

A model-based assessment of the effects of projected climate change on the water resources of Jordan

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A model-based assessment of the effects of projected climate change on the water resources of Jordan

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This paper is concerned with the quantification of the likely effect of anthropogenic climate change on the water resources of Jordan by the end of the twenty-first century. Specifically, a suite of hydrological models are used in conjunction with modelled outcomes from a regional climate model, HadRM3, and a weather generator to determine how future flows in the upper River Jordan and in the Wadi Faynan may change. The results indicate that groundwater will play an important role in the water security of the country as irrigation demands increase. Given future projections of reduced winter rainfall and increased near-surface air temperatures, the already low groundwater recharge will decrease further. Interestingly, the modelled discharge at the Wadi Faynan indicates that extreme flood flows will increase in magnitude, despite a decrease in the mean annual rainfall. Simulations projected no increase in flood magnitude in the upper River Jordan. Discussion focuses on the utility of the modelling framework, the problems of making quantitative forecasts and the implications of reduced water availability in Jordan.

Keywords: climate change; water resources; hydrology; groundwater; Jordan

1. Introduction

Water is scarce in Jordan, and the pressure on this resource will increase as the population is projected to rise from an estimated 5.10 million today to 8.55 million by 2030 owing to natural increase and immigration (United States Statistics Division 2010). Jordan is seeking economic development, thus water is required for industrial expansion and tourism (US Geological Survey 1998). Surface waters Q1

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50 are already fully exploited, and most of those wadis (ephemeral streams) draining
51 to the lower Jordan have dams built in them. The water resource of the upper
52 Jordan and its tributaries is shared between Israel, Jordan, Lebanon, Syria and
53 the West Bank. The main water resource is groundwater, and there are three main
54 aquifers in Jordan, although the full extent and water capacity of these have yet
55 to be determined (Puri 2001; Puri *et al.* 2001; Puri & Aureil 2005; Struckmeier
56 *et al.* 2006). The four aquifers are the Syrian Steppe, the Hauran and Jabal
57 Al-Arab aquifer, the Disi aquifer and the Eastern Mediterranean aquifer. In all
58 cases, recharge is low at 15 mm yr^{-1} or less (Puri 2001). In Jordan, trends in the
59 groundwater salinity are unclear (US Geological Survey 2006).

60 Food security is poor in Jordan. In the marketing year 2005–2006, Jordan
61 imported 93 per cent of its annual wheat and 95 per cent of its annual barley
62 requirements (United States Department of Agriculture 2006). Vegetables are the
63 main crops grown in northwest Jordan where the annual precipitation is highest.
64 These crops are important to the national economy and as a food resource.

65 Water and food security are under further threat from the continued over-
66 abstraction of the water resource likely amplified by climate change. Between now
67 and the end of the twenty-first century, increased near-surface air temperatures
68 and reduced precipitation are projected for the Middle East (IPCC 2007;
69 Krichak *et al.* 2007); thus, it is important to quantify the likely effects of
70 climate change on the hydrology of the Jordan Valley and environs and to
71 interpret this in terms of the socio-economic consequences. Other studies have
72 looked at the water resources of the Jordan Valley and the likely changes
73 given climate projections (e.g., Kunstmann *et al.* 2005; Samuels *et al.* 2009).
74 A simple physically based model suggested that the water yield in Jordan
75 would reduce by up to 60 per cent if precipitation were to decrease by 10 per
76 cent and the region were to become 2°C warmer (Oroud 2008). Bou-Zeid &
77 El-Fadel (2002) suggested zero change in the October to April precipitation
78 over Lebanon by the 2020s with a warming in July of 2°C , leading to increased
79 soil moisture deficits and irrigation demands. A major initiative in the Jordan
80 Valley is the Globaler Wandel des Wasserkreislaufs—Jordan River (GLOWA
81 JR) project (Hoff *et al.* 2006). Results show that although annual streamflow
82 is proportional to total precipitation, provided annual precipitation exceeds
83 400 mm, a projected increase in the frequency of wet spells lasting longer than
84 3 days may result in more frequent and more intense floods in the upper Jordan
85 (Samuels *et al.* 2009).

86 Messenger *et al.* (2006) question the reliability of outputs from hydrological
87 models driven with climate model data. The question of how climate change
88 may impact on river flow is challenging because of the difficulty that climate
89 models have with representing spatial and temporal variability in daily rainfall
90 and the structural and parameter uncertainty in hydrological models. Wilby
91 *et al.* (in press) also note that there is little consensus between climate model
92 output in the Middle East and North Africa region. Thus, modelled forecasts
93 of future river flows are uncertain, although multiple climate model applications
94 that consider a range of emission scenarios can help build confidence or otherwise
95 in projected changes. Despite this, individual model simulations are still useful
96 as they contribute to the total number of model runs available for analysis and,
97 as in this case, provide an example of how climate model output can be used in
98 a modelling framework to assess changes in runoff.

99 The aim of this work is to develop and test a new meteorological and
100 hydrological model framework and to assess the output from this new model chain
101 to assess the likely impacts of climate variability and change on water availability
102 in Jordan. Specifically, the objectives are as follows:
103

- 104 — to link a regional climate model (RCM), a weather generator, a rainfall-
105 runoff model and a runoff routing model to create a framework with which
106 to assess the impacts of climate variability and change;
- 107 — to collate a database to provide sufficient suitable data with which to
108 develop and test a climate-hydrological model chain in a data-poor region;
- 109 — to assess the impact of anthropogenic climate change on flows in the upper
110 River Jordan and the Wadi Faynan and to compare the modelled outcomes
111 with other studies; and
- 112 — to consider the benefits and disadvantages of the approach within the
113 context of other available methods.
114

115 The study has two parts. In the first part, the effects of daily and seasonal
116 precipitation patterns on streamflow in the upper River Jordan are explored using
117 climate scenarios as inputs to the modelling framework. In the second part, the
118 same methodology is applied to a site in western Jordan, the Wadi Faynan, which
119 is considered representative of the wadis draining to the lower Jordan, although
120 the Wadi Faynan itself drains to the Dead Sea rather than the Jordan River.
121 Considered together, these two components provide insight into the mechanisms
122 by which the projected changes in precipitation and evaporation will affect the
123 hydrological cycle in semi-arid environments.
124

125 2. Study areas and data resource

126 (a) *The upper River Jordan*

127 In this study, the upper Jordan (1752 km²) is defined as the catchment area from
128 the headwaters to the Obstacle Bridge gauging station (33.03° N, 35.62° E). This
129 study area was chosen because of its importance in terms of water provision
130 to Jordan, the West Bank and Israel (figure 1). The headwaters of the Jordan
131 drain from Lebanon and from Mount Hermon in the Golan Heights, the highest
132 point in the catchment (2814 m), where precipitation can fall as snow during the
133 winter. The key tributaries of the upper Jordan are the Dan, Snir (of which the
134 Hasbani is a tributary) and the Hermon (of which the Banias is a tributary).
135 The geology of the upper Jordan is predominately limestone, which includes
136 Karst development. The springs, which form the Dan river, drain from the Karst,
137 and the groundwater sustaining the spring flow is estimated to have a retention
138 time of 2–3 years (Rimmer & Salinger 2006). The upper Jordan drains into the
139 Sea of Galilee, and the outlet, which supplies the lower Jordan River, is located
140 near Degania Bet, Israel. Downstream of the Sea of Galilee, the Yarmouk drains
141 into the Jordan River. The King Abdullah Canal is used to provide water for
142 irrigation in northwest Jordan, and water is diverted from the lower Yarmouk
143 to supply the canal, thereby lowering flows in the Yarmouk and the Jordan
144 River. Water is abstracted for irrigation in Israel using the National Water
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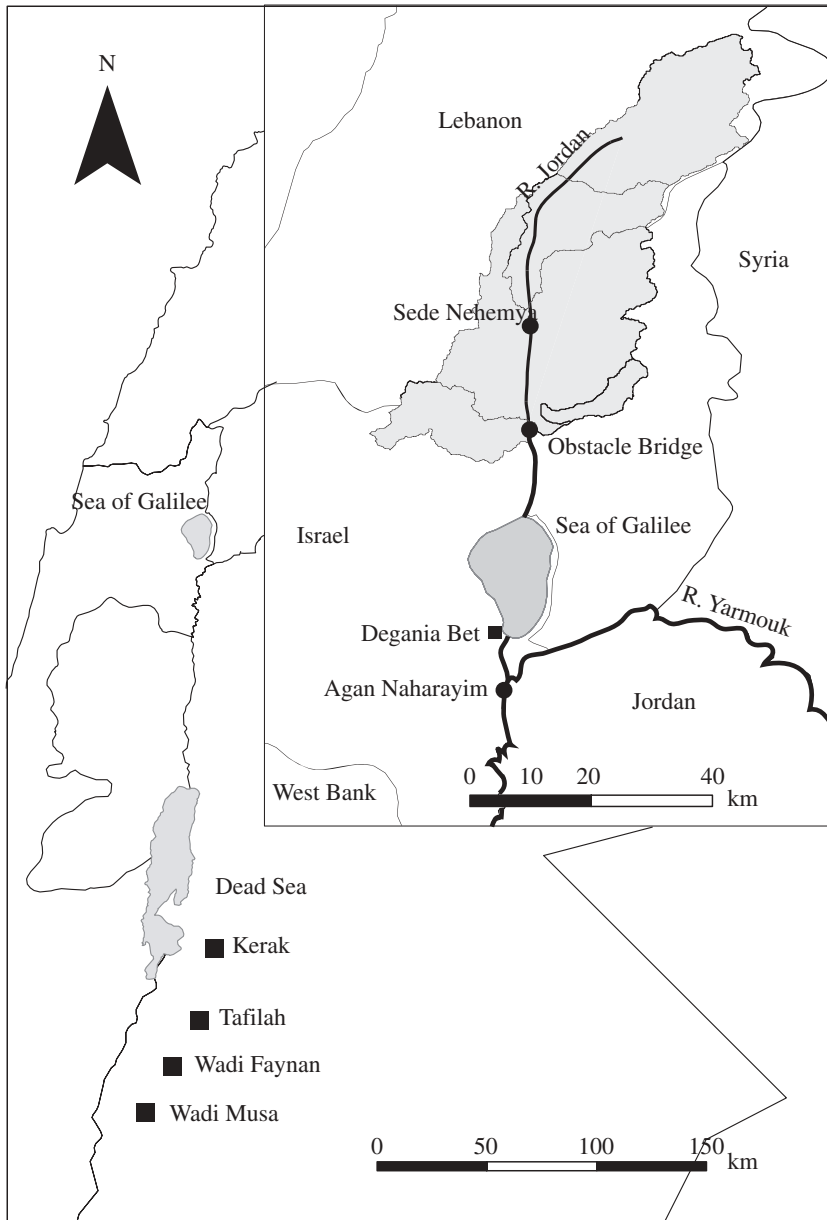


Figure 1. The location of the study sites with an inset schematic map of the upper River Jordan. Square, daily rainfall; circle, daily discharge.

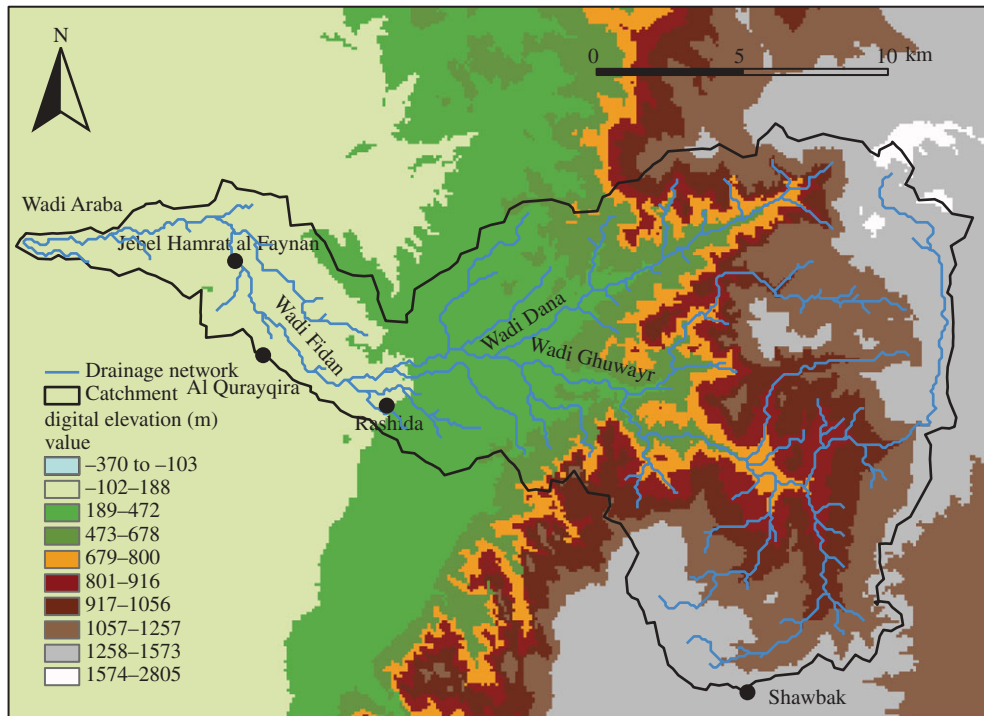
Carrier, which draws water upstream of the inlet to the Sea of Galilee, and this also lowers flow in the Jordan River. Downstream of the confluence with the Yarmouk, the Jordan River flows southward to the Dead Sea where over the past 30 years, water levels have dropped at the rate of 0.5 m yr^{-1} as a result of over-abstraction.

197 Precipitation patterns in Jordan show a strong gradient from west to east.
198 The main storm track affecting northern Jordan is from west to east along the
199 Mediterranean Sea. Precipitation in the south of Jordan can be affected by low
200 pressure systems over the Red Sea, known as Red Sea lows, particularly in the
201 boreal autumn and spring (Alpert *et al.* 2004). The mean annual precipitation
202 over Israel is 500–900 and 200–700 mm in the northwest of Jordan, where the
203 majority of the crops are cultivated. Wadi Araba, the valley along the Israel–
204 Jordan border, is an extension of the Great Rift of Africa. This valley affects
205 the precipitation distribution. To the east of the valley axis is a scarp slope.
206 Along the ridge of the scarp slope and into northwest Jordan, which is at an
207 elevation of between 400 m above sea level at Umm Qais in the north and 1727 m
208 above sea level at Jebel Mubrak in the south, the mean annual rainfall tends
209 to be higher (200–700 mm yr⁻¹) than in the valley bottom (approx. 50 mm yr⁻¹),
210 which, at the Dead Sea, is approx. 400 m below sea level. The scarp slope causes
211 orographic lifting of the moist air masses moving east over Israel and the valley,
212 and this leads to greater precipitation over the ridge of the scarp. Further east,
213 towards the desert centre, the rainfall is much lower at approximately 60 mm yr⁻¹
214 at Ma'an and along the 'pan-handle' of Jordan towards the border with Iraq.

215 The spatial coverage of readily available meteorological and hydrological data
216 is sparse. For the purpose of this study, data were collated from 60 rainfall stations
217 and 7 discharge gauging stations across Israel, Syria, Lebanon, the West Bank
218 and Jordan. Daily rainfall data were purchased from the Israeli Meteorological
219 Service for the period 1984–2005 for nine sites, and further daily rainfall data were
220 available for seven stations in Jordan from 1937 to 1974 from the yearbooks of the
221 Water Resources Division of the National Resources Authority. Monthly rainfall
222 data were available from the United States National Climate Data Centre for 11
223 sites in Israel (1846–1995), 11 sites in Jordan (1960–2000), 15 sites in Lebanon
224 (1888–2000) and 7 sites in Syria (1951–2000).

225 Daily flow data were, in general, difficult to find, but these are needed to
226 assess the flood extremes. Ideally, 15 min data should be used, but no such
227 data were available for this study. Daily data from the United States National
228 Climate Data Centre were available for flow gauges on the Jordan at Sede
229 Nehemya (1984–1992), Obstacle Bridge (1973–1993) and Naharayim (1988–1993).
230 The Naharayim gauging station is located downstream of the confluence of the
231 Jordan and Yarmouk rivers, and although daily measurements are available for
232 the period 1988–1993, the flows at this point are heavily modified by upstream
233 abstractions to supply the National Water Carrier and the King Abdullah Canal.
234 Monthly flow data were available at six stations, and daily and monthly flows
235 were reported for gauges in the 1963 Jordan Hydrological year book (Central
236 Water Authority 1963). This yearbook includes flows for the main channel of the
237 Jordan and contributing side wadis. It should be noted, however, that in many
238 cases, the flows for the side wadis were estimated using engineering calculations
239 (flood hydrographs) rather than measurements. The flow in dryland systems is
240 notoriously difficult to measure as rainfall is infrequent and large floods can
241 damage measuring structures.

242 The rainfall and runoff data were supplemented with data describing the local
243 climate at 12 sites across Jordan. These data included monthly averages for the
244 period 1983–2002 for precipitation, near-surface air temperature, solar radiation,
245 wind speed and sunshine hours.



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Figure 2. A topographic map of the Wadi Faynan.

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Land surface elevation data for the Middle East region were obtained from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). This dataset has a resolution of 90 m and a vertical accuracy of 15 m. Land cover was taken from the Global Land Cover Map 2000 (v. 1.1) downloaded from the HYDE land cover database (Klein Goldewijk 2001).

(b) *The Wadi Faynan*

The Wadi Faynan drains the eastern scarp slope of Wadi Araba, south of the Dead Sea (figures 1 and 2), and is approximately 25 km long flowing east to west. The Wadi Faynan (241 km²) discharges to Wadi Araba after passage through the Jebel Hamrat al Fidan, an Aplite-granite mass located at the mouth of the Wadi Fidan; the Wadi Fidan is the name given to the extension of Wadi Faynan between Al Qurayqira and Jebel Hamrat al Fidan. The climate of Wadi Faynan is currently classified as semi-arid as annual potential evaporation exceeds precipitation (Al-Qawabah *et al.* 2003). The Wadi Faynan has two major tributaries, the Wadi Ghuwayr and the Wadi Dana, developed along two NE-SW trending geological faults (Tipping 2007; figure 2).

The Wadi Faynan region has a rich archaeological heritage comprehensively described in several recent volumes (Barker *et al.* 2007; Finlayson & Mithen 2007; Hauptmann 2007). Given that the focus of this paper is the hydrology, the archaeology is not considered further. Today, the Bedouin located in the Wadi Faynan use the perennial water flowing from springs in the Wadi Ghuwayr to

295 irrigate their fields near the villages of Al Qurayqira and Rashida by conveying
296 the water in plastic pipes under gravity from the mid-reaches of the wadi. There
297 are no major urban centres in the catchment, with the population being sparse
298 in comparison to that of northwest Jordan where the rainfall and topography are
299 more favourable for irrigation. The Wadi Faynan fringes the Dana National Park
300 (Al-Qawabah *et al.* 2003).

301 Geological and hydrological information was derived from digital and paper
302 maps and field-based measurements. The geology of the Wadi Faynan comprised
303 fluvial deposits and eolian sands from the Quaternary period; limestones from the
304 Eocene/Paleocene and Cretaceous periods; sandstones from the Cambrian period,
305 and Porphyrite and Aplite-granite from the Precambrian eon. There is also an
306 outcrop of basalt from the Quaternary on the northeast rim of the catchment,
307 which forms the Jebel al Afa'ita. The Wadi Ghuwayr and the Wadi Dana have
308 contrasting geology, and springs are also found in the Wadi Dana and are used
309 to irrigate gardens and to supply a hotel, though the water from these does
310 not typically reach the Wadi Faynan. The highest point in the Wadi Faynan
311 catchment is Jebel Al Afa'ita at 1641 m above sea level. The elevation of the
312 confluence with the Wadi Araba in the Rift Valley is 300 m below sea level. The
313 range in altitude on the scarp slope varies from approximately 300 m above sea
314 level at the Ghuwayr-Dana confluence on the alluvial plain to 1300 m above sea
315 level on the plateau.

316 Hydrological measurements were collated from previous academic, government
317 agency and engineering studies. These data were integrated with new field
318 measurements of baseflow, open-channel hydraulics (to estimate flood peaks) and
319 water chemistry during field visits in 2006, 2007 and 2008. There was recourse
320 to satellite imagery to confirm the presence of specific geological structures and
321 to verify the catchment boundaries of the study area derived from the SRTM
322 DEM. The full details of these data and the sampling and analysis methods are
323 given in Wade *et al.* (in press a).

324 Rainfall patterns in the region of Faynan are dominated by the orographic
325 effect of the rift escarpment, and the area of highest annual rainfall follows a
326 north-south line between Kerak, Tafilah and the Wadi Musa (figure 1). Mean
327 annual rainfall across the Wadi Faynan catchment decreases from 400 mm yr⁻¹
328 at El Atate on the plateau to 50 mm in the Rift Valley floor; the latter is in
329 a rain shadow being surrounded by highlands. The mean annual rainfall at
330 Shawbak, which is located on the plateau on the southern boundary of the
331 Faynan catchment, is 312 mm yr⁻¹, with a standard deviation of 136 mm yr⁻¹
332 (Tarawneh & Kadioğlu 2003). Rainfall generally occurs between October and
333 May, as elsewhere in Jordan. During winter, the precipitation can fall as snow on
334 the plateau (Al-Qawabah *et al.* 2003).

335 The air temperatures in the Dana Reserve, which are assumed to be
336 representative of those in the Wadi Faynan, are typically a mean of 9°C
337 and 27°C during January and August, respectively (Al-Qawabah *et al.* 2003).
338 The mean annual potential evaporation measured at Tafilah during the
339 period 1999–2003 was 1978 mm yr⁻¹ (EMWATER 2005; Hashemite Kingdom of
340 Jordan—Meteorological Department 2006). Given the higher rainfall in winter
341 and the lower evaporation rates, the optimum period for cropping is winter. The
342 land cover is characterized as desert on the floor of the Wadi Araba, changing to
343 steppe in the mid and upper reaches of the Wadi Faynan.

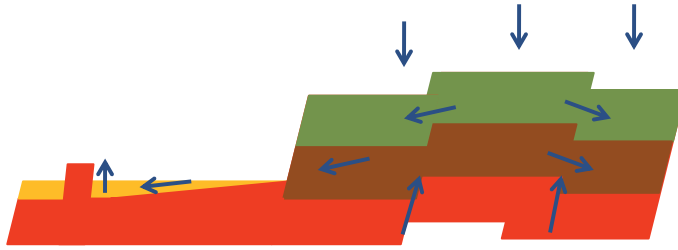


Figure 3. The conceptual model of the Wadi Faynan hydrology. This schematic is based on the geological cross-section of the Geological Map of Jordan 1:250 000, prepared by F. Bender, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover 1968 (Sheet: Aqaba-Ma'an and Amman). Red region, porphyrite and Aplite-granite; brown region, sandstone; green region, limestone; yellow region, alluvial sands, blue arrow, flow pathway.

A conceptual model was developed to describe the Wadi Faynan hydrology (figure 3). This model was built by integrating all the knowledge ascertained from the review of the existing and newly collected data (Wade *et al.* in press *b*). The model is as follows: the major aquifers are defined by the catchment boundary and the major aquifers are the limestone and the sandstone; groundwater recharge of the limestone and sandstone aquifers occurs through the limestone and colluvium mantle in the upper reaches of the Wadi Faynan around Dana and Shawbak; this recharge is supplemented by transmission losses from the main wadi channels to the underlying aquifers and the shallow channel alluvium; springs occur at the contact between the limestone and sandstone and between the sandstone and Precambrian volcanic rocks; the Precambrian volcanic rocks act as an impermeable layer keeping the water near the surface as it flows past from the Wadi Ghuwayr before the sand and gravels in the channel deepen in the Wadi Fidan alluvial plain and the water flows beneath the surface, possibly along the contact with the underlying Aplite-granite; the key pathways are lateral perennial flows through the limestone and sandstone with surface overland flow generated during rainfall events and snow does fall during winter in the headwaters of the catchment, but it is assumed that this will infiltrate into the well-drained soils upon melting. A full justification for these assumptions is provided in Wade *et al.* (in press *b*).

3. Methodology

An overview of the modelling framework is shown in figure 4. It can be seen that the framework consists of hydrological models driven by daily precipitation time series derived using a statistical rainfall model (weather generator) and climatological potential evaporation (Black *et al.* in press). Observed daily precipitation data were used to parametrize the weather generator, and HadRM3-modelled daily precipitation data were used when making projections of flow changes.

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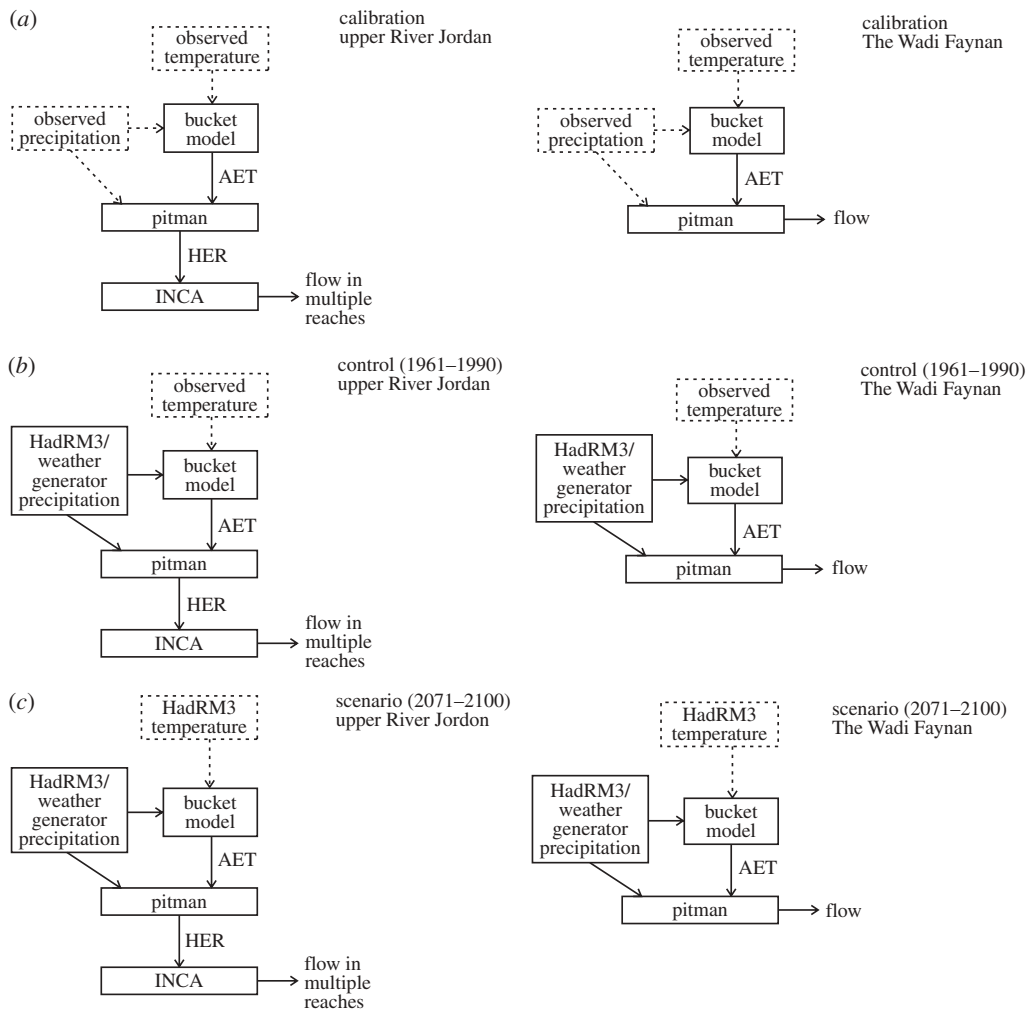


Figure 4. Overview of the modelling framework showing the data and model linkages for the upper Jordan and the Wadi Faynan applications for (a) calibration, (b) the control period (1961–1990), and (c) the scenario period (2071–2100; A2).

(a) Climate component of the modelling framework

The RCM used in this study was a variant of HadRM3. HadRM3 is a regional scale climate model with a spatial resolution of 0.44° (approx. 50 km) for both latitude and longitude developed by the UK Hadley Centre. As such, the model has a finer spatial scale than global circulation models (GCMs) such as HadCM3, which has a spatial resolution of 3.75 by 2.5° for longitude and latitude, respectively. Climate projections were extracted from HadRM3 RCM simulations of the 1961–1990 control and the 2071–2100 future periods. The output from HadRM3 was formally compared with observations in Black (2009). For the control period (1961–1990), the modelled near-surface air

442 temperatures in the eastern Mediterranean were reasonably well represented. The
443 modelled control-period precipitation data show that, while the spatial pattern
444 of precipitation over the 30-year control period was generally modelled well, the
445 resolution of the HadRM3 model was too coarse to capture the subtle variations
446 in rainfall across the extension of the Rift Valley and northern Jordan. Moreover,
447 the intensity in rainfall was underestimated, leading to biases in the annual
448 totals. Thus, these results highlight the need for statistical downscaling, both to
449 interpolate the RCM simulations to a point and to correct the climate model bias.

450 The A2 emission scenario was used for all the 2071–2100 projections. This
451 scenario represents a world with a slow technological response to mitigate climate
452 change and where the economic differences between the industrial and developing
453 worlds do not narrow (IPCC 2001). The greatest changes are expected in near-
454 surface air temperature and precipitation by the end of the century; therefore, the
455 scenario and the period considered represent a ‘bad’ case scenario. Current data
456 suggest that global CO₂ emissions are following the ‘worst’ case A1F1 scenario (le
457 Quéré *et al.* 2009). The consideration of a single emission scenario only and the
458 output from one RCM are limitations of the study. Despite this, the work is still
459 useful as it explores a new modelling framework, and the results are interpreted
460 in terms of those generated from other contemporary model-based assessments.

461 A weather generator was used for the control period and future scenario model
462 runs. The weather generator is described fully and evaluated in Black *et al.*
463 (in press), where it was shown that, while the weather generator was capable
464 of reproducing the main features of the observed rainfall seasonal cycle, there
465 were some biases—with more rain at the margins of the rainy seasons than
466 observed. The weather generator derives rainfall stochastically, according to the
467 underlying patterns of daily rainfall. In the weather generator used, the patterns
468 of daily rainfall were described statistically through the mean rain per rainy day
469 (rainfall intensity) and the probabilities of rain both given rain the day before
470 (PRR) and given no rain the day before (PDR). PRR and PDR were calculated
471 separately and varied by season. In the summer, when rainfall is low, both PDR
472 and PRR were set to 0.01; in the rainy season, PDR varies from approximately
473 0.15 to 0.25 with lower values at the margins of the rainy seasons and PRR
474 from approximately 0.55 to 0.65. The distribution of rainfall intensities (rain per
475 rainy day) was based on the observed time series, with an extra parameterization
476 for extreme rainfall events. The distribution was adjusted to take into account
477 changes in the rain per rainy day in the future scenarios. For the upper Jordan
478 and the Wadi Faynan applications, rainfall observations from Degania Bet and
479 Tafilah were used, respectively. For the future scenario integrations, the changes in
480 rainfall occurrence probabilities (as defined above) were derived from the regional
481 model integrations. In order to correct for model bias, these changes were then
482 applied to the observed probabilities.

483 484 485 (b) *Hydrological components of the modelling framework*

486 The hydrological components of the model framework are the Pitman
487 rainfall–runoff model and the Integrated Catchments model (INCA v. 1.11.10).
488 The Pitman model is a conceptual, process-based model of the rainfall–runoff
489 relationship (Pitman 1973). The Pitman model was chosen because it is a model
490 developed in South Africa for semi-arid hydrological conditions and forms a

491 trade-off between model complexity, data requirements and useful model output
492 appropriate for the aims of this study. The Pitman model was designed to be
493 applicable at the catchment scale and, in this study, was applied at the daily
494 time step to investigate flood characteristics. The Pitman model does not include
495 flow-routing for multiple reaches.

496 INCA is a hydrological and water quality model that incorporates a simple,
497 flow-routing model that divides the main channel into a user-defined number
498 of reaches (Whitehead *et al.* 1998; Wade *et al.* 2002). For this study, only the
499 hydrological components of the INCA model were used. To apply the INCA
500 model, it was necessary to determine the hydrologically effective rainfall (HER)
501 to calculate the water volume contribution from the catchment each day. The
502 HER is the rainfall that contributes to the river flow after evapotranspiration
503 losses and replenishment of the soil moisture deficit are accounted for. In this
504 study, HER was calculated using the Pitman rainfall-runoff model and a bucket-
505 type soil moisture deficit model to calculate the actual evaporation (figure 4).
506 Thus, together the Pitman and INCA models allowed the calculation of the
507 runoff response to rainfall for the upper River Jordan. INCA was not applied
508 at the Wadi Faynan.

511 (c) Model set-up and calibration for the upper River Jordan

513 The Pitman model was configured to simulate the surface and groundwater
514 flows and to calculate the HER at a daily time step using observed precipitation
515 and an estimate of the actual evapotranspiration (AET) by a bucket-type soil
516 moisture model based on the Penman equation. The mean annual HER was
517 estimated as 45 per cent of the mean annual precipitation input and thereby
518 in agreement with the estimate of Kunstmann *et al.* (2005). The estimated HER
519 was input to the INCA model, which was then used to route water along the
520 upper reaches of the River Jordan with a daily time resolution. The INCA water
521 balance is computed on a 1×1 km grid cell, and this is then multiplied by the
522 unit area in each subcatchment to calculate the volume of water transferred from
523 the unit to the main channel. Within each subcatchment, different landscape
524 units are specified according to soil, land use and geological types. The INCA
525 model has two reservoirs in each landscape unit: one represents the flow of water
526 through the unsaturated zone, incorporating the soil, and the other represents
527 the groundwater.

528 Initially, the entire Jordan River basin was subdivided into 19 reaches based on
529 gauging stations and points just downstream of major confluences with tributaries
530 and side wadi channels. The Dead Sea was included and, of the defined reaches,
531 this had the largest drainage area of 49 000 km². The following land cover types,
532 selected from the Global Land Cover Map 2000, were also initially included in the
533 INCA application: broadleaved tree cover (open), shrub cover, cultivated, bare
534 areas, inland water and urban. Shrub cover for the INCA application included
535 closed or open cover, deciduous, sparse herbaceous or sparse shrub cover and
536 regularly flooded shrub and/or herbaceous cover. In practice, it was not possible
537 to use 19 reaches nor to differentiate between land cover types because of a lack
538 of data to calculate the AET for each. Thus, Pitman was set-up for a compound
539 single land cover as was the INCA model.

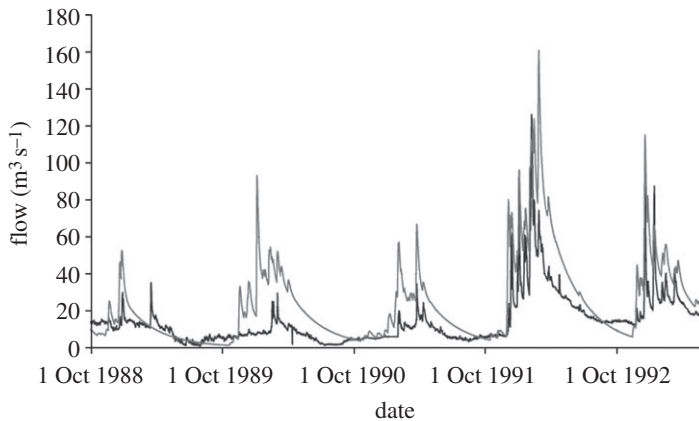


Figure 5. Modelled (grey line) and observed (black line) mean daily flows in the Jordan River at Obstacle Bridge from 1 October 1988 to 30 September 1993. Black line, observation; grey line, calibration.

During the study, it became apparent that only limited daily time-step discharge data could be obtained. Given that the purpose was to look at extremes in flow, this cannot be done with monthly flow data. Downstream of the Sea of Galilee at Naharayim, the observed flows were heavily modified by the upstream abstractions. Thus, the INCA model was applied to the upper four successive reaches (figure 1) from the headwaters to the discharge gauging station at Obstacle Bridge in Israel. The flows measured at Obstacle Bridge were not as heavily modified as at Naharayim so the hydrological response to climate could be better determined.

For the upper River Jordan, the INCA model was calibrated for the period 1 October 1988 to 30 September 1993 (figure 5). The purpose of the calibration was to set the values of the model parameters, and this period was chosen to provide the maximum overlap of available daily rainfall from Degania Bet and flow data from Obstacle Bridge. The unsaturated and the groundwater zone residence times, the instream routing parameters that control the reach residence times and the baseflow indices were adjusted until the modelled output flow matched, as closely as possible, the observed flow time series at Obstacle Bridge. There were insufficient data to perform a split-sample test and to assess the model performance for a second period.

The INCA model performance was assessed using the R^2 -value and the Nash–Sutcliffe criterion. The R^2 -value for the calibration period was 0.7, and the Nash–Sutcliffe criterion was negative. This result indicates that the pattern in the observed flows was simulated, but the actual values were not replicated. This was due to an inability to quantify the volume of abstractions in the upper Jordan owing to a lack of data. Despite this inability to quantify the abstractions, the study is still useful as it provides an indication of how water availability will change relative to the present and the control period.

Once INCA was calibrated, the control period rainfall data derived from HadRM3 and the weather generator were input to the Pitman model to provide a second estimate of the HER for the control period for comparison with the model

589 calibration. These HER data were input to INCA to derive a control period flow
590 series. This process was repeated but using the 2071–2100 scenario precipitation
591 data derived from the HadRM3 runs and the bias correction using the weather
592 generator to derive, through the Pitman model, the HER for the INCA 2071–2100
593 scenario run. Given the difference in the estimated HER between the calibration
594 and control period run, there was a difference in the flows simulated, but this
595 was acceptable: the control period maximum mean daily flow was $138 \text{ m}^3 \text{ s}^{-1}$
596 compared with $161 \text{ m}^3 \text{ s}^{-1}$ during calibration and the comparative Q10 (the flow
597 exceeded 10% of the time), Q50 and Q95 mean daily flows for the control
598 and calibration periods, respectively, were 76 and 110, 15 and 16, 3.3 and
599 $2.6 \text{ m}^3 \text{ s}^{-1}$.

601
602 (d) *Model set-up and calibration for the Wadi Faynan*

603 The Wadi Faynan conceptual model was realized as a numerical model through
604 calibration of the Pitman model (Wade *et al.* in press *b*). The purpose of the
605 model application was not to quantify flood flows exactly. This could not be
606 achieved in this case because of a lack of observed time-series flow data with
607 which to rigorously assess the model performance. Rather, the purpose was to
608 define a hydrological model as a best estimate of the hydrological functioning
609 and then run scenarios to explore how changes in rainfall amounts affect flood
610 characteristics and the baseflow.

611 The Pitman model was applied to the Faynan catchment, defined from a point
612 on the channel network adjacent to the ancient field system and immediately
613 downstream of the confluence between the Wadi Ghuwayr and the Wadi Dana
614 (figure 2). At this point, the upstream contributing area is 115 km^2 . This was done
615 as the lowest point at which the measurements of both the baseflow and peak
616 floods were made was the outflow of the Wadi Ghuwayr and the Wadi Dana, thus
617 allowing estimates of the baseflow and peak flow to be made at the confluence for
618 comparison with those modelled. It was extremely difficult to survey the channel
619 downstream of the confluence, here the alluvial plain has a width of approximately
620 1 km. Modelling the catchment flows to a point on the channel network adjacent
621 to the ancient field system also removes the complication of simulating the
622 transmission losses and water residence (or transit) times in the alluvial plain
623 of the Wadi Fidan and eliminates the need for a definitive understanding of the
624 source of the Fidan spring within this model-based assessment.

625 This application of the Pitman model to the Wadi Faynan required daily
626 estimates of rainfall and the potential evaporation. The use of the rainfall data
627 from Tafilah was appropriate for the model application. Tafilah is located on the
628 plateau 18 km north-northeast of Dana and receives rainfall similar to the upper
629 reaches of the Wadi Faynan. Moreover, a substantial daily record of rainfall was
630 available from 1 October 1937 to 30 April 1974, allowing the model to be run for
631 a relatively long period, which is important when making an assessment of flood
632 magnitude and frequency.

633 An estimate of the daily potential evaporation was derived from monthly
634 measurements of wind speed, sunshine hours, relative humidity and air
635 temperature available for a 2-year period from Ma'an using the Penman equation.
636 This 2-year estimated time series was repeated to form a daily time series of 36
637 years, the same length as the observed daily rainfall time series. This repetition of

638 the 2-year time series, although a clear over-simplification of the changes expected
639 during the 36-year period, was done to allow the model to be run on a daily time
640 step to allow progression with the model application.

641 It is practically impossible to separate the effects of transmission loss from
642 those of infiltration and deep percolation when estimating groundwater recharge.
643 As such, no attempt was made to distinguish transmission loss from infiltration
644 to the soils and the subsequent deep percolation of water to the underlying
645 aquifer within the simulations. Rather, the combined effects of transmission loss,
646 infiltration to the soil and subsequent deep percolation are considered together
647 as a single groundwater-recharge mechanism. To apply the model, estimates of
648 the groundwater volume and infiltration rate were made (Wade *et al. in press b*).

649 The simulated flows output from the PITMAN model generally falls within
650 the baseflow and peak flow constraints identified by field observations for model
651 calibration (not shown). The baseflow in catchment was observed to be in the
652 range $0.02\text{--}0.09\text{ m}^3\text{ s}^{-1}$, and the model replicated this. The simulated annual flood
653 ranged from 2 to $98\text{ m}^3\text{ s}^{-1}$, and for return periods of 1–2 years, the range of the
654 simulated floods was $2\text{--}17\text{ m}^3\text{ s}^{-1}$, which was within broad agreement with the
655 annual floods estimated by the survey ($14\text{--}22\text{ m}^3\text{ s}^{-1}$). The simulated extreme
656 floods with return periods of 12–37 years are lower than the estimated flow range
657 when the channel is flowing full ($120\text{--}180\text{ m}^3\text{ s}^{-1}$). For only 15 per cent of the
658 calibration time-period considered did the simulated flows increase in response
659 to precipitation events, and this hydrological behaviour is typical of semi-arid
660 catchments (Bull & Kirby 2002).

661 662 663 664 4. Results

665 666 (a) *Impact of anthropogenic climate change on the regional rainfall*

667 A reduction in the mean annual rainfall is projected under the A2 scenario for
668 the 2071–2100 period for the Middle East (Black 2009). In the upper Jordan,
669 the largest monthly reductions (around 30% in the River Jordan region) are
670 during December and January (figure 6). The rainy season is predicted to become
671 longer, which partially offsets the marked decrease in precipitation projected at
672 the peak of the rainy season. At the margins of the rainy season, small increases
673 in monthly rainfall are projected by the climate model. The reasons for this are
674 not fully understood, but may be related to changes in the occurrence of Red Sea
675 troughs, which are the dominant observed cause of rain in these seasons (Black
676 2009). The reduction in winter rainfall can be related to changes in the large-scale
677 circulation and is predicted by most climate models (for example, Kitoh *et al.*
678 Q11 2008; Evans 2009; Hemming *et al.* this volume; Jin *et al.* this volume), the same
679 cannot be said for the spring precipitation, which leads to large uncertainties in
680 the prediction of rain in this season (Black *et al. in press*). Sensitivity studies
681 of the hydrological response to rainfall imply that the changes in spring rainfall
682 have relatively little impact, and hence the uncertainties in our predictions of
683 spring rainfall do not prejudice the reliability of the predictions of flow (Wade
684 *et al. in press a*). At the peak of the rainy season, the number of rainy days
685 is projected to decrease, reflecting reductions in both the PRR and the PDR,
686 of approx. 25 per cent (PRR reduced from approx. 0.6 to 0.4–0.5 and PDR

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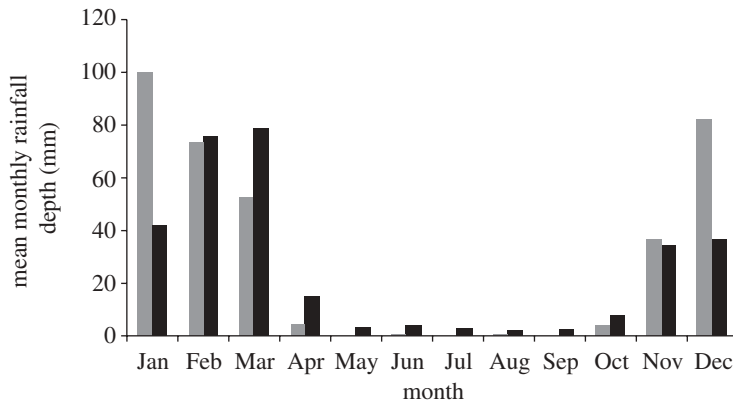


Figure 6. Projected changes in the monthly rainfall totals at Degania Bet, Israel from the HadRM3 and weather generator models for 2070–2100 under the SRES A2 scenario. Grey bars, control; black bars, 2070 A2.

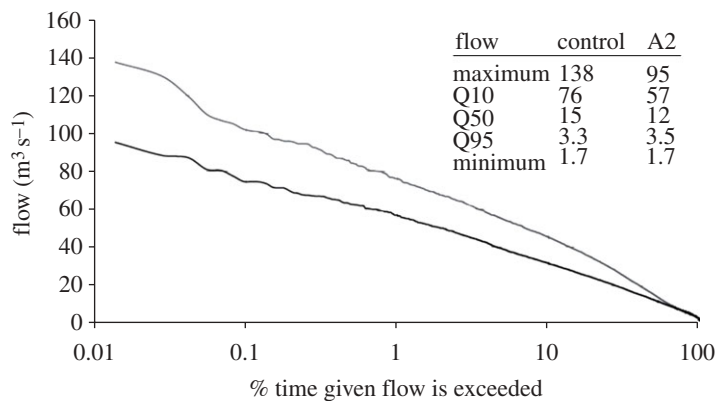


Figure 7. Modelled mean daily flows in the Jordan River at Obstacle Bridge for control (1961–1990) and scenario (2071–2100) periods. Grey solid line, control; black solid line, A2 2070s.

reduced from approximately 0.2 to 0.15). The overall picture is, therefore, of a longer rainy season with a less pronounced peak, with the mean annual rainfall decreasing in the headwaters of the River Jordan and the Wadi Faynan. The reduction in rainfall is accompanied by an increase in temperature by 2°C and hence evaporation increases.

(b) Impact of anthropogenic climate change on flow in the upper River Jordan

In comparison to the control period, the modelled outcome for the 2071–2100 A2 scenario is that the low (base) flows will remain similar to those occurring at present; there is little difference in the forecast median (Q50) flows, and the Q50 in the control and scenario periods are 15 and 12 m³ s⁻¹, respectively (figure 7).

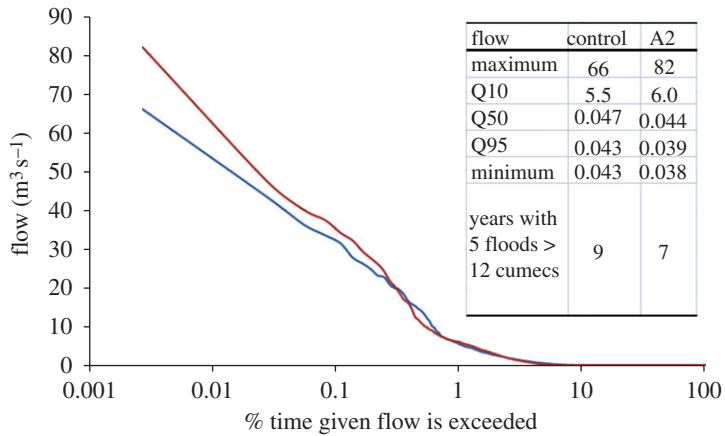


Figure 8. Modelled mean daily flows in the Jordan River in the Wadi Faynan for control (1961–1990) and scenario (2071–2100) periods. Blue solid line, control; red solid line, A2 2070s.

This lack of response is a result of the long residence time in the groundwater component of the INCA model, which suggests that groundwater acts to buffer changes in the rainfall amounts to maintain the low and intermediate flows. The flood response is different. There is a drop in the Q10 flow (exceeded 10% of the time) from 76 to 57 $\text{m}^3 \text{s}^{-1}$ between the control and scenario periods as a result of the reduced winter rainfall, and this indicates that flood magnitudes will be reduced. Increases in the flow extremes, in terms of flood magnitude and occurrence, are not evident, which is consistent with Black (2009), who found no significant changes in rainfall intensity in these projections for this region.

(c) Impact of anthropogenic climate change on flow in the Wadi Faynan

For the Wadi Faynan, the baseflows in the period 2071–2100 under the A2 scenario are predicted to decrease by 12 per cent (figure 8). The number of years with five floods greater than 12 $\text{m}^3 \text{s}^{-1}$ will decrease from 9 to 7 in the 30-year period, and the median flow will decrease by 6 per cent. The flow threshold of five floods greater than 12 $\text{m}^3 \text{s}^{-1}$ is derived from the measurement of flows in the annual flow channel and the number of flows from Bedouin anecdotal evidence of years with good harvests (Lancaster & Lancaster 1999; Wade *et al.* in press *b*). As a result of the projected reduced rainfall and increased near-surface temperature, the baseflow decreases as recharge declines, though because recharge is already low then the impact on the baseflow is small. Interestingly, although the mean annual rainfall decreases, the flow exceeded 10 per cent of the time (Q10), which is representative of the flood extremes, increases, and the maximum flood flow also increases; peak flows will be approximately 1.25 (82/66) times what they are at present. This increase in flood extremes results from subtle changes in the distribution of rainfall intensities in the A2 scenario projections and should therefore be regarded with caution, particularly bearing in mind model bias. This caveat should also be applied to the projected flows in the upper River Jordan.

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5. Discussion

The RCM projections suggest that in a world that does not work to find an integrated way to reduce greenhouse gas emissions, then a temperature increase of 2°C and a decrease in rainfall by 25 per cent are projected in the eastern Mediterranean by the end of this century. In addition to a reduction in the mean annual rainfall, the seasonality of the rainfall will change also as the start and end of wet season are projected to become wetter, but there will be less rainfall in December and January.

In the upper River Jordan, the change in the low flows will depend on the volume of water stored in the Karst system of the northern Jordan valley and the recharge rate, both of which are poorly characterized. The modelled outcomes from the conceptual Hydrological Model for the Karst Environment (HYMKE), described in Rimmer & Salinger (2006), corroborate the results from this study that the low flows will not change. It is unclear over what simulated time period the HYMKE model was run for the modelled scenarios. The INCA model was run for 30 years with a daily time step, so this may be sufficient to examine long-term trends but the relationship between groundwater recharge through percolation and soil moisture has not been modelled in detail. Thus, it is proposed that it will be necessary to run transient scenarios from present day to 2100 to see how the groundwater will change over the long term using both the HYMKE and INCA models and that further consideration be given to the likely groundwater-recharge mechanisms to determine whether the current groundwater components of both models are a good representation of water storage and flow in the Karst.

In a study of the upper Jordan catchment that used a distributed hydrological model informed by RCM input, Suppan *et al.* (2008) predicted that under a scenario in which the present rates of greenhouse gas emission increase slowly, the total runoff will decrease by 23 per cent by the end of the twenty-first century—a conclusion consistent with the linear relationship between annual precipitation and streamflow proposed in Samuels *et al.* (2009). However, in contrast to Samuels *et al.* (2009), which suggested little change in the baseflow, Suppan *et al.* (2008) suggested that groundwater recharge would decrease, resulting in a reduction in the baseflow. Samuels *et al.* (2009) showed that increasing the frequency of rainy spells lasting 3 days or more, without changing the annual total precipitation, increased the impact of high intensity rainfall events on the River Jordan, resulting in more frequent and intense floods. The results for the hydrological projections for the Wadi Faynan corroborate this result, but the projected flows in the upper Jordan suggest that flood magnitude will not increase. This reflects the fact that, in the simulations, rainfall intensity seen in the River Jordan region in the future is very similar to that observed today, whereas in the Wadi Faynan, there is a small increase in the extreme rainy events. However, these results should be regarded with caution because the climate model represents rainfall intensity poorly. Moreover, further work is required to confirm the results of this and other studies and to verify the representation of the rainfall extremes used in the weather generator.

The reduction in the mean annual rainfall and the increase in near-surface air temperatures suggest that irrigation requirements will increase, worsening the water shortage in the region. This suggestion is supported by preliminary applications of the CROPWAT model in the Water, Life and Civilisation study

834 and by applications of a soil-vegetation-atmosphere transfer (SVAT) model
835 TRAIN, which indicate increases in evapotranspiration and water demand
836 (Menzel *et al.* in press). The preliminary predictions of the CROPWAT model
837 suggest that at Ramtha in northwest Jordan, the irrigation demand will increase
838 from 62 to 132 mm of water when growing vegetables under the A2 scenario
839 for 2071–2100 using HadRM3 and an assumed irrigation efficiency of 70 per
840 cent. The TRAIN model provides an overview of the Jordan Valley region, and
841 the modelled outcomes suggest a 6 per cent increase in the water demand for
842 agriculture over the entire region and up to a 50 per cent decrease in water
843 availability in northwest Jordan, Israel and the West Bank (HadCM3, A1B
844 scenario, 2021–2050 compared with 1961–1990 control period). Menzel *et al.*
845 (in press) note that this region includes the Negev, where water scarcity is a factor
846 that will in effect lessen the future projection of water demand. These preliminary
847 results highlight the local and regional differences that might be expected in
848 irrigation demand and do not account for the possibility the crop stomata may
849 close in response to increased near-surface air temperatures, resulting in little
850 difference in crop evapotranspiration, but lower yields owing to the increased crop
851 stress of an increased canopy temperature (Kimball & Bernacchi 2006). Higher
852 atmospheric CO₂ may also reduce stomata activity. An overall increase in local
853 and regional irrigation demand has serious implications for Jordan since further
854 stress, including increased salinity, will be put on the groundwater resource. Israel
855 has already invested heavily in the desalination of groundwater. Jordan may have
856 to do likewise.

857 The modelling framework proposed has the same uncertainties as outlined
858 by Wilby & Harris (2006). These uncertainties in model application are the
859 choice of the SRES scenario; the subsequent regional climate projections; the
860 probabilities and rainfall intensity distribution chosen for the weather generator;
861 the structure and calibration of the hydrological models and the sampling errors
862 of the observed data used to define the structure and parameters of the model
863 ensemble. In particular, there are limited daily flow data with which to calibrate
864 and test the hydrological models, not only in the upper Jordan but also in the
865 side wadis and other tributaries that comprise the Jordan drainage network.
866 As such, this and other model chains cannot provide absolute changes in the
867 rainfall–runoff response, but rather give an indication of the possible changes in
868 the distribution of flows. Further complications in the case of the Jordan River
869 include an inability to quantify exactly the volume of water abstracted from
870 different reaches owing to the numerous and diffuse nature of the abstractions;
871 further regulation or quantification of these abstractions may help manage the
872 resource. Until such quantification is done, it will be difficult to separate the
873 effect of abstractions from that of climate. Further investigation is also required
874 to determine whether the use of a weather generator approach introduces bias
875 itself, as suggested here where more rain was predicted at the margins of the
876 rainy season than observed. In addition, further work is needed to determine how
877 important this bias is in terms of other uncertainties such as structure of the
878 climate model and the choice of emission scenario. A potentially fruitful method
879 for progress in the development of coupled climate-hydrological assessments would
880 be the determination of what aspects of the climate or weather are most critical to
881 the hydrological assessment. The climate and weather projections from a GCM,
882 RCM, weather generator or a combination of these could then be tested, in terms

883 of these aspects, against observation to assess reliability. In addition, further work
884 is required to assess the capability of climate models to simulate the frequency and
885 duration of rainfall events, as well as the magnitude. This capability assessment is
886 required to determine how well antecedent moisture conditions and groundwater
887 recharge can be estimated and whether the increases in the simulated rainfall
888 extremes are valid.

889 Although coupling uncertainties together means that the quantification of the
890 runoff response is likely to be inaccurate, the modelling framework can be used to
891 explore the hydrological system and to assess the impact of different scenarios and
892 management decisions. At present, this study is limited in that only rainfall and
893 runoff are considered. Further work is required to understand the implications
894 of the projected temperature and precipitation changes on other aspects of the
895 water resource, such as groundwater recharge and soil moisture availability. This
896 task has been started by Menzel *et al.* (in press), using another methodology, but
897 further work is required to substantiate initial projections of change.

898 It is recommended that an ensemble approach to climate and hydrological
899 modelling be taken to account for structural uncertainty. In particular, it is useful
900 that a number of studies do the same thing so that results can be compared (e.g.
901 Samuels *et al.* 2009). In addition, it is recommended that a study of the effects of
902 parameter uncertainty in the INCA and Pitman models on the modelled flows be
903 done using an ensemble of generated weather time series. Further applications of
904 the framework proposed here and other coupled climate-hydrological approaches
905 will allow a more extensive review of potential outcomes to population and climate
906 change to be achieved. With such an ensemble approach, care must be taken to use
907 the same SRES emission scenarios, time periods and spatial scale of comparison.
908 This will require discussion and cooperation between hydrological modellers
909 of the nature already achieved in the ENSEMBLES climate-modelling project
910 (<http://www.ensembles7eu.org>). Although such an ensemble approach will be
911 useful to quantify uncertainties, this approach should be balanced with a diversity
912 of climate and hydrological modelling approaches that cover a range of emission
913 scenarios and spatial scales. A diversity of approaches will help understand a
914 range of possible futures and may explain discrepancies in the projected flows
915 between the upper River Jordan and the Wadi Faynan.

916 917 918 6. Conclusions

919 This study is one of the first to combine an RCM, a weather generator and
920 hydrological models to project the likely rainfall–runoff response of the upper
921 River Jordan and side Wadis in Jordan, framing the results within other
922 contemporary research. A substantial dataset has been collated to develop and
923 test the modelling framework, and in a data-poor region, this represents a
924 substantial undertaking. The modelled results provide a contribution to the
925 debate about how the runoff response will change in the upper Jordan River
926 and the side wadis of western Jordan.

927 Owing to the uncertainties associated with the chosen greenhouse gas emissions
928 scenario, the RCM, the weather generator and the hydrological models, the results
929 can only be assumed to be indicative at this stage. Nevertheless, the modelled
930 outcomes suggest that although the mean annual flow of the River Jordan will
931

932 reduce, the baseflow of the upper Jordan will not change significantly in response
 933 to climate change, although flood extremes may increase—a result corroborated
 934 by other comparable studies.

935 The results of this study suggest that the impact of precipitation decreases on
 936 flow may be, to a degree, mitigated by the contribution of groundwater. However,
 937 the combined effects of expected population increase and the changes in the
 938 projected climate are yet to be modelled. Although the groundwater levels appear
 939 to be maintained in response to climate change alone, it is likely that they will
 940 decrease if the population increases. Water security in Jordan, and Israel and the
 941 West Bank, will probably depend on how exploitable the groundwater reserves
 942 prove to be.

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 949 System derivation of the subcatchment boundaries and land cover.

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