Ireland's water budget— model validation and a greenhouse experiment

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ABSTRACT

In a previous paper (Mills, 2000) the author described a simple water budget model that was applied to Ireland for the period 1961-90. The budget stated the relationship between precipitation, evapotranspiration, runoff and change in water storage for a regular set of grid cells (each 25km^2 in area) that cover Ireland. The results of the model appeared to conform to the known climate of the period but no formal attempt at model validation was attempted. In this paper the author examines the relationship between the estimated 'surplus' water calculated for the catchment of the Shannon River with the measured discharge for that river. The close correspondence between these values suggests that the model is capable of estimating water budget components at this scale. A simple climate change experiment is presented that evaluates the impact of Greenhouse warming on the water budget of this catchment. The results indicate that although increased winter precipitation is predicted, increased rates of evapotranspiration results in drier summers.

Key index words: water budget, runoff, Shannon River, Greenhouse effect.

Introduction

In a previous paper (Mills, 2000) the author outlined a simple water budget model that was applied to the island of Ireland over a period 1961-1990. The basis of the model was a simple statement of the water budget at a given point–

1. $$P - E - R = \Delta S.$$

where P represents precipitation, E represents evapotranspiration and R represents runoff. If there is a difference between the water received and removed, the budget is satisfied by either removing water or adding water to storage (ÄS). The maximum amount of water that can be stored in the soil and is available to plants through their root system (that is, its field capacity) is a function of soil type. If the soil is at field capacity any surplus water becomes runoff. This budget is applied to cells (each 25km^2 in area) that cover the island. While P is observed at meteorological stations and is interpolated to grid points, the remaining terms are not. Evapotranspiration is calculated by assuming that, when sufficient water is available (from the atmosphere or soil), it will equal its maximum potential value (that is, potential evapotranspiration (Ep)). This term is estimated from measured values of bright sunshine hours and air temperature, which are also interpolated to the model grid. The reader is invited to read the earlier paper for a full discussion of the methods by which the components of this budget were estimated.

The model has been employed to examine the nature of this budget over Ireland during the period 1961-90 and to assess the impact of a significant drought event in 1975-76. In Mills (2000) the model estimates of the budget components over this period were compared with

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the known climatology however, no formal validation was attempted. Ideally this process would involve a comparison between estimates and observations for selected components. As the model employs observations of precipitation (albeit interpolated values) and observations of evapotranspiration and soil water content are sparse, the obvious choice for comparison is runoff. River discharge measurements (representing the accumulated upstream catchment runoff) are made by a variety of bodies throughout the country and are appropriate for this task.

Model Validation

It is important to emphasise that, in its current form, the model does not calculate river runoff – rather, it calculates the surplus water in any month. This may be defined as the water not been taken up by evapotranspiration and which cannot be placed into soil water storage as the soil is at field capacity. The means by which a surplus emerges as stream runoff are diverse. If the rainfall is sufficiently intense, the rate at which water can percolate into the soil will be exceeded and excess water will move downhill overland. Water that enters the soil can move slowly downhill through the soil layer and emerge along a river course. Another portion of the water will move into a saturated groundwater zone and emerge eventually at springs. Progress along each of these paths will occur at different time rates and runoff will contain water derived from each source. In any given catchment the river will display a unique response to a given rainfall event depending upon its surface and soil properties, substrate configuration and topographic characteristics.

It is not the intention here to model the various routes by which water received at the 25km^2 cells is routed into river systems. In fact, it is doubtful whether the monthly level data used by the model could resolve monthly river runoff which is a result of many individual precipitation-runoff events. Here the approach taken is to select a suitable river catchment for which observed runoff data are available and compare these values statistically with integrated values for the same area obtained from the model.

River Shannon Discharge

In this work the monthly discharge of the river Shannon at Parteen for 1961-90 is selected as appropriate for establishing the correspondence between the model estimates and observations. This river system was selected largely based on its size and relatively slow response to rainfall events so that a reasonable relationship between monthly precipitation and discharge may be expected. The river Shannon is the longest river in Ireland (235km) and it drains approximately 11,250km^2 (McCumiskey, 1975). Along its course lie three of the largest lakes in Ireland: Lough Allen, Lough Ree and Lough Derg. The gradient of the river is very small – between Allen and Derg, a distance of 205km, the river falls just 12m (Heery, 1993). By comparison, the river falls 30m in 30km between Lough Derg and the Shannon estuary. At Parteen, just south of Derg, a weir raises the level of water and a channel diverts water to the hydroelectric plant at Ardnacrusha. The monthly discharge records collected at this weir are employed in this study. These values are calculated on the basis of the known volumes of water passing through the diversion channel or over the weir during times of excess flow.

The small gradient generates low flow rates and persistent winter flooding is a feature of the river between Loughs Ree and Derg (producing a unique riparian environment termed the Callows). Moreover, the substantial lakes provide natural storage reservoirs so that there is a considerable time lag before a precipitation event is revealed as an increase in discharge at

Parteen. Measurements at this point effectively represent the accumulated runoff for the upstream Shannon catchment area. It is assumed that there has been no significant change in the catchment during this period so that discharge values represents the relationship between precipitation events and a largely unchanged environment. While there has been some small scale efforts at arterial drainage and some embankment construction to alleviate the flooding problem, to date there has been no comprehensive flood control system attempted (Lynn, 1975). Thus, the net impact of these changes on monthly discharges is expected to be small, certainly when compared against the expected errors produced by the model.

The evaluation of the model is done by examining the relationship between model water budget terms (P, E and R) and observed Shannon runoff (Ro). Each of the model components is expressed as a depth of water over the Shannon catchment. Similarly, the observed runoff data (Ro) were converted from recorded discharge values (m^3s^{-1}) into the equivalent depth of water distributed over the catchment.

The annual water budget of the Shannon catchment

The annual runoff over the period 1961-90 averaged 535 mm with a maximum of 673mm (1986) and a minimum of 402mm (1976). Over the period in question there was no detectable trend. Assuming no long-term change in water storage (ÄS≈0) then it may be expected that precipitation in the catchment is balanced by runoff and evapotranspiration (E). If we use measured runoff (Ro) then the residual (P-Ro) should provide a reasonable estimate of E for the period in question. For 1961-90 this suggests (standard deviation values in parentheses),

2. $962\ (\pm 81) - 535\ (\pm 84) = 427.$

By comparison a similar calculation carried out by O'Riordan (1936:37) on the period 1893-1935 shows,

3. $969\ (\pm 109) - 581\ (\pm 124) = 388.$

These results indicate that precipitation (and as a consequence, runoff) were less variable during the later period. Moreover, notice that while precipitation values are nearly identical, the ratio of runoff to precipitation (Ro/P) is lower in the later period (0.56 versus 0.60) and, correspondingly, the proportion removed by E is higher. Work completed by McCumiskey (1975) on the period 1950-64 suggested (no measures of variability available),

4. $1029 - 539 = 490.$

Thus, this fifteen-year period was associated with heavier precipitation but a lower proportion was converted to runoff (0.52). Yet, during the 1950s, the Shannon experienced exceptional flooding culminating in a record flood event during the winter of 1954-55. This apparent contradiction could be explained by increased winter time precipitation (when evaporation is low, the soil is saturated and runoff dominates) but increased summer time evaporation.

The average monthly water balance for the catchment over 1961-90 is presented in Figure 1. Depicted on this chart are measured P and Ro alongside calculated E and R from the model. The distribution of precipitation throughout the year follows a familiar pattern. While there is no distinctive seasonality in Irish precipitation, the receipt is greatest during the winter months (August to January average between 80-100mm) and least during the Spring and early Summer (April precipitation averages 60mm). Measured runoff (Ro) displays a u-shaped pattern with maximum values in December and January (about 80mm) and minimum value in July (18mm). This seasonal pattern is caused by the behaviour of E, which is at a maximum in summer (70mm) and a minimum in winter (<10mm). From mid-May to mid-July, E exceeds P and water is withdrawn from the soil. According to the model the difference between E and P is satisfied by water withdrawal and there is (on average) no water shortage (that is, E=Ep). The estimated monthly surplus (R) shows the same pattern as Ro however, the monthly range is greater. When the soil is at field capacity and there is little evapotranspiration, R is very close to P – in other words, nearly all precipitation is surplus. Conversely, during the summer months the surplus is very close to zero. The diagram clearly suggests that R in any given month does not appear in Ro in that month but instead is delivered into the stream over a period of time. This relationship is explored later in this paper.

Precipitation and runoff

Figure 2 shows the relationship between the annual values of P and Ro for 1961-90. A linear fit to these data produced a coefficient of determination (r^2) equal to 0.76 (by comparison, O'Riordan's values produce a value of 0.85). A visual examination indicates that two values (those for 1971 and 1990) have a large influence on this statistic and, if these are removed, r^2 equals 0.85. On average 55 percent of precipitation is removed as runoff but this varies from a high of 63 percent in 1967 to a low of 37 percent in 1971. The relationship between these two variables using monthly data is considerably weaker (r^2 equals 0.24) due to the variation in evapotranspiration (and consequently, runoff) during the year and the time lag between precipitation receipt and runoff response.

The monthly time series of P and Ro can best be examined by calculating the deviations between the value in any given month and the average for that month for the entire period. These deviations are then accumulated and plotted against time. The resulting graph (Figure 3) eliminates the effect created by individual monthly values. Although the curves of P and Ro must terminate in zero at the end of the series, their paths indicate coherent periods of increasing or decreasing values. Figure 3 confirms the close relationship between P and Ro and suggests that from 1969 to the mid-1970s, both decreased over time reaching a minimum between 1977-79. Thereafter, both variables increased in value. The author cannot explain the divergence in these series that occurs between 1967 and 1968, however their joint behaviour elsewhere is consistent. The graph shows that a change in the rainfall regime from a dry to wet period occurred in the period 1977-79 and that Shannon runoff responded accordingly. This transition corresponds with a 'change point' detected by Kiely (1999) in the time series of both river discharge and precipitation records at sites around Ireland. His work indicates that the increase in precipitation after this point was principally associated with increases in March and October and this was associated with a change in the circulation regime to more westerly airflow.

Estimated surplus and runoff

Figure 4 displays the annual time series of estimated surplus (R) and Ro, which over the course of a year should approximately equal. Overall, the two series correspond closely (again, 1967 and 1971 are notable exceptions). The statistics of these series (Table 1) reveal that on average the model underestimates runoff (513mm and 536mm for R and Ro, respectively) and, while their standard deviations are nearly equal, the maximum and minimum for R is higher than the equivalent values for Ro. The mean absolute error (where error is the difference between R and Ro) is 38.5mm.

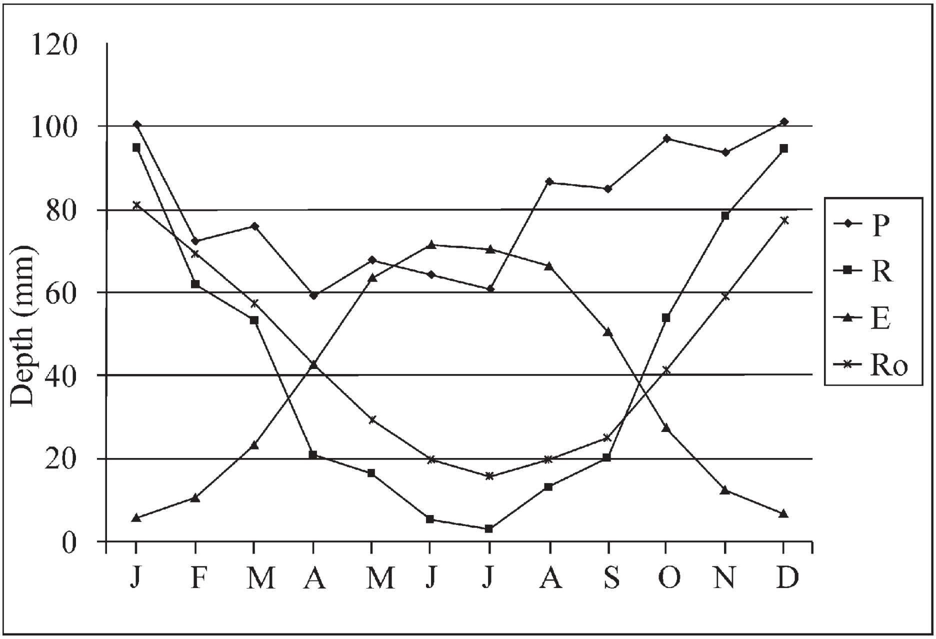

Figure 1: The average water budget for the Shannon catchment over 1961-90. Precipitation (P), actual evapotranspiration (E) and surplus (R) are calculated by the water budget model. Values for potential evapotranspiration are identical to those for E. The runoff of the River Shannon is also plotted (Ro).

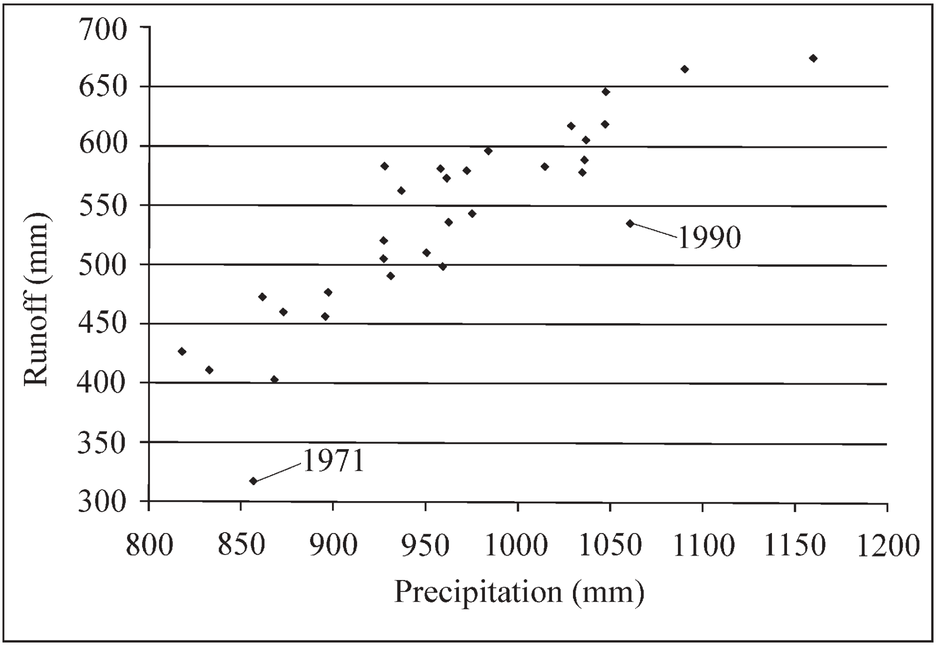

Figure 2: Scattergram of relationship between annual precipitation in the Shannon catchment and runoff for the River Shannon for the period 1961-90.

Table 1: Descriptive statistics for monthly values of the water budget model components (precipitation (P), evapotraspiration (E) and surplus (R)) and observed Shannon runoff (Ro) for the period 1961-90.

	P	E	R	Ro	Ro/P
Mean	961.7	448.9	512.7	535.2	55.4
Median	958.0	445.1	511.5	551.9	55.9
Standard Deviation	81.3	22.2	83.6	83.6	5.4
Maximum	818.1	410.3	360.7	316.6	36.9
Minimum	1158.6	501.1	740.5	674.0	62.8

Some of the discrepancies between R and Ro can be expected given the spatial and temporal complexity of precipitation-runoff relationships. Thus rainfall in different parts of the catchment will have different relationship with discharge at Parteen. Moreover, some of the precipitation received in a given year is effectively stored and released as Ro in the following year so that R and Ro may not be entirely coincident. Nevertheless, it is apparent that there are still some significant errors in the model estimates. The author's view is that these are largely due to the estimation of E, which is based on empirical relationships between observations of evapotranspiration, sunshine and temperature at a few available sites.

In examining the relationship between monthly data it may be expected that a proportion of R in a given month will be removed in that month but that declining proportions of this surplus will be removed in subsequent months. In other words, the presence of a significant lag in response time between R and Ro must be accounted for. The nature of this relationship may be explored in a cross-correlation analysis where the two time series are correlated against each other at different time lags. For example, at lag zero the R values for each month are correlated for Ro values for that same month, at lag one R values are correlated with Ro values for the following month (January with February), and so on. The results show statistically significant positive relationships out to lag three (January with April, etc). A subsequent regression analysis suggests the following relationship,

5. $$\text{Ø}o = 12.81 + 0.403R_t + 0.339R_{t-1}$$

where the subscripts refer to the value of R in that month (t) or in the previous month (t-1). This statistical model explains 87 percent (significant at $\alpha<0.001$) of the variation in Ro.

The above analyses suggest that the water budget model is capable of reproducing many of the observed features in Shannon runoff over the period 1961-90 and may be employed to evaluate likely changes to this budget in a changed climate scenario.

A Greenhouse experiment

By way of a discussion it is informative to evaluate how the water budget of this catchment could change in an altered climate. Currently, a substantial body of international research is focussed on the possibility of human induced climate change through altering the composition of the atmosphere. The current models that assess potential climate change incorporate the physics that govern exchanges between the atmosphere, oceans and land surfaces. In addition, oceanic circulation and complex feedbacks are included. Typically, these models are ‘benchmarked’ by evaluating their ability to simulate the current climate before modifying parameters and simulating future climates. Current climate change modeling experiments are focussed on the potential impact of increased Carbon Dioxide (CO_2) concentration in the atmosphere. The pre-industrial value for this gas is estimated at 270 parts per million (ppm) but this value is expected to double by 2050. The consequences of this alteration are still a matter of considerable debate owing to the complexity of the earth-atmosphere system (EAS), our incomplete understanding and the necessity for ‘compromises’ between physical understanding and available computational power. Nevertheless there is general agreement that the consequences of this alteration will be global warming, rising sea-levels and changed patterns of precipitation. The regional nature and significance of these changes is a topic of considerable interest (Raper *et al.*, 1997, Sweeney, 1994).

One of the necessary compromises made by GCMs is the density of grid points employed to represent the EAS— as an example, the Hadley Centre climate model (HadCM2) employs a spatial resolution of 2.5° latitude by 3.75° longitude (300x350km, at Ireland’s latitude). To elucidate the significance of GCM results to finer scales requires a process of ‘downscaling’ whereby the statistics for the global model grid are used to generate climate statistics at a denser set of grid points. Sophisticated downscaling methods rely on equally comprehensive regional climate models that employ the output of global models as inputs to initiate and inform detailed simulations. By comparison, the crudest approach is to take the predicted changes in climate variables and simply apply these values in an additive manner to the existing climate (Hulme and Jenkins, 1998).

The latter approach has been taken in this simple experiment to estimate the water budget in the Shannon catchment in a Greenhouse scenario. Among the various Greenhouse scenarios explored in experiments carried out by the Hadley Centre using HadCM2 was one in which the CO_2 concentration in the atmosphere was increased from its current value of 360ppm to 528ppm by 2080. The results generated an increase in the global annual temperature of 2.4°C and a sea-level rise of 0.67m. A more detailed examination of the results for the grid cell that covers the area of the Shannon catchment predicts an increase in annual temperature of 2.8°C and an 11 percent increase in precipitation (Hulme and Jenkins, 1998). On a seasonal basis the temperature change will occur throughout the year but the precipitation increase is expected to be greater in the winter and spring (Table 2). These seasonal results have been applied to the average monthly values (based on the 1961-90 period) for each grid cell within the catchment area. The model was run several times using these altered monthly values to generate an average picture in such circumstances. For each run the soil conditions in December were employed as existing conditions in the January calculations.

Once the results of the model had come into equilibrium with the ‘new’ climate the water budget for the entire catchment was calculated in the same manner as previously. The annual budget estimated becomes,

$$6. \qquad P - R - E = 1037 - 474 - 563$$

Given the uncertainty in model estimates of E it seems reasonable to evaluate this term using another approach. If it is assumed that the relationship between R and Ro derived from the 1961-90 series was to hold in this altered environment then E can also be estimated as a residual,

$$7. \qquad P - Øo = E \qquad 1037 - 506 = 531$$

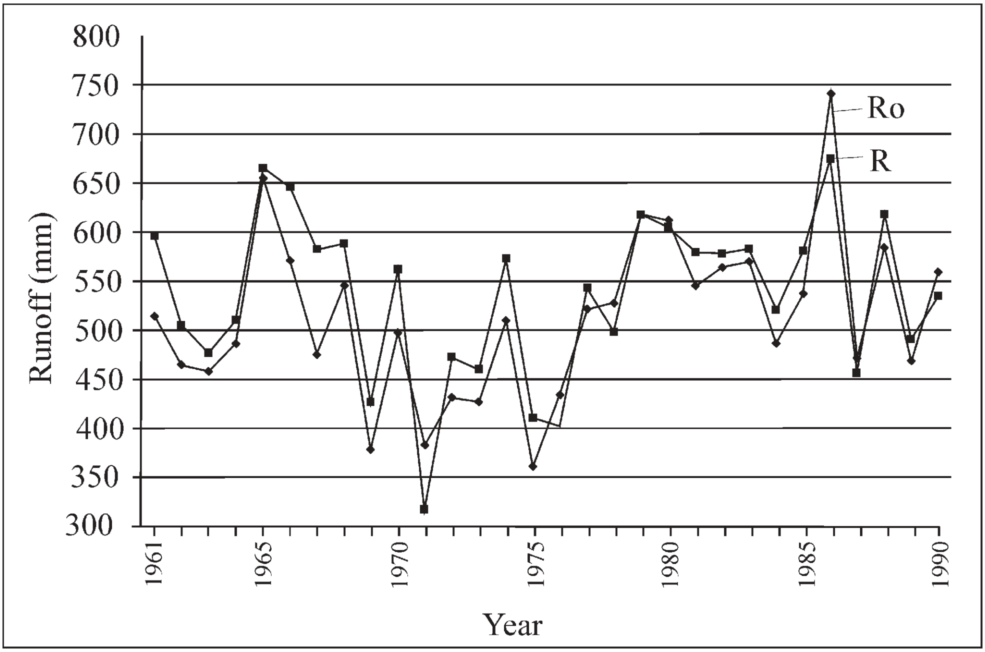

Figure 3: Monthly time series of the accumulated deficits of precipitation and Shannon river runoff from their respective monthly averages.

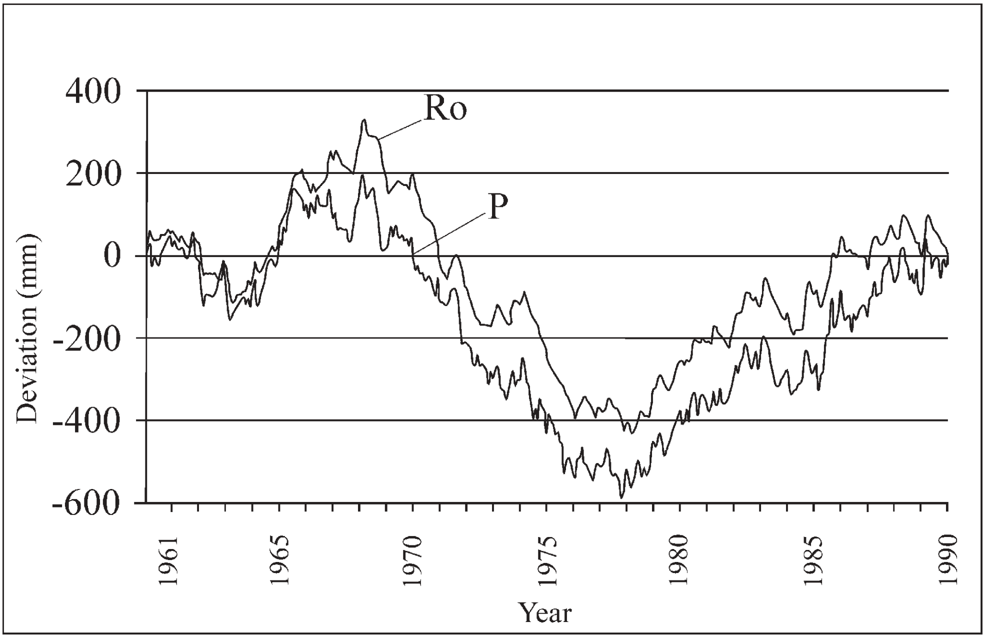

Figure 4: The annual time series of measured (Ro) and estimated (P) Shannon runoff.

Øo is now the estimated value based on equation 5. Interestingly, both approaches suggest that, despite the increase in precipitation, the greater proportion is taken up in evapotranspiration rather than runoff.

Table 2: Changes to the 1961-90 climate applied to the water budget model. Values are based upon those reported for Ireland in 2080 under the high emission scenario experiment conducted by the Hadley Centre (Hulme and Jenkins, 1998).

Months	Precipitation	Temperature	Cloudiness
DJF	+23%	+2.7°C	-1 %
MAM	+23%	+2.7°C	0 %
JJA	-7%	+2.7°C	0 %
SON	-7%	+2.7°C	0 %

This result can be explained with reference to Figure 5, which shows the monthly water budget in this climate. Of particular note is that the precipitation changes are confined to the winter and spring months resulting in greater seasonality in precipitation. In the model, E is related to both sunshine and temperature. While the former experiences little change, the latter displays significant increases throughout the year. The net result is that the model estimates that there is no surplus water (R) generated in the catchment from May to August. During these months evaporation exceeds precipitation and water is drawn out of storage. From June to August a small deficit is calculated as vegetation experiences difficulty in extracting water from a depleted soil. The Shannon runoff (Ro) would also become more seasonal than it currently is. Although it may seem counter-intuitive this could result in increased winter-spring flooding and summer-autumn dry spells.

The scenario likely to produce the greatest change over this period has been deliberately selected to establish how marked changes in precipitation and temperature can impact the water budget. Although some of the changes estimated are relatively small (for example, the annual deficit increases from nearly 0mm to 5mm), it is important to bear in mind that these calculations are based on changes in the climate averages and do not account for year-to-year variations which could be significant.

Summary and conclusions

The primary objective of this paper was to evaluate a water budget model by comparing its results against observations. River runoff data represents the accumulated drainage from a catchment area and is an obvious choice for comparison with estimated budget components. The relationship between river runoff and precipitation is complex and no attempt is made to simulate these processes in the model. Moreover, the temporal resolution of the data would allow only a crude approximation to these processes. Instead the approach taken is to examine the annual and monthly time series of precipitation (P), surplus water (R) and river runoff (Ro). The Shannon River system represents an ideal system for comparison with model data as its large size and small gradient mean that its response to individual rainfall events is very slow.

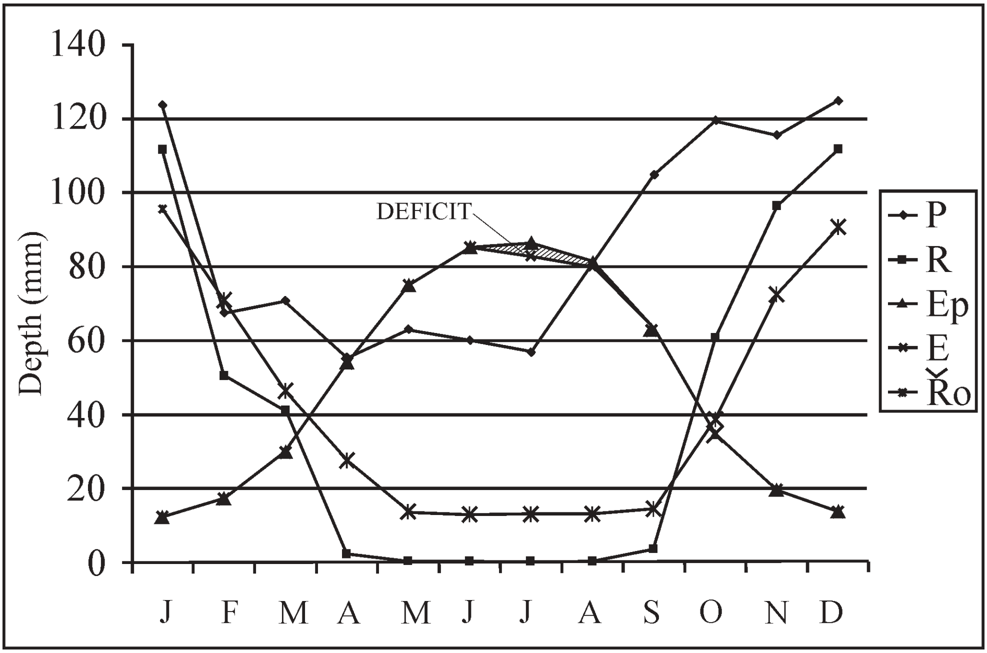

Figure 5: The average water budget for the Shannon catchment under a Greenhouse scenario. Precipitation (P), actual (E) and potential evapotranspiration (Ep) and surplus (R) are calculated by the water budget model. The runoff of the River Shannon (Øo) is estimated.

The annual water budget for the Shannon catchment for the period 1961-90 indicates that 55 percent of P is diverted to river runoff. The time series of P and Ro suggests that the precipitation climatology of the catchment underwent a distinctive change over this period. From 1969 to 1977 both P and Ro decreased, thereafter they jointly increased. The timing of this transition is supported by the work of others (Kiely, 1999) and suggests that the precipitation estimates for the catchment are trustworthy. Estimates of surplus water (R) show good agreement with measured runoff however, some of the larger errors suggest that the estimation of evapotranspiration in the model is a source of error. On a monthly basis it appears that runoff can be estimated reasonably well with knowledge of the surplus in the current month and previous month.

A simple experiment is presented that demonstrates the potential for a simple model to facilitate understanding of the potential impact of climate change at a local scale. The predictions for a future climate under a scenario of substantial increase in CO_2 concentrations were applied in a crude manner to the Shannon catchment. The water budget under this new climate regime of enhanced winter precipitation and a year-round increase in temperature indicated significant increases in runoff during winter months and significant decreases in summer months. The results suggest both increased flooding in winter/spring and dry conditions in summer/autumn.

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