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The Impact of Climate Change on Storage-Yield Curves for Multi-Reservoir Systems

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In this paper, we report on the results of an investigation into the impacts of climate change on the storage-yield relationships for two multiple-reservoir systems, one in England and the other in Iran. The impact study uses established protocol and obtains perturbed monthly inflow series using a simple runoff coefficient approach which accounts for non-evaporative losses in the catchment, and a number of recently published GCM-based scenarios. The multi-reservoir analysis is based on the sequent-peak algorithm which has been modified to analyse multiple reservoirs and to accommodate explicitly performance norms and reservoir surface fluxes, *i.e.* evaporation and rainfall. As a consequence, it was also possible to assess the effect of including reservoir surface fluxes on the storage-yield functions. The results showed that, under baseline conditions, consideration of net evaporation will require lower storages for the English system and higher storages for the Iranian system. However, with perturbed hydroclimatology different impacts were obtained depending on the systems' yield and reliability. Possible explanations are offered for the observed behaviours.

Introduction

A recent report by the Intergovernmental Panel on Climate Change (IPCC 1996) has produced the most compelling evidence yet that global warming is taking place as a result of increased atmospheric concentrations of "greenhouse" gases due to industrial and other anthropogenic activities. The greenhouse effect occurs as a result of outgoing long-wave radiation emitted by the Earth being unable to escape the earth's atmosphere due to the presence of the greenhouse gases, notably carbon dioxide (CO_2), methane and water vapour.

A warmer climate is sure to put phenomenal pressures on water resources in many parts of the world and so the need then arises for climate change impacts assessment to ascertain the extent of the problem and plan mitigating measures. A considerable number of studies have addressed this problem (see Arnell 1996 for a review), frequently using climate change scenarios developed from simulation experiments of General Circulation Models (GCMs). Another common feature of the previous studies is that only single reservoir systems have been considered. There have been very little in the way of multiple reservoirs or of how considerations of reservoir surface fluxes, such as evaporation and direct rainfall which are also liable to climate change impacts, can affect the storage-yield relationship. These fluxes may be important in arid and semi-arid regions since any accentuation of the net evaporation (due to climate change) can cause a significant reduction in the useable yield of water resources systems.

The main objective of this study is to investigate the likely impacts of climate change on the storage-yield relationships of multiple reservoir systems. Complete storage-yield-reliability curves will be constructed for aggregate multi-reservoir systems, both for baseline and perturbed hydroclimate, and used to assess the impacts. A secondary objective examines how the incorporation of surface fluxes, *i.e.* rainfall onto and evaporation from the reservoir surface, in the analysis will affect the climate change impacts. Both these objectives will use two case studies, one from each of two different climatic regions.

Methodology

Storage-Yield-Reliability Analysis

Given the objectives of the study, the storage-yield-reliability technique adopted must be capable of analysing multiple reservoir systems and including, explicitly, reservoir surface-area-dependent fluxes such as the net evaporation. The modified sequent peak algorithm, SPA (Lele 1987; Adeloye and Montaseri 1998) is capable of these. Preference for the modified SPA stems from the fact that, unlike the behaviour approach (Adeloye and Nawaz 1998; McMahon and Mein 1986), the determination of storage-yield for a desired reliability is no longer a trial and error procedure. Being able to impose a limit on supply shortfall during failure periods with the modified SPA also means that system's vulnerability or volumetric failure risk (Hashimoto *et al.* 1982) can be selected *a priori*. Furthermore, because the SPA by default uses two cycles of the historical record, the usual problems associated with the choice of the starting state of the reservoir is no longer an issue. The initial state of the reservoir has a significant impact on the outcome of a behaviour analysis. The SPA is essentially a single reservoir technique; however, an extension of the technique to multiple reservoirs analysis, using the Space Rule operating policy (Bower *et al.* 1962) is described in Adeloye and Montaseri (1998) and was used for the study.

Climate Change Impact Study

The climate change impact was conducted in accordance with the protocol outlined in Carter *et al.*(1994). The perturbation of the baseline hydrology was achieved using a runoff coefficient technique (Wigley and Jones 1985; Glantz and Wigley 1987). Arnell (1996) and Xu and Singh (1998) review a number of rainfall-runoff models of varying degrees of sophistication which could be used to simulate runoff from rainfall and other climatic variables; however, because sufficient data may not always be available for calibrating such sophisticated models, it is important that simplicity and flexibility is ensured in the choice of the scheme for translating rainfall into runoff.

Starting from the annual water balance equation (and ignoring any non-evaporative losses such as infiltration-percolation for the moment), we have

$$R_b = P_b - E'_b \tag{1}$$

$$R_f = P_f - E'_f \tag{2}$$

where the subscripts b and f denote baseline and future conditions respectively, R is annual runoff (mm), P is the annual precipitation (mm) and E' is the annual actual evapotranspiration, AE, (mm). Now let $P_f = \alpha P_b$ and $E'_f = \beta E'_b$, where α and β are factor changes in the annual precipitation and AE, respectively, as a result of climate change, then from Eqs. (1) and (2),

$$\frac{R_f}{R_b} = \frac{P_f - E'_f}{R_b} = \frac{\alpha P_b - \beta E'_b}{R_b} = \frac{\alpha P_b - \beta(P_b - R_b)}{R_b} = \frac{\alpha - (1 - R_b/P_b)\beta}{R_b/P_b} \tag{3}$$

Replacing R_b/P_b in Eq. (3) by γ_b, the baseline runoff coefficient, the sensitivity of annual runoff becomes

$$\frac{R_f}{R_b} = \frac{\alpha - (1 - \gamma_b)\beta}{\gamma_b} \tag{4}$$

Eq. (4) is a simple way to assess the relative sensitivity of annual runoff to changes in annual precipitation and AE. However, while it is not unreasonable to ignore the non-evaporative losses in the annual model, such losses must be accounted for in monthly models. Glantz and Wigley (1987) extended the above approach to incorporate non-evaporative losses to obtain

$$\frac{\Delta R}{R_b} = \frac{1}{\gamma_b}\frac{\Delta P}{P_b} - \frac{\Delta E'}{E'_b}\left\{\frac{1 - \xi_b}{\gamma_b} - 1\right\} - \frac{\xi_b}{\gamma_b}\frac{\Delta L}{L_b} \tag{5}$$

where Δx refers to the difference between future and baseline values of variable x; L is the sum total of all other losses (*e.g.* infiltration, seepage and deep percolation) and $\xi \equiv L/P$. (Note that E' in Eq. (5) now refers to the monthly *AE*). Eq. (5) can be rewritten in the form of Eq. (4) as

$$\frac{R_f}{R_b} \equiv \frac{1}{\gamma_b}\left\{(\alpha-1)-\left((\beta-1)(1-\xi_b-\gamma_b)\right)-\left(\xi_b(\theta-1)\right)\right\}+1 \qquad (6)$$

where $\theta = L_f/L_b$. ξ_b can also be written as

$$\xi_b = 1-\gamma_b-\frac{E'_b}{P_b} \qquad (7)$$

If a further assumption is made that the non-evaporative losses remain unchanged with time, then L_f/L_b becomes unity and hence the monthly changes in runoff become

$$\frac{R_{f_i}}{R_{b_i}} \equiv \frac{1}{\gamma_{b_i}}\left\{(\alpha_i-1)-\left((\beta_i-1)(1-\xi_{b_i}-\gamma_{b_i})\right)\right\}+1, \qquad i=1,2,\ldots,12 \qquad (8)$$

To apply Eq. (8) will require γ_{b_i}, α_i, β_i and ξ_{b_i}. Both α_i and β_i are provided by the climate change scenarios for rainfall and evapotranspiration, respectively for each month i. γ_{b_i}, the baseline runoff coefficient for month i, was obtained by dividing the corresponding mean monthly runoff by the corresponding rainfall for that month. ξ_{b_i} was evaluated according to Eq. (7) using estimates of the mean *AE* and the mean rainfall for month i. The method used to calculate the *AE* is described in the next section.

Eq. (8), unlike most other rainfall-runoff schemes used in climate change impact studies to produce perturbed inflow series, is simple and does not require any formal calibration. As noted by Beven (1989), there are large uncertainties associated with calibrating the parameters of catchment models primarily due to lack of model identifiability; such uncertainties tend to magnify as the model becomes complex and the number of parameters grows (Dooge 1977). On the contrary, Eq. (8) does not have any parameters and is directly applicable to any catchment in any region, which is an important consideration given the desire to investigate data from two different climatic regions.

The assumption underpinning Eq. (8), *i.e.* that θ is unity, is necessary to avoid the problem associated with quantifying L_f which is not an output of GCMs and hence for which scenarios are not available. Admittedly, the dominant component in L, *i.e.* infiltration, will be greatly affected by land use changes. However, until climate has actually changed and L is measured under the new climate, there will be no other way of knowing by how much L has been affected. It can therefore be taken that the current assumption about θ remains a reasonable one.

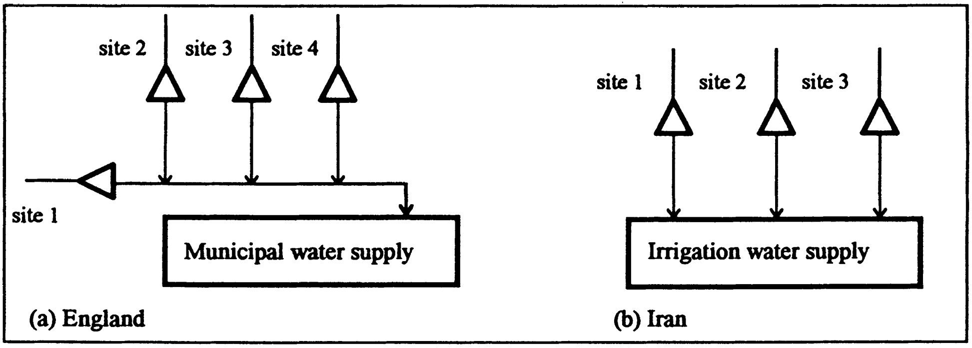


Fig. 1. Simplified schematics of the multiple-reservoir systems.

Application

Catchments and Data

Two multiple reservoir systems formed the basis of this investigation. The first system, from north-east England and simplified into the schematic in Fig. 1(a), is an existing complex multi-reservoir system which provides for domestic, industrial and compensation releases. Its operation is aimed at satisfying the full demand, although during extreme droughts, reductions in releases can be made. The second system, typifying a semi-arid climate, is in Iran and comprises three reservoirs in parallel to be used for providing irrigation water (Fig. 1b). Operation of the reservoirs will be aimed at satisfying the demand at all times if possible and at least 75% of the demand during droughts. Relevant characteristics of the two systems are shown in Table 1. Although as shown in Table 1, data are available over different periods, the baseline analyses were for the standard period 1961-1990, the same standard period for the GCMs' predictions (Arnell *et al.* 1997).

Table 1 – Characteristics of the catchments analysed.

System Location	Site	Name	Area (Km^2)	Ann. flow (x $10^6 m^3$)	Annual flow CV	Availability of records Rainfall	*PE*	Flow
England	1	Gorpley	2.8	2.6	0.22			
	2	Hebden	26.4	25.1	0.20	1961-	1918-	1936-
	3	Luddenden	5.4	5.1	0.18	1990	1995	1995
	4	Ogden	5.4	4.3	0.22			
Iran	1	Baranduz	618	272	0.34	1950-	1950-	1950-
	2	Nazlu	1715	390	0.41	1993	1993	1993
	3	Shahr	418	170	0.38			

Mean monthly rainfall and open-water evaporation, as estimated from the available time series data, were used to obtain reservoir surface net water flux. Fennessey (1995) found this approach to give almost the same results as using time series data of rainfall and evaporation. Open water evaporation data, derived from Class A Pan evaporation measurements, were available for the Iranian catchments. For the English system, open-water evaporation data were obtained by scaling from the available MORECS (Meteorological Office 1981) potential evapotranspiration, *PE*, estimates, using $E_p = kE_o$ where E_o is the open-water surface evaporation (mm); E_p is the *PE* (mm) and k has the value of 0.6 for November-February; 0.7 for March, April, September and October and 0.8 for the remaining months, based on European conditions (Shaw 1994). The area-storage relationship for converting evaporation (m) to (10^6 m^3) for use in the SPA was approximated by $A = 0.0815S + 0.0056$ for the English reservoirs and by $A = 0.0317S + 1.688$ for the Iranian reservoirs, where A is the surface area (km^2) and S is the storage (10^6 m^3). The former expression was found by fitting a linear regression equation to area-capacity data for fifty reservoirs in England and Wales ($R^2 = 0.8817$) while the Iranian expression was based on area-storage data for three Iranian reservoirs ($R^2 = 0.9947$). Each of the Iranian reservoirs had ten measurements of area and corresponding storage, giving a total of thirty data points for deriving the average area-storage relationship.

Mean monthly *AE* data are required for computing ξ_{b_i} in Eq. (7). For the English catchments, long time series data records of *AE* with which to estimate the monthly means with sufficient accuracy were not available for the reservoir catchments. However, there was a much shorter (1993-1996) monthly data record of MORECS-based *AE* and *PE* for a 40 km by 40 km square grid which encompasses all the studied reservoir groups. This latter record was used to derive the *AE* data for the period 1918-1995, corresponding to the period of the available *PE* data record (see Table 2), as follows. First, using the four year grid data, the ratio of the mean *AE* to the mean *PE* for each month of the year was obtained. These ratios were then used to scale the available *PE* time series data to obtain the time series data of *AE*, whence derive the monthly mean estimates. This approach assumes that the ratio of *AE* to PE at the catchments is equal to that for the grid, which is reasonable given that all the catchments are located within the MORECS grid. Despite this, however, it was decided still not to use the grid's monthly mean actual evapotranspiration directly in

Table 2 – Rainfall ratio ($\alpha_i = P_{fi}/P_{bi}$).

Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
HADCM1(2050)	1.18	1.10	1.15	0.95	0.92	1.07	1.14	0.94	1.02	1.18	1.30	1.03
HADCM1(2020)	1.09	1.05	1.09	0.97	0.96	1.05	1.08	0.98	1.03	1.11	1.16	1.02
GG1m	1.02	1.08	1.04	1.06	1.08	0.99	0.97	1.05	1.06	1.11	1.11	1.06
GS1m	1.04	1.02	1.03	1.05	1.05	1.01	0.98	1.01	0.99	1.06	1.03	1.02
GS1t	1.04	1.04	1.05	1.13	1.16	0.85	0.91	0.95	1.05	1.22	0.99	1.00

Eq. (7) because of the potentially large sampling variability of such small sample (*i.e.* four years) estimates. On the contrary, the sampling variability of the monthly means derived with the 1918-1995 record will be much lower, implying that such estimates will be more reliable and hence more representative of the true mean *AE*.

In the absence of needed data, the same monthly ratios derived for the English catchments were used in scaling the evaporation data at the Iranian sites to obtain their *AE*.

Scenarios

Arnell *et al.* (1997) summarise changes in climate by the 2020's for six regions in the UK as obtained from two UK Hadley Centre's GCMs: HADCM1 and HADCM2. HADCM1 and HADCM2 output is in the form of monthly percentage change (relative to the 1961-1990 baseline period) in rainfall, temperature, radiation, humidity and wind speed for 80,000 km^2 grid squares. Changes in climate by the 2050's produced by HADCM1 for eight regions in the UK are also summarised by Arnell (1996), which also contains further details about the GCMs' experiments and the development of the climate scenarios. The basic 2050's UK-wide scenarios upon which Arnell's more detailed work are based were developed by the UK Climate Change Impacts Review Group (CCIRG 1996).

The rainfall and *PE* scenarios are presented in Table 2 and Table 3, respectively. The *PE* scenarios were obtained by Arnell *et al.* (1997) using both the Penman and Penman-Monteith formulae. Five scenarios from both HADCM1 and HADCM2 GCMs as reported in Arnell *et al.* (1997) for north-east of England and Arnell (1996) for the north of England, where the English system is located. HADCM1-2020 and HADCM1-2050 are from HADCM1 which assumes a gradual compound increase of 1% in CO_2 concentrations each year from 1990 to the end of the next century (Arnell *et al.* 1997). GG1m, GS1m and GS1t, are produced by HADCM2 which is an updated version of HADCM1 (Arnell 1996). Natural climate variability and change need to be separated because the modelling process only accounts for the latter; hence GG1m and GS1m scenarios have both involved "re-scaling" for a *medium* climate sensitivity thus the term "m" (Arnell *et al.* 1997). This problem was avoided in the GS1t scenario by using results from repeated runs of the model with each run made from a slightly different starting condition. Additional differences are that

Table 3 - *PE* ratio ($\beta_i = E_{fi}/E_{bi}$).

Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
HADCM1(2050)	1.00	1.40	1.15	1.25	1.00	1.27	1.00	1.07	1.23	1.10	1.50	0.78
HADCM1(2020)	0.95	1.11	1.02	1.08	0.99	1.04	0.99	1.02	1.03	1.00	1.21	0.80
GG1m	0.86	0.91	0.96	0.99	1.01	1.00	1.03	1.01	1.02	0.99	0.83	0.75
GS1m	0.88	0.93	0.98	0.99	1.00	0.99	1.02	1.03	1.04	1.00	0.95	0.90
GS1t	0.95	0.94	0.99	0.94	0.93	1.05	1.06	1.15	1.12	1.06	0.99	0.95

GG1m is based on greenhouse gases only; GS1m includes the effects of sulphate aerosols as well as greenhouse gases; GS1t is similar to GS1m except that it has a different spatial pattern of change (Arnell *et al.* 1997).

Climate scenarios were not immediately available for the Iranian catchments. However, because the GS1t scenario gave the highest reduction in summer rainfall and the highest rise in summer evapotranspiration (see Tables 2 and 3), it was employed as a spatial analogue for the Iranian catchments.

Results and Discussion

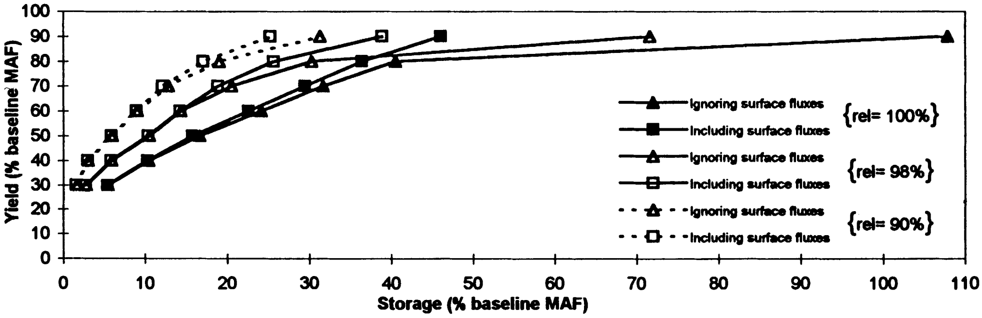
The storage-yield-reliability curve provides the most complete information about a reservoir system. During planning, it is used to determine the storage required for given yield and reliability. For an existing system with known storage capacity, the curve can be used to determine the sustainable yield. Furthermore when, as is usual, the axes are scaled by the mean annual runoff, the curve provides a means for "regionalising" the storage-yield function and hence for estimating storage or yield at ungauged sites. As a consequence, the results herein will be presented within the framework of the storage-yield curves. Other issues such as resiliency and vulnerability are not explicitly considered in the study although, inferences will be made about how these two performance metrics are likely to be affected. It should be noted, however, that the modified SPA can analyse for pre-specified vulnerability and resiliency (Montaseri and Adeloye 1998). For reasons of lack of space, results will only be presented for the aggregated system rather than for each individual reservoir in a multi-reservoir system.

Effect of Surface Fluxes on Baseline Storage-Yield Relationships

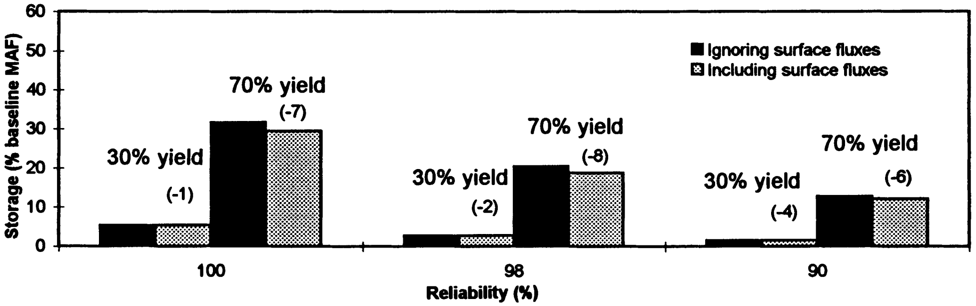
Fig. 2 shows the impact of incorporating reservoir surface water fluxes due to net evaporation on the storage-yield function for the baseline records. For the English system (see Figs. 2a and b), the inclusion of reservoir surface net evaporation flux resulted in reductions in the required storage capacity for a given yield. These reductions averaged about 7% for the 70% yield but lower (2%) for the 30% yield. This is to say that if the capacity were fixed, then more water could be supplied from the fixed storage if net evaporation was considered in the analysis than if it was not. This behaviour can be attributed to the fact that, for the English catchments, rainfall generally exceeds the evaporation and so the effect of including the net evaporation flux is an additional inflow into the reservoir.

On the other hand, for the Iranian catchments where evaporation exceeds rainfall, the inclusion of net evaporation flux means that there is a net outflow flux from any reservoir surface. Such a net outflow constitutes an additional demand on top of the design yield, thus requiring increased storage to meet such a design yield (Figs. 2c) and d). Failure to provide such an additional storage will mean that either a reduc-

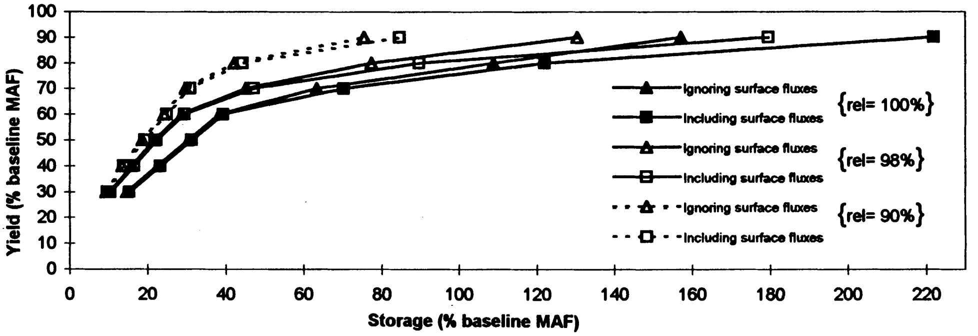
(a) English System



(b) English System



(c) Iranian System



(d) Iranian System

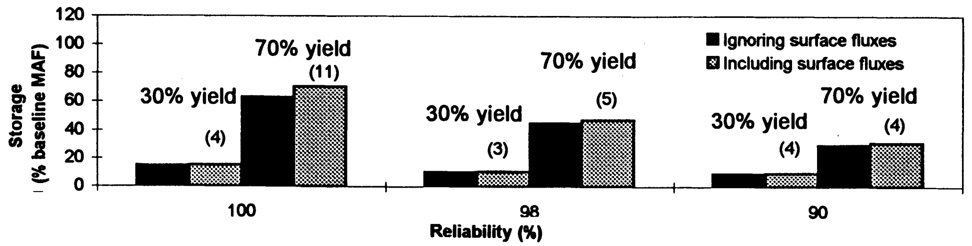


Fig. 2. Impact of reservoir surface evaporation and rainfall fluxes on storage-yield-reliability relationship (baseline records). Values in parenthesis in (b) and (d) are % difference in storage due to incorporation of surface fluxes.

tion in the deliverable yield from the reservoir has to occur or a reduction in the reliability of supply has to be contented with if supplying at the design yield were to occur. Similarly, any insistence on supplying the design yield in such a situation will inevitably increase the size of the shortfall during failure (*i.e.* vulnerability) and compromise the ability of the system to recover following failure (*i.e.* resilience). The fact that both the reductions in required storage (England) and increases in required storage (Iran) magnify with increasing yield is due to the increasing exposed surface area of the reservoirs with yield; hence the loss/gain of water through the surface will magnify as the yield changes. The changes in storage also increase as the system reliability increases for the same reason.

Table 5 contains the impact on the yield for a fixed capacity of 30% of mean annual runoff and 100% reliability for the baseline records. The incorporation of net evaporation flux for the English system increases the deliverable yield from 68.91 to 71.86 Ml/d for the baseline record, an increase of 4%, whereas for the Iranian system, there was a 2% reduction in deliverable yield from 1126 to 1103 Ml/d.

The above results have practical implications for reservoir water management in humid climates such as the English catchments where for most part surface flux is often ignored on the excuse that it is unimportant. However, as demonstrated in this study, while it is unimportant from the point of view that it may not lead to water shortage, it does have some practical significance because facilities planned ignoring such fluxes currently represent an over-design, and the buffer of such over-design would go some way in meeting any shortfall in future storage requirements. As a result such reservoirs may be able to accommodate the likely requirement placed by future climate change for example.

Climate Change Impacts on Runoff

The resulting (monthly) runoff ratios, R_f/R_b, are shown in Table 4 for all the climate scenarios considered. For the English catchments, most of the scenarios are predicting increased flow in winter months and reduced flows during the three summer months of June-August. This trend broadly agrees with that presented in Arnell *et al.* (1997) for the region of England where these catchments are located, although the inflow perturbations in their study were obtained using a more sophisticated monthly water balance rainfall-runoff modelling approach. This is a further proof of the adequacy of Eq. (8).

The GS1t scenario, with its most severe reductions in summer rainfall, produced the biggest change (reduction) in the summer runoff. This further confirms observations by previous workers (*e.g.* Boorman and Sefton 1997) that changes in the rainfall have a greater impact on the runoff than changes in the *PE*, particularly when the baseline rainfall is higher than the baseline evapotranspiration. For example, in Table 4, the GS1t scenario predicts a 49% reduction in the mean June runoff for a mere 15% reduction in mean rainfall and an unchanged *PE*. However, If the baseline rainfall is very low (relative to the baseline evapotranspiration), then the influence of a

Table 4 – Future streamflow factors.

System Location	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
England	HADCM1 (2050)	1.19	1.08	1.17	0.77	0.88	0.75	1.28	0.86	0.90	1.22	1.35	1.05
	HADCM1 (2020)	1.10	1.04	1.12	0.91	0.95	1.07	1.17	0.95	1.03	1.15	1.19	1.04
	GG1m	1.03	1.09	1.06	1.09	1.10	0.97	0.90	1.08	1.09	1.15	1.17	1.09
	GS1m	1.05	1.03	1.05	1.08	1.07	1.04	0.94	1.00	0.96	1.08	1.05	1.03
	GS1t	1.04	1.05	1.07	1.23	1.33	0.51	0.75	0.82	1.01	1.28	0.99	1.00
Iran	GS1t	1.17	1.24	1.19	1.29	1.22	0.86	0.81	0.12	0.03	1.29	1.00	1.07

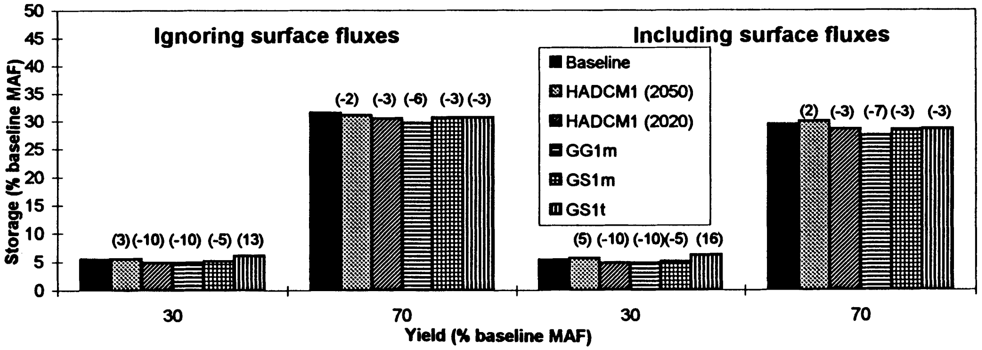
rise in evapotranspiration will become more pronounced since the low rainfall is likely to go entirely into satisfying such a rise, leaving little or nothing for runoff. This was the case for August and September when the GS1t scenario was applied to the Iranian catchments. The predicted high increases in evapotranspiration (15% and 12% respectively for the two months), took up nearly all the rainfall, giving predicted runoff ratios of only 12% and 3% respectively.

Climate Change Impacts on Storage-Yield-Reliability Relationships

The impacts of climate change on the storage capacity are illustrated for the English system in Fig. 3 using results for the 30% and 70% yields. In this Figure, it is apparent that most of the scenarios are predicting lower storages for both yields when compared to the baseline, the only exceptions being the HADCM1-2050 and GS1t scenarios which are predicting larger storages for the 30% yield. Put differently, any existing reservoir of a given capacity which receives the predicted future inflows will generally be able to supply a higher yield than it presently does. However, the per cent reductions in storage are higher at the 30% yield due to its low associated storage, this being dominated by within-year requirements. As the yield increases and over-year requirements become significant, the capacity will increase and any associated difference, in relative terms, will decrease. The importance of within-year requirements at low yields is also probably responsible for the increase in storage requirements predicted by both HADCM1-2050 and GS1t for the 30% yield. For this yield, these two scenarios are predicting increases in required storage of between 3-5% (HADCM1-2050) or 13-16% (GS1t), the top end of both ranges relating to when surface fluxes are considered. As shown in Table 4, these two scenarios actually resulted in the highest reduction in summer inflows, the effect of which will be to increase the within-year imbalance between inflow and release, which is why larger storages are being required.

The results for the Iranian catchments are shown in Fig. 4 for the GS1t scenario. As noted previously, only this scenario was considered for the Iranian catchments.

(a) Climate impact on storage (rel=100%)



(b) GS1t future scenario

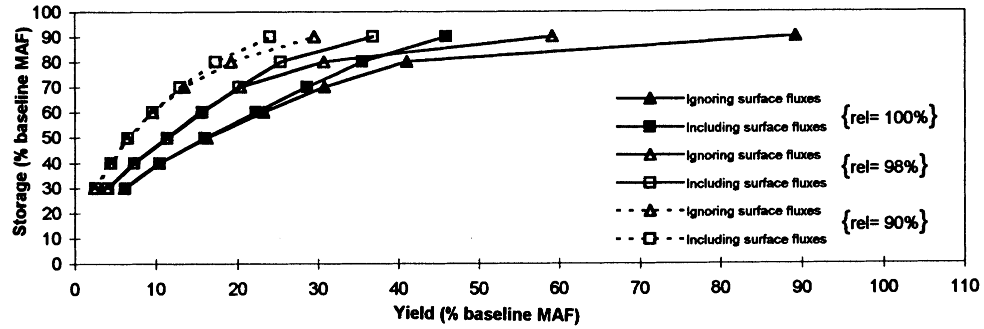
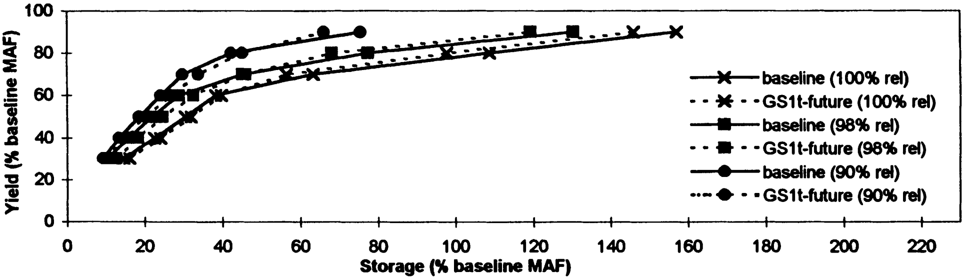


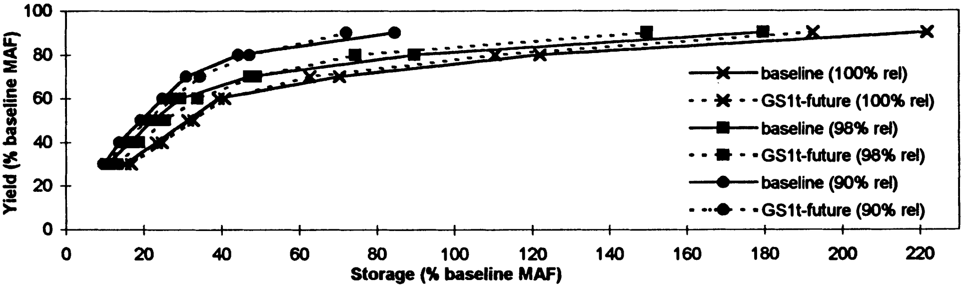
Fig. 3. Impact of five possible future climates on reservoir storage-yield-reliability for the English system. Values in parenthesis in (a) are % difference in storage from the baseline.

The results in Fig. 4, like those for the English system with the GS1t scenario, also show an increased storage requirement at low yields and a lower storage at high yields in the future for 100% reliability. This behaviour is further amplified in Figs. 4(a) and (b) where the complete storage-yield-reliability curves for the Iranian system are shown. In these two Figures, the 100% reliability storage-yield curves for baseline condition occurs to the right of the GS1t curve from the 60% yield onwards (an over-design of storage); before this yield, the storage curve for the GS1t occurs to the right of the baseline curve (an under-design of storage). As the reliability reduces, however, the change from storage under-design to over-design occurs at beyond the 60% yield which is why, for 98% reliability, larger storages (by 2-4%) are being predicted for the 70% yield by GS1t for the Iranian system, in contrast to the 11% reduction in storage at 100% reliability for the same yield. Unlike the English system, the incorporation of surface fluxes did increase storage requirement for all yields with the GS1t scenario, when compared to when the fluxes were ignored (see Fig. 4d).

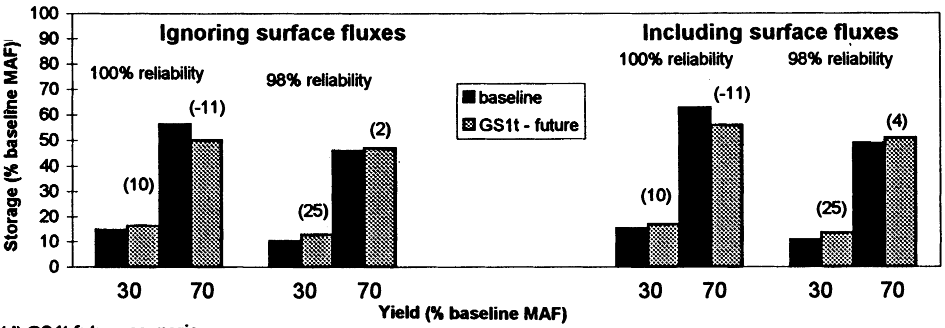
(a) Ignoring surface fluxes



(b) Including surface fluxes



(c) Climate change impact for 100% and 98% reliability



(d) GS1t future scenario

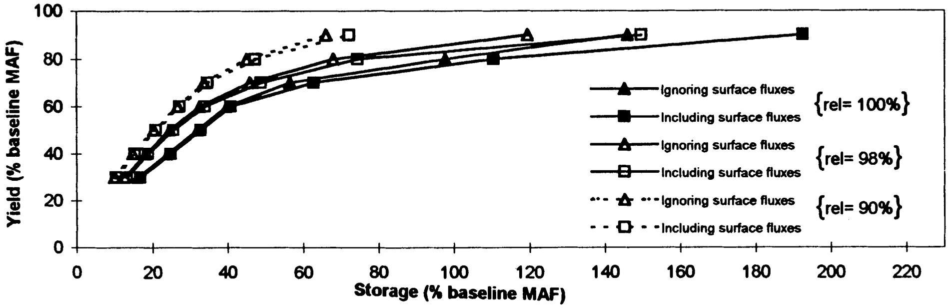


Fig. 4. Impact of GS1t future climate change scenario on reservoir storage-yield-reliability for the Iranian system. Values in parenthesis in (c) are the % difference in storage from the baseline.

Table 5 – Impact of reservoir surface fluxes and climate change on reservoir yield for 100% reliability and assumed storage capacity of 30% mean flow.

Reservoir system location	Assumed active storage capacity (billion litres)	Climate scenario	Yield (Ml/d) Ignoring surface fluxes	Yield (Ml/d) Including surface fluxes
England	11.13	baseline	68.91	71.86
		HADCM1(2050)	69.52	71.05
		HADCM1(2020)	70.44	73.08
		GG1m	71.45	74.81
		GS1m	70.03	73.28
		GS1t	70.03	73.08
Iran	249.60	baseline	1126.05	1103.25
		GS1t	1085.02	1057.66

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The impact of climate change on yield is illustrated in Table 5 for a fixed storage capacity of 30% mean annual flow and 100% reliability. For these conditions, all the scenarios are predicting that higher yields will be possible from this capacity for the English system, whether or not surface fluxes are considered in the analysis. On the contrary for the Iranian system, reductions in the deliverable yields are needed if the reliability of the system is to be maintained at 100% as expected.

Comparisons with other Studies

Comparing results of climate change impacts studies is risky because, as noted by Boorman and Sefton (1997), such results depend on the rainfall-runoff model used and the climate scenarios. Even using the same scenarios will produce different impacts with different rainfall-runoff models. At present, we are unaware of any published study which has applied the 1996 CCIRG and later scenarios used in our current analysis for water resources impact study in England and, on that score, strict comparisons are impossible. However, there have been published results based on earlier scenarios for England, such as the 1991 CCIRG scenarios (Arnell and Reynard 1993), in which it is suggested that reservoir storage requirement will increase as a consequence of climate change (see for example Arnell 1996) for any yield. This slightly contradicts our present result in which increased storage is only predicted for low yields whereas at higher yields, less storage will be required for meeting the yield. However, we are not surprised by our current results given that most of the climate change scenarios used have predicted wetter winters and drier summers. The drier summers have a pronounced effect on within-year storage requirements which dominate total storage at low yields, which is why higher storages are being predicted by the scenarios for such yields. The Iranian study is unique in being first of its kind as far as we know, although the use of the GS1t scenario as a spatial analogue is a slight limitation.

Regarding the impact of surface fluxes on storage-yield curves, the present results broadly agree with what previous investigators have found. For example, Gan *et al.* (1991) used data from Australia and found that the storage requirement increases slightly with incorporation of surface fluxes, similar to the results obtained for the Iranian catchment. Fennessey (1995) was concerned with testing the sensitivity of model time step of evaporation in yield analysis; nonetheless, he also observed that for any storage, the yield of the Massachusetts systems analysed decreased by about 6% with surface fluxes, which is slightly higher than the 2% recorded for the Iranian system (see Table 5). Fennessey only considered 100% reliability; hence there is no information on the sensitivity of his results to systems' reliability. There have been no previously published work looking specifically at the sensitivity of storage-yield to surface flux for the English conditions with which to compare the present results.

Conclusion

This study has investigated the sensitivity of the storage-yield relationships of two multiple reservoir systems to climate change and to the incorporation of reservoir surface net evaporation flux. One of the systems is located in the humid England and the other in the semi-arid climate of Iran. It was observed that for the English system, the inclusion of the net evaporation flux in the yield analysis caused the storage required for meeting a given yield to decrease. The average reduction was 7% for 70% yield and 2% for 30% yield. Put differently, such an inclusion will allow more water to be available for release from an existing reservoir system with a given capacity. This behaviour was attributed to the additional net inflow caused by the evaporation being generally less than the rainfall in the catchments. The effect of net evaporation is accentuated at high yields and reliability levels, because of the larger exposed reservoir surface under such conditions. The behaviour of the Iranian system was opposite to that of the English system. Because for the Iranian catchments evaporation is higher than rainfall, there is a net additional outflow which leads to an increase in storage requirement for a given yield or a reduction of the useable yield from a reservoir of a given capacity. The average increase in storage requirement for the Iranian system was 7% at the 70% yield and 4% for the 30% yield.

Both of the above results have implications for reservoir management in the two regions. For example, while it will always be important to account for net evaporation in Iranian situation so as not to under-design for yield, its neglect for the English system may actually be beneficial because it would result in over-design of the storage capacity and hence represents a built-in factor of safety as far as systems' yield, resilience, reliability and vulnerability are concerned. Such built-in safety factor could help in mitigating against climate change impacts and other uncertainties such as those associated with the use of limited data record lengths for reservoir analysis.

Climate change impacts were examined in terms of the effect of five climate change scenarios on the runoff and the reservoir storage-yield-reliability relationships. These scenarios were based on various UK Hadley Centre GCMs. The runoff scenarios were developed using a runoff coefficient approach while the storage-yield functions were based on an extended SPA. For the English catchments, most of the scenarios predict wetter conditions except for the brief (summer) period between June – August when a reduction in average rainfall is predicted. These findings generally agree with the results in Arnell *et al.* (1997), who also constructed runoff scenarios for the region of England in which the catchments are located using a different rainfall-runoff scheme. It was also observed that the reductions in the runoff coincided with reduction in rainfall, thus further confirming the view that the runoff reacts more to rainfall than to evaporation. In fact, the reduction in rainfall is magnified several times in the runoff as shown in one of the scenarios, GS1t, where almost a 50% reduction in runoff resulted from a reduction of only 15% in the rainfall. This same scenario applied as a spatial analogue for the Iranian catchments predicted a 97% reduction in September runoff because much of the baseline rainfall went into satisfying the high evapotranspiration increase predicted by GS1t for the month.

The generally higher inflows predicted by the scenarios for the English system mean that lower storages will be required for meeting a given demand or, where the storage is fixed, more water can be supplied from the fixed capacity. Reductions in the required storage was almost universal except at low yields of 30% or below where some of the scenarios, notably those predicting the largest reduction in summer runoff (*i.e.* HADCM1-2050 and GS1t), predict an increase in storage. The behaviour at the low yields was attributed to the within-year storage requirements which dominate total storage at such low yields. In other words, small reservoirs which are essentially aimed at meeting seasonal discrepancy between runoff and demand will be more prone to climate change impacts because existing facilities will be unable to meet the demand if predicted climate change materialises. Any insistence on meeting the yield under such circumstances can only be at the expense of systems reliability, resilience and vulnerability because they will deteriorate. For high yield, over-year systems, however, such seasonal requirements are masked by the much larger year-on-year requirements and climate change is not likely to result in severe water shortage.

The GS1t applied to the Iranian system produced the same pattern of change as the corresponding one recorded for the English system; however, due to the larger reduction in the Iranian summer runoff, the influence of within-year storage is more pronounced and hence the increased storage requirements predicted at low yields, which can reach 25%, are much higher than those recorded for the English system.

In concluding, it should be stressed that this work has only used climate scenarios from one GCM and given the often wide variability of scenarios among GCMs, it will be important to repeat the study using other GCMs scenarios. Another area where the study could be improved is to use more appropriate set of scenarios for the Iranian catchments instead of the spatial analogue employed in the study. These together with issues of climate change impacts on systems' resilience and vulnerability, and how adaptation and multi-reservoir operational practices can mitigate such impacts constitute areas for further study.

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