85
10/10/2008	V	0.77	268.94	36	3	0.93
10/21/2008	C	–1.17	2836.86	40	4	0.41
10/22/2008	V	0.90	115.96	26	4	0.92
10/23/2008	C	0.95	9.28	17	5	0.95
10/28/2008	V	0.80	45.3	36	2	0.88
11/01/2008	C	0.81	44.55	37	3	0.90
11/25/2008	V	0.68	217.61	37	3	0.76
11/26/2008	C	0.04	39.87	31	4	0.66
11/29/2008	V	0.81	33.53	40	2	0.82
11/30/2008	C	0.94	55.06	19	4	0.95
12/01/2008	V	0.69	298.91	26	3	0.73
12/04/2008	C	0.75	19.64	28	4	0.81
12/09/2008	V	0.67	406.94	30	3	0.68
12/12/2008	C	0.31	996.76	2	5	0.45
12/14/2008	V	0.74	308.02	30	3	0.76
12/28/2008	C	–0.3	2743.11	1	2	0.47
12/31/2008	V	0.75	395.11	17	5	0.75
01/02/2009	C	0.98	36.46	19	4	0.98
01/03/2009	V	0.77	801.22	18	20	0.87
01/20/2009	C	0.94	300.81	23	4	0.94
01/25/2009	V	0.97	59.65	18	4	0.98
02/02/2009	C	0.77	440.85	31	3	0.78
02/06/2009	V	0.97	53.80	23	4	0.97
020/7/2009	C	0.78	456.97	21	4	0.80

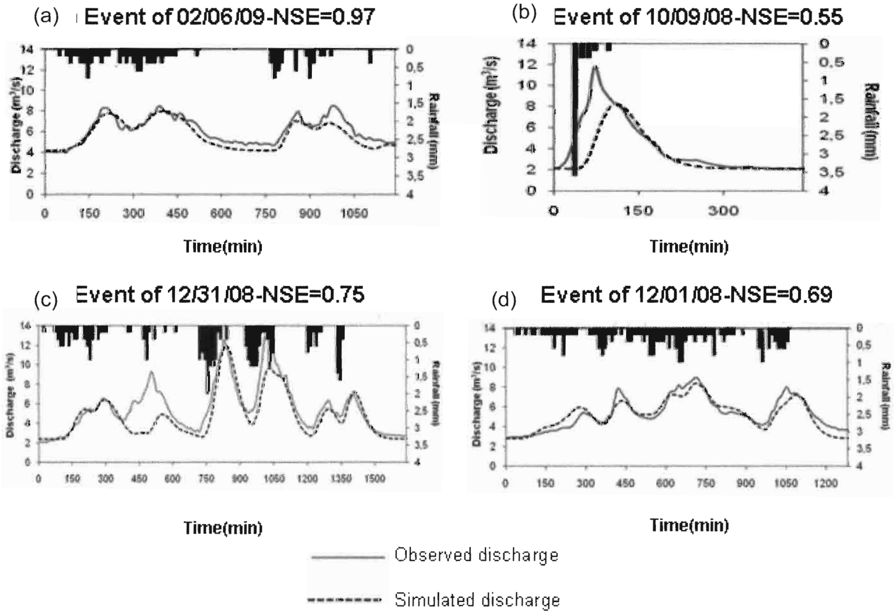

Fig. 4 Representative examples of simulated hydrographs.

An individual calibration test was undertaken to see whether the results could be further improved. The results indicate no drastic improvement, despite wider variations ranges for the calibrated parameters, especially for parameter *k*. The model output being more sensitive to *N* than to *k*, this finding is not surprising. When comparing the results of the two calibration procedures, it can be seen that the decrease in one parameter is compensated by an increase in another, as is commonly observed when model parameters are not independent.

An attempt was made to investigate the possible links between the event characteristics and modelling results. However, no conclusive results were found. Among the problematic events, those having short duration and small rainfall values seem to be worse than others. However, other short duration events have been modelled successfully (Nash = 0.94). The best explanation most likely lies in the spatial variability of rainfall and the distance (about 5 km) between the rainfall gauge and the streamflow gauging station. This leads to a false estimation of the rainfall amount or start time, leading to erroneous simulations (Fig. 4(b)). However, the NSE criterion alone is not sufficient to fully describe the goodness of fit of simulations. Figure 4 illustrates this case, although the NSE criteria are different, both hydrographs are equally well simulated.

DISCUSSION AND CONCLUSION

The results obtained during the first year of the study highlight the particularities of Oued Fez's hydrological behaviour. Our studies so far have focused on the urban part of the catchment whose impact on the pollution of Oued Sebou has been established for a long time (Khamar *et al.*, 2000; Koukkal *et al.*, 2004).

The analysis of the rainfall–runoff events has shown a linear relationship between runoff and rainfall, as usually observed on urban catchments (Boyd *et al.*, 1993). In terms of modelling, we observed that contrary to most event-based modelling results on non-urban semi-arid catchments (Maneta *et al.*, 2007), a single set of parameters is able to accurately reproduce all flood events. However, the calibrated parameter values are dependent on the time-step used. Thus, when using hourly data, the same set of parameters yields relatively poorer results.

Over the years, many attempts have been made to link the parameters of the unit-hydrograph-Nash cascade to the catchment's morphological characteristics (Beven, 2002). Various values have been reported for parameter *N* in the literature: for small flat urban catchments parameter *N* may be equal to 1 (Van der Kloet *et al.*, 1977), for a small forested catchment with steep slopes, it is reported to vary between 0.95 and 4.75 (Aguirre *et al.*, 2005) while on a 37.2 km^2 mountainous catchment (Nourani *et al.*, 2009) it ranges between 1.75 and 4.5. The calibrated values of parameter *N* are in accordance with those reported in the literature. The value of parameter *k*, which is thought to be related to a catchment's response time (Chow *et al.*, 1998) and to depend on land-use, is within the range reported in the above-mentioned studies.

The results presented in this study should be considered as preliminary. Indeed, one of the most important aspects of Mediterranean rainfall events is their high spatial variability. Currently, this feature is not taken into account in our work because of the lack of spatial rainfall and runoff data. Thus, future work will focus on the spatial variability of flows and their representation in a distributed model.

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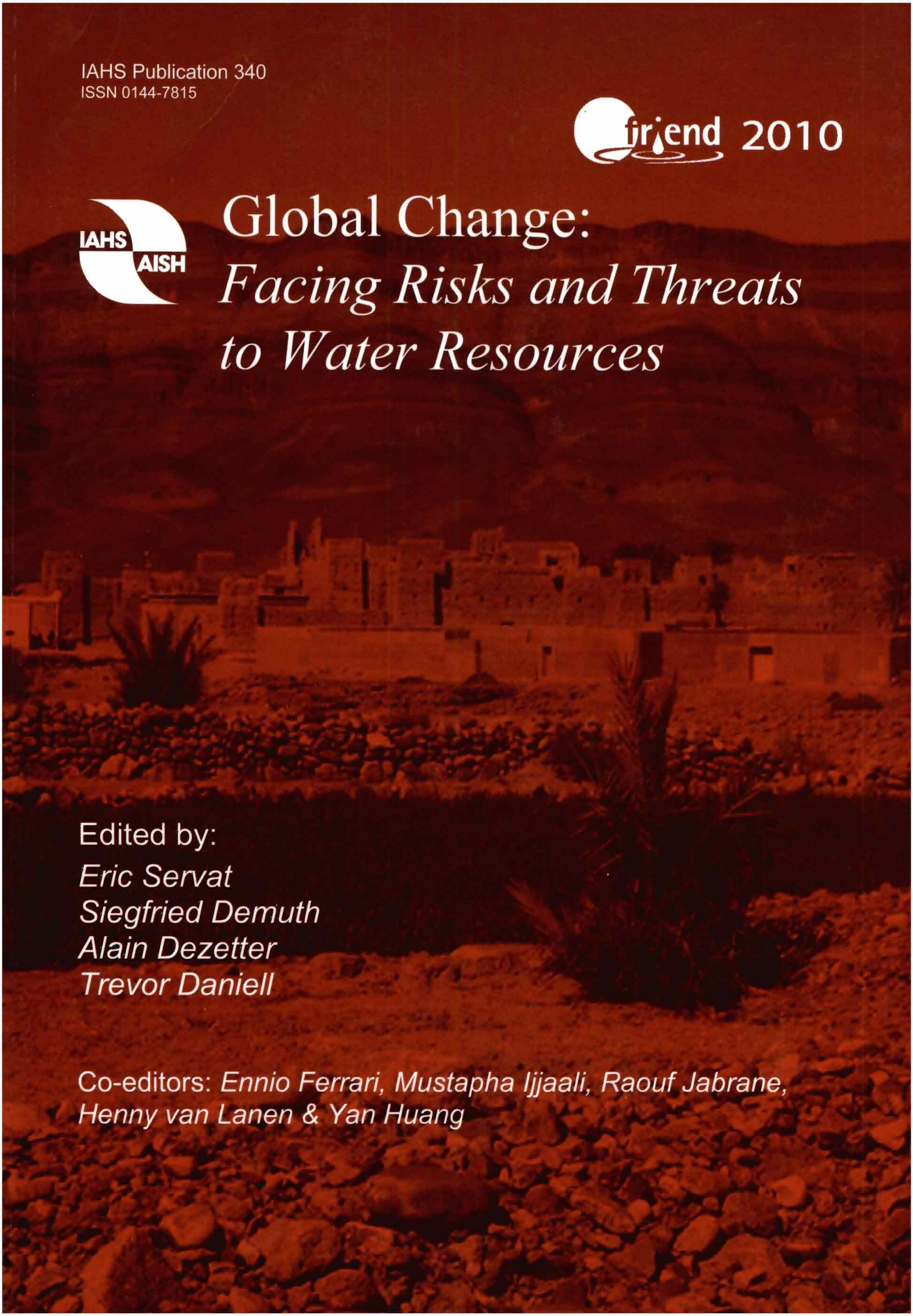

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Edited by:

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UMR HydroSciences Montpellier (HSM),
Université Montpellier 2, France

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