WILEY
Publishers Since 1807

JOHN WILEY & SONS, LTD., THE ATRIUM, SOUTHERN GATE, CHICHESTER P019 8SQ, UK

*** PROOF OF YOUR ARTICLE ATTACHED, PLEASE READ CAREFULLY ***

PLEASE AIM TO RETURN YOUR CORRECTIONS WITHIN 48 HOURS OF RECEIPT OF YOUR PROOF, THIS WILL ENSURE THAT THERE ARE NO UNNECESSARY DELAYS IN THE PUBLICATION OF YOUR ARTICLE

☐ **READ PROOFS CAREFULLY**

ONCE PUBLISHED ONLINE OR IN PRINT IT IS NOT POSSIBLE TO MAKE ANY FURTHER CORRECTIONS TO YOUR ARTICLE

- This will be your only chance to correct your proof
- Please note that the volume and page numbers shown on the proofs are for position only

☐ **ANSWER ALL QUERIES ON PROOFS** (Queries are attached as the last page of your proof.)

- List all corrections and send back via e-mail to the production contact as detailed in the covering e-mail, or mark all corrections directly on the proofs and send the scanned copy via e-mail. Please do not send corrections by fax or post

☐ **CHECK FIGURES AND TABLES CAREFULLY**

- Check sizes, numbering, and orientation of figures
- All images in the PDF are downsampled (reduced to lower resolution and file size) to facilitate Internet delivery. These images will appear at higher resolution and sharpness in the printed article
- Review figure legends to ensure that they are complete
- Check all tables. Review layout, titles, and footnotes

☐ **COMPLETE COPYRIGHT TRANSFER AGREEMENT (CTA) if you have not already signed one**

- Please send a scanned signed copy with your proofs by e-mail. **Your article cannot be published unless we have received the signed CTA**

☐ **OFFPRINTS**

- 25 complimentary offprints of your article will be dispatched on publication. Please ensure that the correspondence address on your proofs is correct for dispatch of the offprints. If your delivery address has changed, please inform the production contact for the journal – details in the covering e-mail. Please allow six weeks for delivery.

Additional reprint and journal issue purchases

- Should you wish to purchase a minimum of 100 copies of your article, please visit http://www3.interscience.wiley.com/aboutus/contact_reprint_sales.html
- To acquire the PDF file of your article or to purchase reprints in smaller quantities, please visit http://www3.interscience.wiley.com/aboutus/ppv-articleselect.html. Restrictions apply to the use of reprints and PDF files – if you have a specific query, please contact permreq@wiley.co.uk. Corresponding authors are invited to inform their co-authors of the reprint options available
- To purchase a copy of the issue in which your article appears, please contact cs-journals@wiley.co.uk upon publication, quoting the article and volume/issue details
- Please note that regardless of the form in which they are acquired, reprints should not be resold, nor further disseminated in electronic or print form, nor deployed in part or in whole in any marketing, promotional or educational contexts without authorization from Wiley. Permissions requests should be directed to mailto: permreq@wiley.co.uk

COPYRIGHT TRANSFER AGREEMENT

Date: ____________________ Contributor name: ____________________

Contributor address: ____________________

Manuscript number (Editorial office only): ____________________

Re: Manuscript entitled ____________________

____________________ (the "Contribution")

for publication in ____________________ (the "Journal")

published by ____________________ ("Wiley-Blackwell").

Dear Contributor(s):
Thank you for submitting your Contribution for publication. In order to expedite the editing and publishing process and enable Wiley-Blackwell to disseminate your Contribution to the fullest extent, we need to have this Copyright Transfer Agreement signed and returned as directed in the Journal's instructions for authors as soon as possible. If the Contribution is not accepted for publication, or if the Contribution is subsequently rejected, this Agreement shall be null and void. **Publication cannot proceed without a signed copy of this Agreement.**

A. COPYRIGHT

1. The Contributor assigns to Wiley-Blackwell, during the full term of copyright and any extensions or renewals, all copyright in and to the Contribution, and all rights therein, including but not limited to the right to publish, republish, transmit, sell, distribute and otherwise use the Contribution in whole or in part in electronic and print editions of the Journal and in derivative works throughout the world, in all languages and in all media of expression now known or later developed, and to license or permit others to do so.

2. Reproduction, posting, transmission or other distribution or use of the final Contribution in whole or in part in any medium by the Contributor as permitted by this Agreement requires a citation to the Journal and an appropriate credit to Wiley-Blackwell as Publisher, and/or the Society if applicable, suitable in form and content as follows: (Title of Article, Author, Journal Title and Volume/Issue, Copyright © [year], copyright owner as specified in the Journal). Links to the final article on Wiley-Blackwell's website are encouraged where appropriate.

B. RETAINED RIGHTS

Notwithstanding the above, the Contributor or, if applicable, the Contributor's Employer, retains all proprietary rights other than copyright, such as patent rights, in any process, procedure or article of manufacture described in the Contribution.

C. PERMITTED USES BY CONTRIBUTOR

1. Submitted Version. Wiley-Blackwell licenses back the following rights to the Contributor in the version of the Contribution as originally submitted for publication:

a. After publication of the final article, the right to self-archive on the Contributor's personal website or in the Contributor's institution's/employer's institutional repository or archive. This right extends to both intranets and the Internet. The Contributor may not update the submission version or replace it with the published Contribution. The version posted must contain a legend as follows: This is the pre-peer reviewed version of the following article: FULL CITE, which has been published in final form at [Link to final article].

b. The right to transmit, print and share copies with colleagues.

2. Accepted Version. Re-use of the accepted and peer-reviewed (but not final) version of the Contribution shall be by separate agreement with Wiley-Blackwell. Wiley-Blackwell has agreements with certain funding agencies governing reuse of this version. The details of those relationships, and other offerings allowing open web use, are set forth at the following website: http://www.wiley.com/go/funderstatement. NIH grantees should check the box at the bottom of this document.

3. Final Published Version. Wiley-Blackwell hereby licenses back to the Contributor the following rights with respect to the final published version of the Contribution:

a. Copies for colleagues. The personal right of the Contributor only to send or transmit individual copies of the final published version in any format to colleagues upon their specific request provided no fee is charged, and further-provided that there is no systematic distribution of the Contribution, e.g. posting on a listserve, website or automated delivery.

b. Re-use in other publications. The right to re-use the final Contribution or parts thereof for any publication authored or edited by the Contributor (excluding journal articles) where such re-used material constitutes less than half of the total material in such publication. In such case, any modifications should be accurately noted.

c. Teaching duties. The right to include the Contribution in teaching or training duties at the Contributor's institution/place of employment including in course packs, e-reserves, presentation at professional conferences, in-house training, or distance learning. The Contribution may not be used in seminars outside of normal teaching obligations (e.g. commercial seminars). Electronic posting of the final published version in connection with teaching/training at the Contributor's institution/place of employment is permitted subject to the implementation of reasonable access control mechanisms, such as user name and password. Posting the final published version on the open Internet is not permitted.

d. Oral presentations. The right to make oral presentations based on the Contribution.

4. Article Abstracts, Figures, Tables, Data Sets, Artwork and Selected Text (up to 250 words).

a. Contributors may re-use unmodified abstracts for any non-commercial purpose. For on-line uses of the abstracts, Wiley-Blackwell encourages but does not require linking back to the final published versions.

b. Contributors may re-use figures, tables, data sets, artwork, and selected text up to 250 words from their Contributions, provided the following conditions are met:

(i) Full and accurate credit must be given to the Contribution.
(ii) Modifications to the figures, tables and data must be noted. Otherwise, no changes may be made.
(iii) The reuse may not be made for direct commercial purposes, or for financial consideration to the Contributor.
(iv) Nothing herein shall permit dual publication in violation of journal ethical practices.

D. CONTRIBUTIONS OWNED BY EMPLOYER

1. If the Contribution was written by the Contributor in the course of the Contributor's employment (as a "work-made-for-hire" in the course of employment), the Contribution is owned by the company/employer which must sign this Agreement (in addition to the Contributor's signature) in the space provided below. In such case, the company/employer hereby assigns to Wiley-Blackwell, during the full term of copyright, all copyright in and to the Contribution for the full term of copyright throughout the world as specified in paragraph A above.

2. In addition to the rights specified as retained in paragraph B above and the rights granted back to the Contributor pursuant to paragraph C above, Wiley-Blackwell hereby grants back, without charge, to such company/employer, its subsidiaries and divisions, the right to make copies of and distribute the final published Contribution internally in print format or electronically on the Company's internal network. Copies so used may not be resold or distributed externally. However the company/employer may include information and text from the Contribution as part of an information package included with software or other products offered for sale or license or included in patent applications. Posting of the final published Contribution by the institution on a public access website may only be done with Wiley-Blackwell's written permission, and payment of any applicable fee(s). Also, upon payment of Wiley-Blackwell's reprint fee, the institution may distribute print copies of the published Contribution externally.

E. GOVERNMENT CONTRACTS

In the case of a Contribution prepared under U.S. Government contract or grant, the U.S. Government may reproduce, without charge, all or portions of the Contribution and may authorize others to do so, for official U.S. Government purposes only, if the U.S. Government contract or grant so requires. (U.S. Government, U.K. Government, and other government employees: see notes at end)

F. COPYRIGHT NOTICE

The Contributor and the company/employer agree that any and all copies of the final published version of the Contribution or any part thereof distributed or posted by them in print or electronic format as permitted herein will include the notice of copyright as stipulated in the Journal and a full citation to the Journal as published by Wiley-Blackwell.

G. CONTRIBUTOR'S REPRESENTATIONS

The Contributor represents that the Contribution is the Contributor's original work, all individuals identified as Contributors actually contributed to the Contribution, and all individuals who contributed are included. If the Contribution was prepared jointly, the Contributor agrees to inform the co-Contributors of the terms of this Agreement and to obtain their signature to this Agreement or their written permission to sign on their behalf. The Contribution is submitted only to this Journal and has not been published before. (If excerpts from copyrighted works owned by third parties are included, the Contributor will obtain written permission from the copyright owners for all uses as set forth in Wiley-Blackwell's permissions form or in the Journal's Instructions for Contributors, and show credit to the sources in the Contribution.) The Contributor also warrants that the Contribution contains no libelous or unlawful statements, does not infringe upon the rights (including without limitation the copyright, patent or trademark rights) or the privacy of others, or contain material or instructions that might cause harm or injury.

CHECK ONE BOX:

☐ Contributor-owned work

ATTACH ADDITIONAL SIGNATURE PAGES AS NECESSARY

Contributor's signature ____________________ Date ____________

Type or print name and title ____________________

Co-contributor's signature ____________________ Date ____________

Type or print name and title ____________________

☐ Company/Institution-owned work
(made-for-hire in the course of employment)

Company or Institution (Employer-for-Hire) ____________________ Date ____________

Authorized signature of Employer ____________________ Date ____________

☐ U.S. Government work

Note to U.S. Government Employees
A contribution prepared by a U.S. federal government employee as part of the employee's official duties, or which is an official U.S. Government publication, is called a "U.S. Government work," and is in the public domain in the United States. In such case, the employee may cross out Paragraph A.1 but must sign (in the Contributor's signature line) and return this Agreement. If the Contribution was not prepared as part of the employee's duties or is not an official U.S. Government publication, it is not a U.S. Government work.

☐ U.K. Government work (Crown Copyright)

Note to U.K. Government Employees
The rights in a Contribution prepared by an employee of a U.K. government department, agency or other Crown body as part of his/her official duties, or which is an official government publication, belong to the Crown. U.K. government authors should submit a signed declaration form together with this Agreement. The form can be obtained via http://www.opsi.gov.uk/advice/crown-copyright/copyright-guidance/publication-of-articles-written-by-ministers-and-civil-servants.htm

☐ Other Government work

Note to Non-U.S., Non-U.K. Government Employees
If your status as a government employee legally prevents you from signing this Agreement, please contact the editorial office.

☐ NIH Grantees

Note to NIH Grantees
Pursuant to NIH mandate, Wiley-Blackwell will post the accepted version of Contributions authored by NIH grant-holders to PubMed Central upon acceptance. This accepted version will be made publicly available 12 months after publication. For further information, see www.wiley.com/go/nihmandate.

HYDROLOGICAL PROCESSES
Hydrol. Process. **23**, 0–0 (2009)
DOI: 10.1002/hyp.7393

AQ2

River flow modelling in two •large river basins: the Paraná (South America) and the Niger (West Africa)

Declan Conway[1]* and Gil Mahé[2]
[1] *School of Development Studies, University of East Anglia, Norwich NR4 7TJ, UK*
[2] *IRD (Ex-ORSTOM), 01 BP 182, Ouagadougou 01, Burkina Faso*

Abstract:

A conceptual water balance model is applied in a distributed manner to model monthly river flow in tributaries of two very large river systems, the Paraná river in South America and the River Niger in West Africa. The approach utilises global data sets of rainfall and potential evaporation (PE) time series and soil available water capacity at 0·5 degree latitude and longitude resolution. River flow data for tributaries ranging in size from 631 to 71 510 km^2 for the period 1931–1990 (Paraná) and 1950–1989 (Niger) are used to calibrate and validate the model. The results show varying degrees of model performance during both the calibration and validation procedure. The analysis highlights some interesting issues pertaining to the development and application of water balance models such as sensitivity of model performance and parameter values to input data sets, particularly the method chosen to estimate PE. The paper ends with an analysis of prolonged fluctuation in flow characteristics exhibited by both rivers after the early 1970s, associated with fluctuation in rainfall regime and possibly change in land use or land cover. Between 1931–1971 and 1972–1990 Paraná river flows increased by ~28% (rainfall increase ~5%) and between 1950–1969 and 1970–1989 Niger river flows decreased by ~34% (rainfall decrease ~14%). Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS South America; West Africa; modelling; river basin; rainfall variability; land cover change

AQ1

Received •; Accepted 1 October 2008

INTRODUCTION

Water balance models of varying degrees of complexity have been widely used in a number of hydrological applications (Alley, 1984; Xu and Singh, 1998). Here, we apply a simple conceptual water balance first developed by Thornthwaite and Mather (1955) in a distributed manner to model monthly river flow in tributaries of two very large river systems, the Paraná river in South America and the Niger river in West Africa. This approach utilises a monthly water balance with gridded inputs of rainfall and potential evaporation (PE) along the lines of Vörösmarty *et al*. (1989) on the Amazon and Conway (1997) on the Blue Nile. The paper presents preliminary river flow modelling results from two separate research projects, one investigating the implications of climate variability and change for water resources in the Rio de la Plata (Conway *et al*., 1999) and a longer term research programme investigating climate and water resource dynamics in West Africa. The paper uses a consistent modelling procedure and standard spatial data sets for both river basins to examine model performance and the effects of employing different input PE data sets in two contrasting large river basins. The paper ends with an examination and discussion of fluctuations in the rainfall and river flow regimes of both basins that occurred during the early 1970s.

The Paraná river comprises a major part of the Rio de la Plata basin, draining parts of Bolivia, Paraguay, Uruguay, the southern states of Brazil, and Argentina, with a total area of 3 100 000 km^2. This paper deals with the Paraná upstream of the river gauge at Posadas, an area of 933 360 km^2 with mean annual discharge of 12 329 m^3 s^{-1}. The area drained is largely within south-eastern Brazil, a highland area (300–1200 m) with heavy seasonal rains (1000–2400 mm), and high temperatures. Soils derive from heavily weathered parent materials which have formed erodible yellowish or reddish-yellow latosols with low fertility rich in iron and aluminium oxides and kaolinitic clays (Bonetto *et al*., 1987). The Paraná basin encompasses major urban areas including São Paolo and Brasilia, many of the tributaries are heavily developed for hydropower with numerous dams providing up to 18 715·2 MW year^{-1} (over 50% of Brazil's total) and the river serves an important navigation function.

The Niger upstream of the gauge at Koulikoro drains parts of Guinea and Mali with a total area of 120 000 km^2 and mean annual discharge of 1390 m^3 s^{-1} The upper basin of the River Niger at Siguiri (67 600 km^2) gathers runoff from four tributaries inside Guinea, the Tinkisso, the Niger itself, the Niandan and the Milo. Rainfall ranges from 1300 mm in the north to 2200 mm in the humid and mountainous areas (up to 1700 m) in the south and south-west, at the border with Sierra-Leone and Liberia. The other neighbouring countries are Ivory Coast and Senegal. The geology is mainly of granites and gneisses

---

* Correspondence to: Declan Conway, School of Development Studies, University of East Anglia, Norwich NR4 7TJ, UK.
E-mail: d.conway@uea.ac.uk

of the old African Infracambrian, with moderate capacity for groundwater reserves. These rivers are perennial, have tropical regimes and supply flood water to the Niger Inland Delta that expands from about 4000 to 20-•30 000 km^2 in the flood season providing opportunities for flood-related cropping, fishing and seasonal grazing.

DATA SETS

Gridded data sets

The approach utilises global data sets of rainfall, potential evaporation and soil available water capacity at 0·5 degree latitude and longitude resolution. Monthly time series of rainfall from 1901 to 1995 were used from New *et al.* (2000). PE time series were constructed using the 1901–1995 mean monthly temperature (t_{min} and t_{max}), vapour pressure, and sunshine hour time series from New *et al.* (2000) and constant baseline windspeed data for the period 1961–1990 from New *et al.* (1999). The global rainfall and temperature data sets of New *et al.* were augmented with additional station data from regional sources and re-gridded to improve the spatial coverage over both river basins.

A number of PE functions were used for the analysis but results with only two are presented here. A version of Penman ($\mathrm{PE_{TO}}$—Thom and Oliver, 1977) and a reference crop potential evaporation ($\mathrm{PE_{RC}}$—Shuttleworth, 1993) with resistances defined as for clipped grass, 0·12m high. There are significant differences between the methods within and between regions. The basin average PE is much higher with $\mathrm{PE_{RC}}$ than $\mathrm{PE_{TO}}$ over the Niger but slightly lower with $\mathrm{PE_{RC}}$ than $\mathrm{PE_{TO}}$ over the Paraná. The widest range in annual values occur with $\mathrm{PE_{RC}}$ over both regions and the maximum values for $\mathrm{PE_{RC}}$ are unrealistically high in both regions, particularly the Niger, and are used here for means of comparison only. Comparison with locally derived PE estimates for parts of the Niger basin using FAO Penman shows reasonable agreement with $\mathrm{PE_{TO}}$ in the dry season and slight underestimates ($\sim$10%) in the wet season. $\mathrm{PE_{RC}}$ overestimates FAO Penman throughout the year, but to a much greater extent in the dry season.

The 0·5 degree resolution data set of plant-extractable water capacity from Dunne and Willmott (1996) was used to provide an estimate of soil water capacity. These values are calculated from FAO soil profile data, using horizon particle size data and thickness, soil organic matter content estimated empirically from climate data and plant rooting depth and ground coverage obtained from an unpublished vegetation characteristic data set. Values of plant-extractable water range from 10 to 225 mm (Paraná) and 6 to 190 mm (Niger).

Station data

River flow data for tributaries ranging in size from 631 to 71 510 km^2 for the periods with best data coverage 1931–1990 (Paraná, six tributaries) and 1950–1989 (Niger, three tributaries) are used to calibrate and validate the model. Longer duration series are used from the main stem of the Paraná (Posadas, 1901–1992) and the Niger (Koulikoro, 1907–2000) to analyse long-term trends in river flow. All the river flow series have been quality controlled and corrected for the effects of reservoirs in the case of the Paraná and its tributaries (Garcia and Vargas, •1996). Koulikoro is downstream of a junction with a major tributary, the Sankarani River, on which there is a small dam, which mainly affects the regime by maintaining low flows at roughly 200 m^3 s^{-1} and slightly delays the peak flood. The Niger data were collected by IRD (ex-ORSTOM) before the 1960s, and by the National Services since then. The quality of the data have been checked recently during the joint French-Malian EQUANIS research program in Mali, aimed at studying the changes in the hydrological regime and transport of sediment and dissolved solutes by the River Niger.

THE MODEL

The model is fully described in Conway (1997) and uses a soil moisture accounting procedure where rainfall excess over PE is used to fill a soil moisture reservoir, taken as the soil water capacity. When the soil reservoir is full, any remaining excess is added to a linear storage reservoir where a proportion (β) becomes runoff in the current timestep and the remainder is held over into the following timestep. Where rainfall is less than PE, the soil moisture is depleted with an exponential drying function from Vörösmarty *et al.* (1998). A small proportion of rainfall (α) is partitioned directly into the storage reservoir to allow for river flow in those months where PE is greater than rainfall. In its simplest form, the model has just the two parameters α and β, however, for the highly seasonal rainfall regime in the Niger, three different values of α and β were introduced for three conditions of PE and rainfall ($\alpha1$ and $\beta1$ where $P <$ PE; $\alpha2$ and $\beta2$ where $P >$ PE and $P <$ 1·7 PE; and $\alpha3$ and $\beta3$ where $P >$ 1·7 PE). The extra parameter values were introduced to improve the simulation of the seasonal cycle of Niger river flow by the model which tended to underestimate (overestimate) in the dry (wet) season. Runoff and storage are calculated for all contributing whole or partial 0·5 degree grid cells within each catchment. Runoff is then summed to produce an estimate of overall monthly river flow.

RESULTS

Model results

Calibrations were performed over the period 1961–1990 (Paraná) and 1950–1969 (Niger) using performance criteria listed in Tables I and II: the coefficient of efficiency (CE—Nash and Sutcliffe, 1970), greatest weight was given to this in the calibration; percent error between the mean annual observed and modelled river flow (%AN); and correlation between annual observed and modelled river flow (r_{a}). Modelling results are shown

Table I. Paraná, optimised parameter values for calibration period (1961–1990) and performance statistics (see text for explanation of acronyms) during calibration and validation (1931–1960)

	α	β	Cal CE	Cal %AN	Cal r_a	Val CE	Val %AN	Val r_a
Grande	0·15	0·25	0·76	−19	0·86	0·59	−20	0·63
	0·20	*0·40*	*0·48*	*−44*	*0·79*	*0·39*	*−41*	*0·64*
Pardo	0·16	0·25	0·79	−10	0·90	0·64	−9	0·72
	0·24	*0·35*	*0·55*	*−33*	*0·86*	*0·40*	*−32*	*0·75*
Araguari	0·12	0·20	0·82	−7	0·85	0·51	+6	0·28
	0·15	*0·30*	*0·57*	*−38*	*0·84*	*0·34*	*−29*	*0·32*
Jordao	0·18	0·65	0·72	−24	0·97	0·42	0	0·70
	0·30	*0·75*	*0·51*	*−37*	*0·96*	*0·43*	*−20*	*0·74*
Iguazú	0·11	0·50	0·69	−16	0·96	0·73	−14	0·96
	0·30	*0·75*	*0·44*	*−31*	*0·93*	*0·49*	*−24*	*0·91*
Jacui	0·25	0·20	0·68	−9	0·90	0·48	−20	0·71
	0·30	*0·15*	*0·50*	*−22*	*0·88*	*0·42*	*−26*	*0·73*

Results with PE_{TO} on first line and PE_{RC} on second line (italics).

Table II. Niger, optimised parameter values for calibration (1951–1970) and performance statistics (see text for explanation of acronyms) during calibration and validation (1971–1989)

	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\beta 1$	$\beta 2$	$\beta 3$	Cal CE	Cal %AN	Cal r_a	Val CE	Val %AN	Val r_a
Siguiri	0·05	0·02	0·00	0·23	0·33	0·30	0·78	+43	0·75	0·43	+92	0·59
	0·03	*0·00*	*0·00*	*0·53*	*0·60*	*0·41*	*0·94*	*+4*	*0·77*	*0·97*	*+32*	*0·52*
Baro	0·00	0·03	0·03	0·23	0·34	0·32	0·79	+35	0·73	0·52	+68	0·81
	0·06	*0·07*	*0·08*	*0·52*	*0·52*	*0·41*	*0·89*	*−2*	*0·70*	*0·82*	*+16*	*0·74*
Kankan	0·00	0·00	0·01	0·18	0·29	0·29	0·58	+59	0·69	0·51	+78	0·84
	0·00	*0·02*	*0·03*	*0·31*	*0·44*	*0·37*	*0·84*	*+16*	*0·70*	*0·86*	*+24*	*0·83*

Results with PE_{TO} on first line and PE_{RC} on second line (italics).

in Tables I and II for six (Paraná) and three (Niger) tributaries, respectively, for the calibration and validation periods (validation: Paraná 1931–1960; Niger 1970–1989).

The results show differences in model performance between and within the two river systems, with choice of PE function, and across the calibration and validation periods. PE_{TO} results in better performance than PE_{RC} in all six Paraná tributaries, with CEs all above 0·68 and good simulation of interannual variability. Errors in the annual water balance are rather large in nearly all cases, with both PE functions producing runoff underestimates and PE_{RC} producing very large underestimates. For the validation period, model performance is reduced in all cases except for slight improvements in the Iguazú. The tendency to underestimate the annual water balance also occurs, but to a slightly lesser extent, in the validation period. Large errors occur with both PE functions in the Jordao (overestimated) and the Jacui (underestimated). Optimised parameter values vary widely between the tributaries primarily due to differences in seasonal rainfall and PE regimes (not shown). Storage parameter β is low (indicative of higher storage in the model) in the Grande, Pardo, Araguari and Jacui, where rainfall is highly seasonal. Parameter β is higher (low storage) in the Iguazú and Jordao, where rainfall is much less seasonal.

Preliminary results for the Niger contrast markedly with those for the Paraná. With PE_{TO}, there are very large overestimates of river flow in all three tributaries, even with the reasonable CE and correlation between observed and simulated annual runoff. Better agreement is achieved with PE_{RC} because the unrealistically high values offset the runoff overestimates to produce a closer catchment water balance. Over the validation period (1970–1989), there is a decrease in the CE with PE_{TO} (little change with PE_{RC}) and slight improvement in annual correlation in two out of three tributaries. There are marked increases in the runoff overestimates in all cases which are likely to be related to the fluctuation in rainfall and river flow regimes, discussed below, that occurred between the periods used for calibration and validation.

Fluctuation in river flow regimes

Figure 1 shows annual river flow, rainfall and runoff coefficient of the Paraná at Posadas (1901–1990) and the Niger at Koulikoro (1907–2000). A notable shift occurred in the rainfall and discharge regimes of both rivers around the beginning of the 1970s. The fluctuation in rainfall and runoff regimes over the upper basins and tributaries is highlighted in Table III by comparing the periods 1931–1971 with 1972–1990 for the Paraná (1950–1969 with 1970–1989 for the Niger). River flow increased by approximately 28% in the Paraná and decreased by 34% in the Niger between their respective periods. Rainfall fluctuation over the Paraná basin is

DOI: 10.1002/hyp

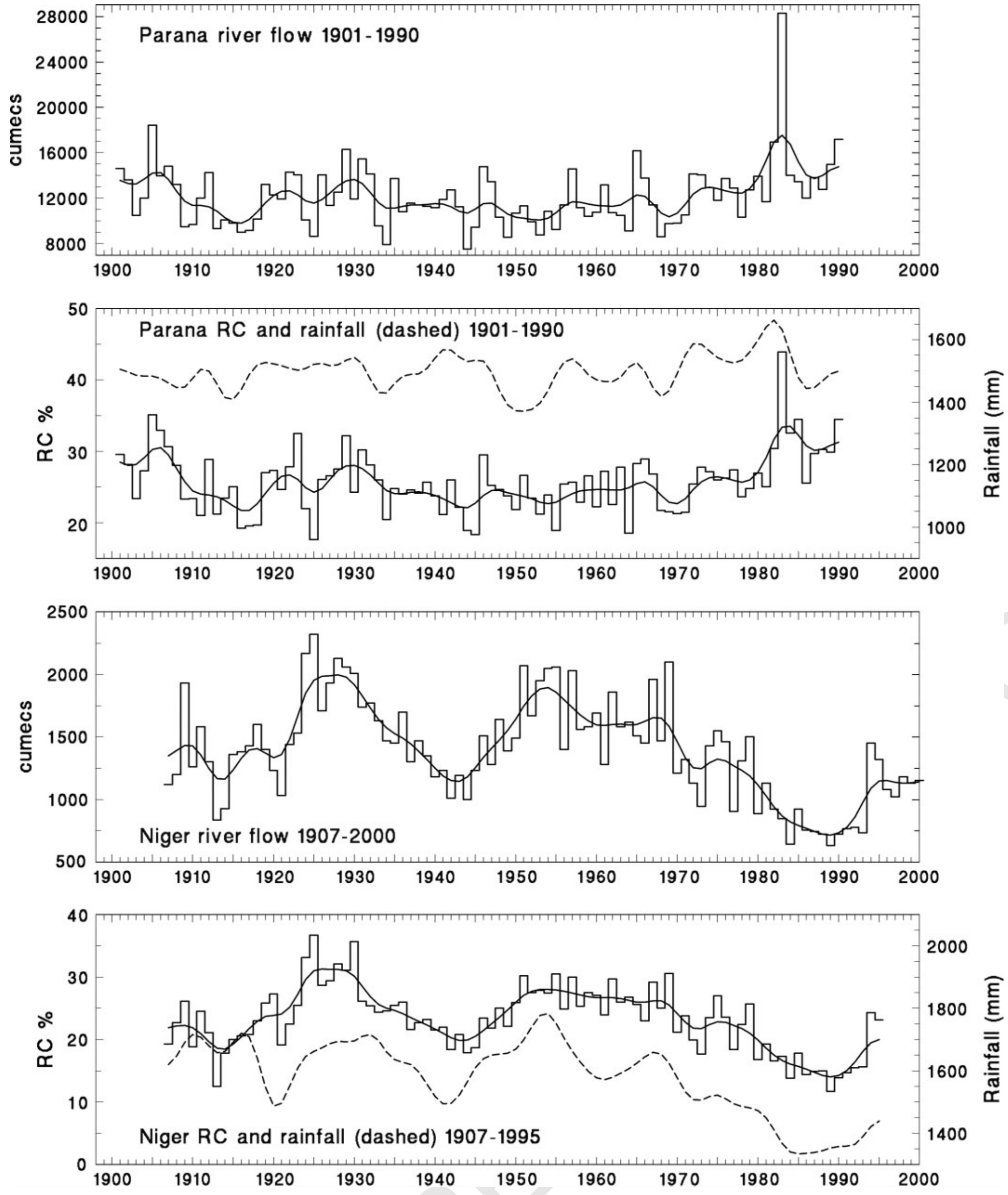

Figure 1. Paraná (at Posadas) and Niger (at Koulikoro): annual and 10-year smoothed river flow (Gaussian filter); 10-year smoothed basin average rainfall (Gaussian filter, dashed line); and annual and 10-year smoothed runoff coefficient (RC in percent)

generally much lower in percentage terms than the decreases over the Niger. The slight decrease in rainfall and substantial increase in runoff over the Jordao is surprising but may be related to errors in the rainfall data set and deserves further study. The tributaries record differences in runoff between the two periods ranging from −39 to +28%, which are much larger in percentage terms than the fluctuations in rainfall, which range from −16 to +10%. This reflects the nonlinear nature of rainfall–runoff processes due to variability in rainfall intensities and catchment surface and subsurface characteristics, variations in PE and antecedent moisture conditions. Figure 1 and Table III show the fluctuations in rainfall and runoff regime are accompanied by fluctuations in the runoff coefficients of some of the tributaries. The regime changes have been documented and analysed in a number of studies and in the case of the Paraná hypothesised to also be associated with changes in land use, namely a large-scale move from perennial to annual cultivation in parts of the basin (Tucci and Clarke, 1998). Given the size and duration of rainfall fluctuation over both basins, particularly the Niger, there is also the possibility that climatically induced changes in land cover may have altered established rainfall–runoff relationships.

Figure 2a and b shows the rainfall–runoff relationship for three separate periods; the recent wet/dry periods in the Paraná/Niger, the preceding years dating back to the beginning of the model calibration period, and the available record prior to the start date used for model calibration. For the Paraná, there is much overlap between all three periods and wide scatter evidenced by low regression results. The extreme rainfall and flow year of 1983 has been removed because of its strong outlier

Table III. Mean annual rainfall (P, mm), river flow (Q, m^3 s^{-1}) and runoff coefficient (RC, %) and percentage change between two periods, 1931–1971 and 1972–1990 for the Paraná and 1950–1969 and 1970–1989 for the Niger

AQ3

	Area●	P	Q	RC	P	Q	RC	P	Q	RC
Paraná			1931–1971			1972–1990			% Change	
Paraná[a]	993 360	1478	11 200	25·5	1554	14 289	30·8	+5·1	+27·6	+20·8
Grande	6280	1427	132	46·5	1508	144	48·0	+5·7	+8·7	+3·2
Pardo	2566	1662	55	40·7	1727	60	42·7	+3·9	+9·6	+4·9
Araguari	15 300	1471	280	39·3	1549	309	41·1	+5·3	+10·3	+4·6
Jordao	4480	1737	108	43·8	1730	138	56·2	−0·4	+27·2	+28·3
Iguazú	29 900	1464	592	42·7	1605	718	47·2	+9·6	+21·3	+10·5
Jacui	631	1457	11	37·8	1596	12	37·6	+9·5	+9·6	−0·5
Niger			1950–1969			1970–1989			% Change	
Niger[b]	120 000	1663	1719	27·2	1436	1048	19·0	−13·7	−39·0	−30·2
Siguiri	67 600	1735	1236	33·3	1464	755	24·1	−15·6	−38·8	−27·6
Baro	12 770	1974	271	33·9	1740	189	26·8	−11·9	−30·3	−20·9
Kankan	9260	1974	211	35·1	1762	160	29·8	−10·7	−24·1	−15·1

[a] The whole upper Paraná from the gauge at Posadas.
[b] the whole upper Niger from the gauge at Koulikoro.

effects which reduces the regression R^2 from 0·57 to 0·27 (Figure 2a), and more than halves the regression line gradient ($y = 15{\cdot}6x - 9968$). The main difference between the wet and preceding periods in the Paraná is the higher runoff during the wet period, averaging around 2000 cumecs more for a given rainfall. For the Niger, there is much less overlap between the dry and the preceding periods, the regression gradient is slightly steeper in the dry period and runoff averages about 200 cumecs higher during the preceding period for a given rainfall. For both rivers, the earliest periods have the weakest relationships, possibly as a result of the reduced number of rain gauges contributing to the basin rainfall series, something which is difficult to check using gridded data products. Thirty-year running correlations between rainfall and runoff (not shown) clearly indicate improving correlation over time from around $r = 0{\cdot}50$ (Paraná) and 0·40 (Niger) in the 1920s, reaching a plateau value in the early 1960s of 0·70 (Paraná) and 0·90 (Niger).

DISCUSSION AND CONCLUSIONS

Both model performance and parameter values are sensitive to the characteristics of input data sets, particularly the method used to estimate PE. These differences have an impact on the simulated water balance in the tributaries and, to a certain extent, can be accounted for in the model calibration process. There is an interesting contrast in the results for both river basins. Using a similar modelling approach and consistent data sets, runoff in the Paraná tributaries is substantially underestimated and runoff in the Niger tributaries overestimated. Although the best model results for the Niger were obtained with a standard reference crop Penman function, this formula produces unrealistically high values in both river basins (particularly over the Niger) and is used here only to highlight an extreme case. The more realistic $\mathrm{PE}_{\mathrm{TO}}$ function produces the best results in all six Paraná tributaries. As it has been found in the United States choice of PE function to close catchment water balances is not clear-cut and affects the results of hydrological models (Vörösmarty *et al.*, 1998).

The large overestimate of runoff in the Niger tributaries may be due to failure to represent additional sources of water loss in the catchments. These may include percolation to deep aquifers, evaporation losses from surface water and an overall underestimate of soil moisture storage. Future work will concentrate on this final possibility by comparing the soil data set used here with other global data sets and locally available information on soils (Mahé *et al.*, 2004). Vörösmarty *et al.* (1991) also needed to adjust PE estimates to compensate for a systematic overestimate of mean annual runoff by almost 200% in the Zambezi river basin. For the FAO's water balance model of Africa (FAO, 2001), correction factors for soil moisture and PE were applied to humid areas to reduce model runoff and applied to dry areas to increase model runoff. They suggest that the need for correction factors in humid areas could be explained by the fact that no vegetation factors were applied to the PE estimates leading to underestimates of actual PE by dense vegetation with high interception and transpiration capacities. Such factors may also apply in the source areas of the upper Niger modelled here.

The observed fluctuations in rainfall and river flow regimes raise a number of interesting questions relating to data quality, split sample approaches to model calibration and validation, the role of land use change and the challenge of modelling future climate change impacts. For rainfall and PE data quality, the period 1961–1990 is likely to be the most accurate (New *et al.*, 2000), however, moving back in time the number of gauges contributing to catchment series will decline substantially and is likely to be very low during the early decades of the century. For many of the tributaries of both rivers, the correlations between observed and simulated annual river flow are quite high, particularly for the tributaries of the Paraná, which suggests the rainfall estimates used here are good in terms of capturing interannual variability, if

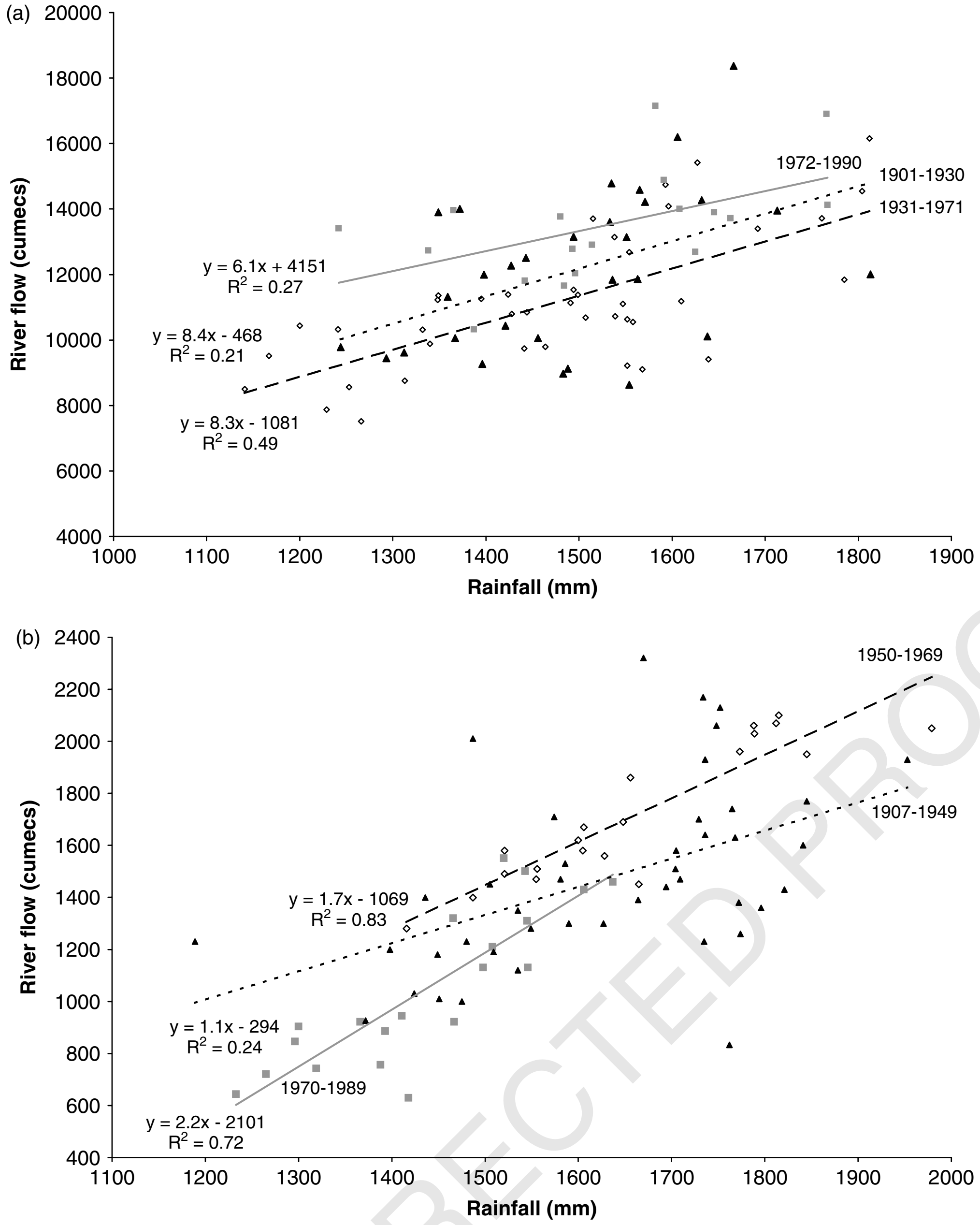

Figure 2. Rainfall–runoff relationships for three separate periods; the recent wet/dry periods in the Paraná/Niger (grey squares), the preceding years dating back to the beginning of the model calibration period (open diamonds), and the available record prior to the start date used for model calibration (filled triangles). (a) Paraná, (b) Niger

not true catchment-wide rainfall depths. The reliability of flow records used here deserves further scrutiny, particularly records for the Paraná and the effects of reservoirs. Here, it has not been possible to update the Paraná records to establish whether conditions have stayed wet or returned to pre-1972 levels. The Niger flows and Sahel rainfall during the 1990s have remained low relative to pre-1971 conditions (L'Hôte *et al.*, 2002).

These regime changes have implications for split sample model calibration and validation procedures. In this example, the validation results are biased because the calibration was performed using a mainly wet period (Paraná) and before the dry period (Niger). The results of this are clearest in the Niger, where simulated runoff volumes increase substantially in the validation period, because the observed change in regime falls very close to the dividing point between the calibration and the validation periods. The impact is less clear for the Paraná because roughly one-third of the calibration period lies before the observed increases in rainfall and runoff (Table III), which are also are smaller and less consistent than in the Niger.

The rainfall and river flow fluctuations in the Sahel are well documented elsewhere; however, to date few studies have examined the contribution of land use and land cover change to changes in runoff during this period. Land cover change has been postulated as a contributory factor in the observed increases in Paraná runoff (Tucci and Clarke, 1998). There is not enough evidence here, however, to unequivocally demonstrate any influence of land cover change on rainfall–runoff relationships in either basin. We emphasize the preliminary nature of this study and further work is necessary to quantify the nature and magnitude of land cover changes, to resolve questions of data reliability and to examine change at a variety of spatial scales (Conway *et al*., submitted).

The nonlinear sensitivity of runoff to rainfall change supports conceptual, empirical and modelling results (e.g. for the case of climate change; Nemec and Schaake, 1982). The recent regime fluctuations in both basins provide excellent potential to study the inter-relationships of rainfall variability and land cover change. In terms of future climate change, both basins can give insights into the hydrological impact of relatively large variations in rainfall, the socio-economic and institutional responses to such change. Modelling these high levels of variability represents a stringent test of any hydrological model's performance and one that is a necessary pre-condition for their application to climate impact studies where even greater changes may be expected to occur.

ACKNOWLEDGEMENTS

This work was supported partly by the European Community INCO Research Programme (contract: ARG/B7-3011/94/25a). The plant-extractable water capacity data were obtained from K.A. Dunne.

REFERENCES

Alley WM. 1984. On the treatment of evapotranspiration, soil moisture accounting and aquifer recharge in monthly water balance models. *Water Resources Research* **20**: 1137–1149.

Bonetto AA, Castello HP, Wais IR. 1987. Stream Regulation in Argentina, including the Superior Paraná and Paraguay Rivers. *Regulated Rivers: Research and Management* **1**: 129–143.

Conway D. 1997. A water balance model of the Upper Blue Nile in Ethiopia. *Hydrological Sciences Journal* **42**: 265–286.

Conway D, Jones PD, Garcia NO, Vargas WM. 1999. Assessing the impacts of future climate change on the water resources and the hydrology of the Rio de la Plata Basin, Argentina. Final Report to the Commission of the European Communities. Norwich: Climatic Research Unit Publication; 300.

Conway D, •Jones PD, Garcia NO. Submitted. Climate variability and change in the Paraná River, Río de la Plata basin, Part II: rainfall-runoff relationships and sensitivity of runoff to climate change. *Journal of Hydrology*. AQ6

Dunne KA, Willmott CJ. 1996. Global distribution of plant-extractable water capacity of soil. *International Journal of Climatology* **16**: 841–859.

FAO. 2001. *Atlas of Water Resources and Irrigation in Africa*. *FAO Digital Land and Water Media Series* 13. Rome: FAO.

Garcia NO, Vargas WM. 1996. The spatial variability of runoff and precipitation in the Rio De La Plata basin. *Hydrological Sciences Journal* **41**: 279–299.

L'Hôte Y, Mahé G, Somé B, Triboulet JP. 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. *Hydrological Sciences Journal* **47**: 563–572.

Mahé G, Paturel JE, Servat E, Conway D, Dezetter A. 2004. Impact of land use change on soil water holding capacity and river modelling of the Nakambe River in Burkina-Faso. *Journal of Hydrology* **300**: 1–4; 33–43.

Nash IE, Sutcliffe JV. 1970. River flow forecasting through conceptual models. Part I: a discussion of principles. *Journal of Hydrology* **10**: 282–290.

Nemec J, Schaake J. 1982. Sensitivity of water resource systems to climate variation. *Hydrological Sciences Journal* **27**: 327–343.

New MG, Hulme M, Jones PD. 1999. Representing 20th century space-time climate variability. I. Development of a 1961–1990 mean monthly terrestrial climatology. *Jouranl of Climate* **12**: 829–856.

New MG, Hulme M, Jones PD. 2000. Representing 20th century space-time climate variability. II. Development of 1901–1996 monthly terrestrial climate fields. *Journal of Climate* **13**: 2217–2238.

Shuttleworth WJ. 1993. Evaporation. In *Handbook of Hydrology*, Maidment RD (ed.). New York: McGraw-Hill; 4·1–4·53.

Thom AS, Oliver HR. 1977. On Penman's equation for estimating regional evaporation. *Quarterly Journal of the Royal Meteorological Society* **103**: 345–357.

Thornthwaite CW, Mather JR. 1955. Instructions and tables for computing potential evapotranspiration and the water balance. In *Publications in Climatology* vol. 10. Centerton, NJ: Laboratory of Climatology, Drexel Institute of Technology; 311.

Tucci CEM, Clarke RT. 1998. Environmental issues in the La Plata basin. *International Journal of Water Resources Development* **14**: 157–174.

Vörösmarty CJ, Moore B, Grace AL, Gildea MP, Melillo JM, Peterson BJ, Rastester EB, Steudler PA. 1989. Continental scale models of water balance and fluvial transport—an application to S. America. *Global Biogeochemical Cycles* **3**: 241–265. AQ7

•Vörösmarty CJ, Moore B, Grace A, Peterson BJ, Rastetter EB, Melillo J. 1991. Distributed parameter models to analyse the impact of human disturbance of the surface hydrology of a large tropical drainage basin in southern Africa. In *Hydrology for the Water Management of large River Basins*, Van de Ven FHM, Gutnecht D, Loucks DP, Salewicz KA (eds). IAHS Pub. No. 201; 233–244.

Vörösmarty CJ, Federer CA, Schloss AL. 1998. Potential evaporation functions compared on US watersheds: possible implications for global-scale water balance and terrestrial ecosystem modelling. *Journal of Hydrology* **207**: 147–169.

Xu CY, Singh VP. 1998. A review on monthly water balance models for water resources investigations. *Water Resources Management* **12**: 31–50.

QUERIES TO BE ANSWERED BY AUTHOR

IMPORTANT NOTE: Please mark your corrections and answers to these queries directly onto the proof at the relevant place. Do NOT mark your corrections on this query sheet.

Queries from the Copyeditor:

AQ1 Please provide received date for this article

AQ2 We have provided the short title "RIVER FLOW MODELLING: PARANÁ AND NIGER" for the running head for this article. Please clarify whether it is appropriate.

AQ3 Please provide the unit for the column "Area".

AQ4 Please check the value 20–30 000

AQ5 We have changed Garcia and Vargas (1997) to Garcia and Vargas (1996) to match the reference list. Please check.

AQ6 Please provide year and DOI if volume, issue and page numbers are not yet available

AQ7 Please provide the publisher's names for this reference. Please provide the place of publication for this reference.

WILEY

WILEY AUTHOR DISCOUNT CLUB

We would like to show our appreciation to you, a highly valued contributor to Wiley's publications, by offering a **unique 25% discount** off the published price of any of our books*.

All you need to do is apply for the **Wiley Author Discount Card** by completing the attached form and returning it to us at the following address:

The Database Group (Author Club)
John Wiley & Sons Ltd
The Atrium
Southern Gate
Chichester
PO19 8SQ
UK

Alternatively, you can **register online** at www.wileyeurope.com/go/authordiscount
Please pass on details of this offer to any co-authors or fellow contributors.

After registering you will receive your Wiley Author Discount Card with a special promotion code, which you will need to quote whenever you order books direct from us.

The quickest way to order your books from us is via our European website at:

http://www.wileyeurope.com

Key benefits to using the site and ordering online include:

- Real-time SECURE on-line ordering
- Easy catalogue browsing
- Dedicated Author resource centre
- Opportunity to sign up for subject-orientated e-mail alerts

Alternatively, you can order direct through Customer Services at:
cs-books@wiley.co.uk, or call +44 (0)1243 843294, fax +44 (0)1243 843303

So take advantage of this great offer and return your completed form today.

Yours sincerely,

Verity Leaver
Group Marketing Manager
author@wiley.co.uk

*TERMS AND CONDITIONS

This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There must be no resale through any channel. The offer is subject to stock availability and cannot be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to amend the terms of the offer at any time.

REGISTRATION FORM
For Wiley Author Club Discount Card

To enjoy your 25% discount, tell us your areas of interest and you will receive relevant catalogues or leaflets from which to select your books. Please indicate your specific subject areas below.

Accounting [ ]
- Public [ ]
- Corporate [ ]

Chemistry [ ]
- Analytical [ ]
- Industrial/Safety [ ]
- Organic [ ]
- Inorganic [ ]
- Polymer [ ]
- Spectroscopy [ ]

Encyclopedia/Reference [ ]
- Business/Finance [ ]
- Life Sciences [ ]
- Medical Sciences [ ]
- Physical Sciences [ ]
- Technology [ ]

Earth & Environmental Science [ ]

Hospitality [ ]

Genetics [ ]
- Bioinformatics/Computational Biology [ ]
- Proteomics [ ]
- Genomics [ ]
- Gene Mapping [ ]
- Clinical Genetics [ ]

Medical Science [ ]
- Cardiovascular [ ]
- Diabetes [ ]
- Endocrinology [ ]
- Imaging [ ]
- Obstetrics/Gynaecology [ ]
- Oncology [ ]
- Pharmacology [ ]
- Psychiatry [ ]

Non-Profit [ ]

Architecture [ ]

Business/Management [ ]

Computer Science [ ]
- Database/Data Warehouse [ ]
- Internet Business [ ]
- Networking [ ]
- Programming/Software Development [ ]
- Object Technology [ ]

Engineering [ ]
- Civil [ ]
- Communications Technology [ ]
- Electronic [ ]
- Environmental [ ]
- Industrial [ ]
- Mechanical [ ]

Finance/Investing [ ]
- Economics [ ]
- Institutional [ ]
- Personal Finance [ ]

Life Science [ ]

Landscape Architecture [ ]

Mathematics [ ]
Statistics [ ]

Manufacturing [ ]

Materials Science [ ]

Psychology [ ]
- Clinical [ ]
- Forensic [ ]
- Social & Personality [ ]
- Health & Sport [ ]
- Cognitive [ ]
- Organizational [ ]
- Developmental & Special Ed [ ]
- Child Welfare [ ]
- Self-Help [ ]

Physics/Physical Science [ ]

Please complete the next page /

I confirm that I am (*delete where not applicable):

a **Wiley** Book Author/Editor/Contributor* of the following book(s):
ISBN:
ISBN:

a **Wiley** Journal Editor/Contributor/Editorial Board Member* of the following journal(s):

SIGNATURE: ………………………………………………………………………… Date: ……………………………………

PLEASE COMPLETE THE FOLLOWING DETAILS IN BLOCK CAPITALS:

TITLE: (e.g. Mr, Mrs, Dr) …………………… FULL NAME: ……………………………………………………………………………

JOB TITLE (or Occupation): ………………………………………………………………………………………………

DEPARTMENT: ……

COMPANY/INSTITUTION: ……………………………………………………………………………………………………

ADDRESS: ……

……

TOWN/CITY: ………

COUNTY/STATE: ………

COUNTRY: ……

POSTCODE/ZIP CODE: ………………………………………………………………………………………………………

DAYTIME TEL: ……

FAX: ………

E-MAIL: ………

YOUR PERSONAL DATA
We, John Wiley & Sons Ltd, will use the information you have provided to fulfil your request. In addition, we would like to:

1. Use your information to keep you informed by post of titles and offers of interest to you and available from us or other Wiley Group companies worldwide, and may supply your details to members of the Wiley Group for this purpose.
   [ ] Please tick the box if you do **NOT** wish to receive this information

2. Share your information with other carefully selected companies so that they may contact you by post with details of titles and offers that may be of interest to you.
   [ ] Please tick the box if you do **NOT** wish to receive this information.

E-MAIL ALERTING SERVICE
We also offer an alerting service to our author base via e-mail, with regular special offers and competitions. If you **DO** wish to receive these, please opt in by ticking the box [ ].

If, at any time, you wish to stop receiving information, please contact the Database Group (databasegroup@wiley.co.uk) at John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK.

TERMS & CONDITIONS
This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There should be no resale through any channel. The offer is subject to stock availability and may not be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to vary the terms of the offer at any time.

PLEASE RETURN THIS FORM TO:
Database Group (Author Club), John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK author@wiley.co.uk
Fax: +44 (0)1243 770154