Hydrology of the Mediterranean and Semiarid Regions (Proceedings of an international symposium held at Montpellier, April 2003). IAHS Publ. no. 278, 2003.

Applications of remote sensing and GIS for groundwater modelling of large semiarid areas: example of the Lake Chad Basin, Africa

MARC LEBLANC[1], CHRISTIAN LEDUC[2], MOUMTAZ RAZACK[3], JACQUES LEMOALLE[2], DOMINIQUE DAGORNE[4] & LINUS MOFOR[5]

1 *School of Ecology and Environment, Deakin University, Warrnambool 3280, Victoria, Australia* marcl@deakin.edu.au

2 *IRD, Maison des Sciences de l'Eau, Montpellier, France*

3 *Laboratoire d'Hydrogéologie, University of Poitiers, France*

4 *IRD, Brest, France*

5 *School of Technology, Civil Engineering, University of Glamorgan, UK*

Abstract Because of its large extent and the extremes of its climatic and environmental conditions, the Lake Chad Basin is an example of a region where it is extremely difficult to collect hydro(geo)logical field observations. So far, the scale and the scope to which remote sensing and GIS can assist groundwater modelling in such regions has not been fully exploited. We detail applications of remote sensing and GIS to improve groundwater modelling of the large superficial Quaternary aquifer, which covers 500 000 km^2 and forms the main water resource of the basin. Satellite imagery and GIS enabled us to refine the location of recharge and discharge areas. In a GIS framework, relevant maps and pertinent satellite images were analysed together with hydrogeological data. The rationale was to search and map key characteristics in the terrain that indicate groundwater discharge and recharge areas. In addition, maps and low cost satellite data, such as AVHRR and Meteosat, were used for a thorough mapping of the fluctuations of Lake Chad extent over the last three decades. Using GIS, this valuable information was implemented in a transient groundwater model, with the MODFLOW program. The model calibration was greatly improved by the use of remote sensing data.

Key words GIS; groundwater modelling; Lake Chad Basin; large superficial aquifer; Quaternary aquifer; remote sensing; semiarid

INTRODUCTION

The Lake Chad Basin covers about 2 500 000 km^2 in Africa (Fig. 1) and is the largest endorheic basin in the world (Herdendorf, 1982). Our research focuses on its central part. The climate of this region is semiarid to arid with a rainy season from May to September and a dry period the rest of the year. The topography is very flat and the distribution of the climate follows a south–north gradient. During the period 1951–1989, the average rainfall at 10°N was 800 mm year^{-1}, but only 100 mm year^{-1} at 15°N (L'Hôte & Mahé, 1995). The central part of the Lake Chad Basin is occupied by the large fresh water Lake Chad, fed by two perennial rivers (the Chari and the Logone) and an ephemeral one (the Komadugu Yobe). Yet, in the central part of the Lake Chad Basin, the main water resource available for the population is the Quaternary aquifer; a

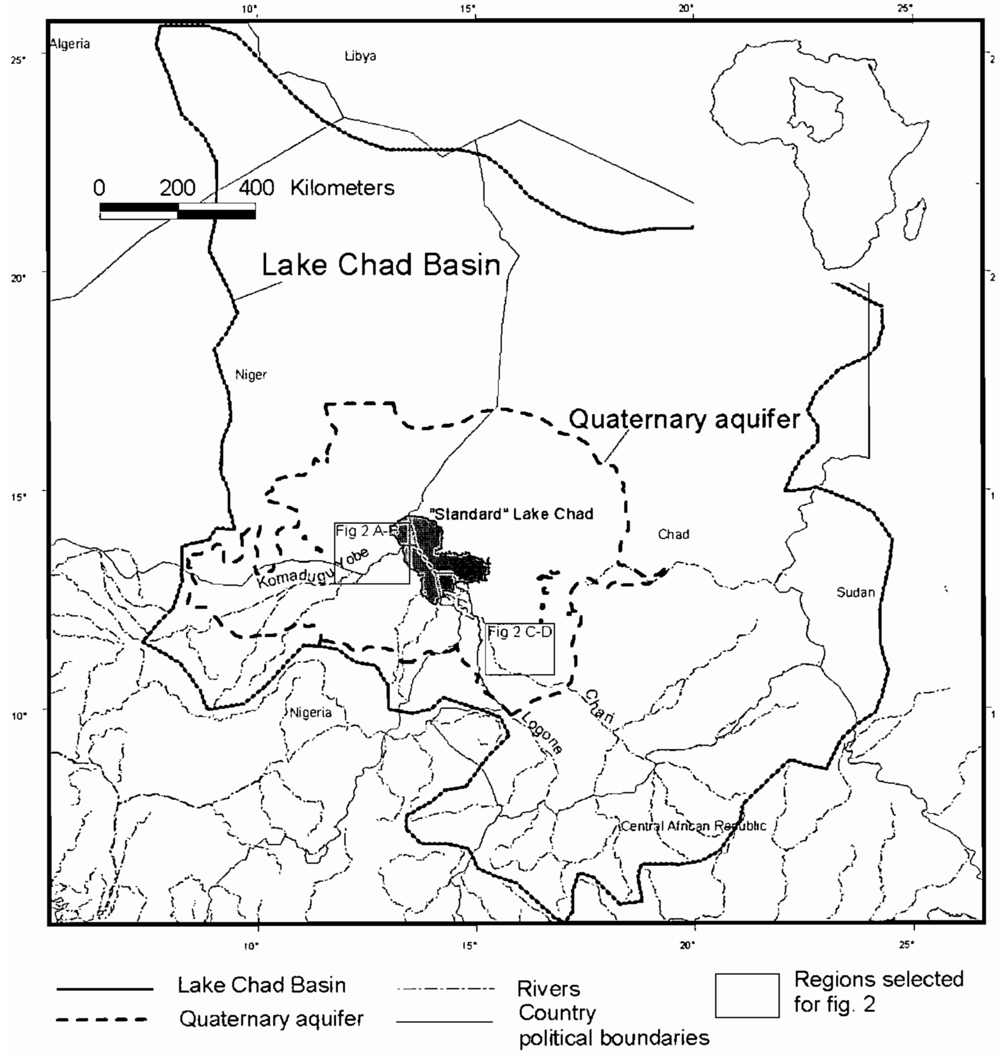

Fig. 1 Location of the Lake Chad Basin and the Quarternary aquifer.

continuous phreatic water table contained in fluvio-lacustrine and aeolian deposits and isolated from the underlying aquifers by a thick layer of Pliocene clay (Carter *et al.*, 1963; FAO-Schroeter & Gear, 1973; Schneider & Wolff, 1992; UNESCO-PNUD-CBLT, 1972). This extensive reserve covering 500 000 km^2 offers a relatively easy and permanent access to water.

The scale of the Quaternary aquifer and the lack of infrastructure are major challenges for data collection, analysis and management. For such a large area, satellite imagery is an appropriate way to acquire up-to-date data with good spatial and/or temporal resolution. New applications of GIS and remote sensing are, therefore, investigated to support a detailed groundwater model of the whole of the Quaternary aquifer. The first section of this paper examines applications for mapping recharge and discharge areas and recalls the importance of such information for precise groundwater modelling. The second section gives details of the long-term fluctuations of Lake Chad's surface area, thanks to satellite imagery and GIS.

REFINING THE LOCATION OF RECHARGE AND DISCHARGE AREAS

The first challenge is the definition, in place and intensity, of the recharge/discharge of the Quaternary aquifer. Previous authors have given significantly different estimates, and no maps have been published except of some groundwater modelling studies in consulting reports (Bonnet & Meurville, 1995; Eberschweiler, 1993).

A first calibration of a steady-state groundwater model of the Quaternary aquifer was conducted without using remote sensing and GIS. Various scenarios of recharge and discharge were tested within the range of the values found in the literature (Leblanc, 2002). At this stage, the groundwater model gave a rough estimate of where discharge and recharge areas are needed and of their values, but it was unable to show precisely the location of the boundaries of these recharge and discharge areas.

Although they have not often been applied to map recharge and discharge areas in semiarid regions, GIS and remote sensing can be used for this purpose (Leblanc, 2002). Maps and satellite images were integrated in a GIS to locate pertinent characteristics or features in the terrain that reveal or influence recharge and discharge processes. For example, over the Quaternary aquifer, regions of low infiltrability were mapped using information on soil moisture at the end of the rainy season from satellite images and maps of soil types. Indexes of vegetation activity from satellite data reveal regions of active vegetation during the dry season and thus presumably discharge areas. In semiarid environments, ponding occurs in topographical depressions and small ephemeral channels (wadis) where rainfall water concentrates after runoff, and has been found to engender a higher recharge rate (localized recharge) of the aquifer (Favreau, 2000; Leduc *et al.*, 1996, 2001; Lerner *et al.*, 1990; Simmers & Hendrickx, 1997). Across the Quaternary aquifer, satellite data with a good spatial resolution were employed to map regions of dense ponding at the end of the rainy season. Regions where the water table is shallow are favourable to strong evapotranspiration processes and may correspond to discharge areas. For the whole of the Quaternary aquifer, a new map of the depth to the water table was created in a GIS.

Applying this methodology for two selected regions of the Quaternary aquifer, Fig. 2 shows how recharge and discharge areas were defined in the groundwater model before (Fig. 2 (a),(c)) and after (Fig. 2(b),(d)) using remote sensing and GIS. To the northwest of Lake Chad (Fig. 2(a),(b)) the very flat topography, the low permeability of the ground and the absence of ponding indicate that a discharge area (where evapotranspiration dominates vertical exchanges over rainfall recharge) extends to the limit of the Kadzell region and its border with the Manga dunefield. This is also backed up with the study of the soil moisture thanks to Meteosat thermal data. In the region of Massenya (Fig. 2(c),(d)), the extent of a large recharge zone is defined by a zone of dense ponding and high variation of the local topography. By progressing in this manner and testing the observations in parallel with the groundwater model, a detailed map of recharge and discharge area for the whole Quaternary aquifer has been obtained.

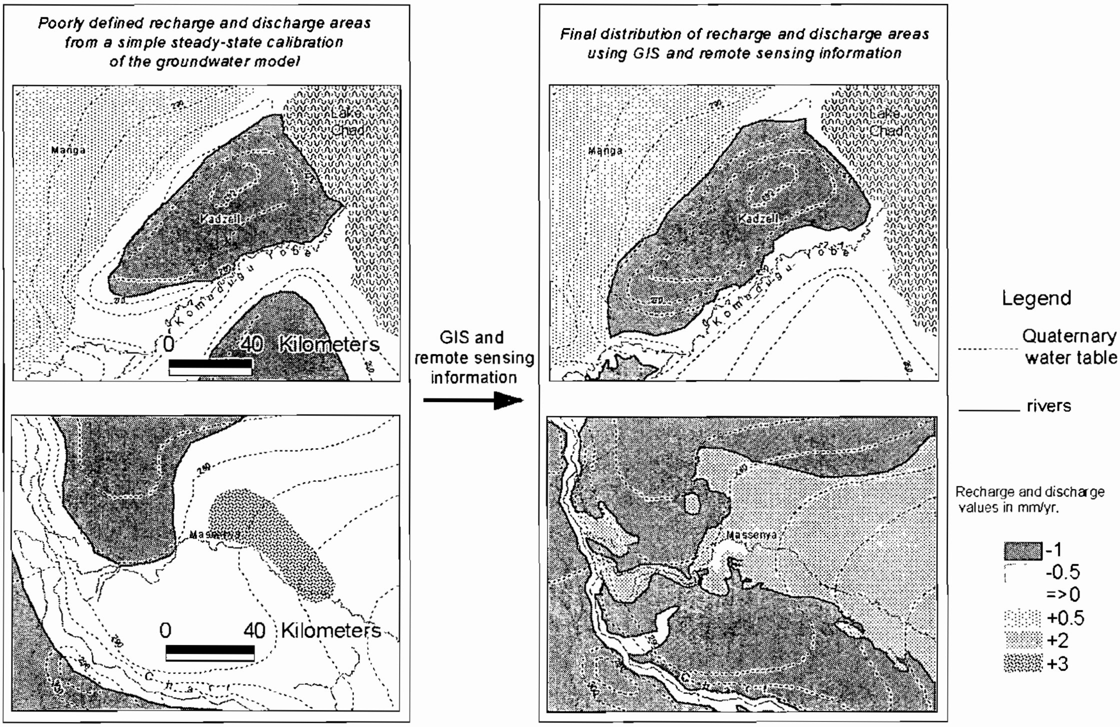

Fig. 2 Examples of the mapping of recharge and discharge areas before (a), (c), and after (b), (d), using remote sensing and GIS information. The locations of the two selected regions: Kadzell/Manga and Chari-Baguirmi are shown in Fig. 1.

RETRACING THE LONG-TERM FLUCTUATIONS OF LAKE CHAD

A "standard" Lake Chad is about 25 000 km^2 but it has considerably changed since the 1970s (Olivry *et al.*, 1996). The Quaternary aquifer is interconnected with Lake Chad and a large part of what used to be a recharge area to the aquifer is now subject to evaporation. We retraced the fluctuations of the extent of Lake Chad between 1960 and 2001 to implement this information in the transient groundwater model, and assess the impact of Lake Chad shrinkage on the aquifer. This represents a major challenge given the vastness of the area, the complexity of the processes, the rapidity with which changes occur, and finally the need to retrace the evolution over a long period (40 years). Such requirements can only be met with the use of information from multiple sources.

Some published maps were available for certain limited periods. The international map of the world 1:1 000 000 N'Djamena ND-33 (published in 1969) was considered representative of Lake Chad extent in the 1960s and early 1970s, as one can assume that variations of the surface area during this period were relatively small. The period between June 1973 and October 1977 was studied by Lemoalle (1979) using Landsat MSS data and aeroplane surveys. This work was updated with the use of Meteosat data and led to the publication of the extent of Lake Chad northern pool in January ("maximum annual extent") from 1973 to 1990 (Lemoalle, 1991).

Archive satellite images complement these published maps with a comprehensive monitoring of the Lake from 1986 to date. We chose AVHRR/LAC and Meteosat thermal images (1 and 5 km spatial resolution respectively) because of their high temporal resolution and availability over a long period. For many periods AVHRR/LAC were not available or affected by clouds. They were supplemented with Meteosat Tmax 30-day thermal composite data, obtained from IRD-CMS, Lannion, France. Meteosat Tmax composite data were archived from 1986 to 2001. They are obtained by first processing the Maximum Value Composite (MVC) of all the brightness temperatures obtained in one day with the sensor's infrared channel. A 30-day composite image is later processed as the mean of the MVC obtained over six spans of five days. The method has the advantage of suppressing the clouds, whilst maintaining a relatively good memory of surface events (Guillot & Lahuec, 1994).

Since its shrinkage, dense mats of floating vegetation have invaded large parts of the remaining Lake Chad. The difficulty of mapping open water as well as water under aquatic vegetation is overcome by using thermal AVHRR and Meteosat data. The rationale of the methodology is that, in such an environment, both open water and water covered with aquatic vegetation have a higher thermal inertia than the surrounding bare dry land and non-aquatic vegetation (see also Rosema, 1990; Travaglia, 1995). That is, they warm-up less during the day. This robust method is illustrated in Fig. 3. An AVHRR/LAC near infrared image only detects the open water (see Fig. 3(a)), but the AVHRR NDVI (Fig. 3(b)) shows that the vegetation around this open water is very active. In fact, at that time of the dry season such active vegetation can only be sustained by the water of the Lake. This is aquatic vegetation. The thermal images (Fig. 3(c), (d)) detect both the open water and the aquatic. Note the similarity of the water area detected by thermal AVHRR data and Meteosat Tmax.

Using this approach, frequent records of the Lake extent were acquired to coincide with the groundwater model time step and the rapid fluctuations of Lake Chad. 136 maps showing the extent of Lake Chad from 1960 to 2001 were generated. They provide detailed inputs for the transient groundwater model. This information was stored in a GIS and pre-processed as input for the groundwater model. Where surface water from the Lake occurred (both open water and water under aquatic vegetation), flow exchanges between Lake Chad and the aquifer took place and were represented using the MODFLOW96 River Package. Wherever the Lake dried up these exchanges stopped and evaporation processes were applied to the aquifer.

DISCUSSION

The calibration of the groundwater model with remote sensing and GIS improves our knowledge of the location and intensity of recharge and discharge processes. For example, this study reveals that discharge areas may cover up to 30% of the Quaternary aquifer. This highlights the endorheism of the system with a significant part of the outflows being assured internally.

Meteosat Tmax has proved to be an excellent tool for monitoring the Lake extent. For some years, the detection of Lake Chad's surface area was impossible during the rainy season because of the persistence of clouds. Apart from this, the reconstitution is thorough, with a time step of one month from 1986. To obtain detailed inputs for the

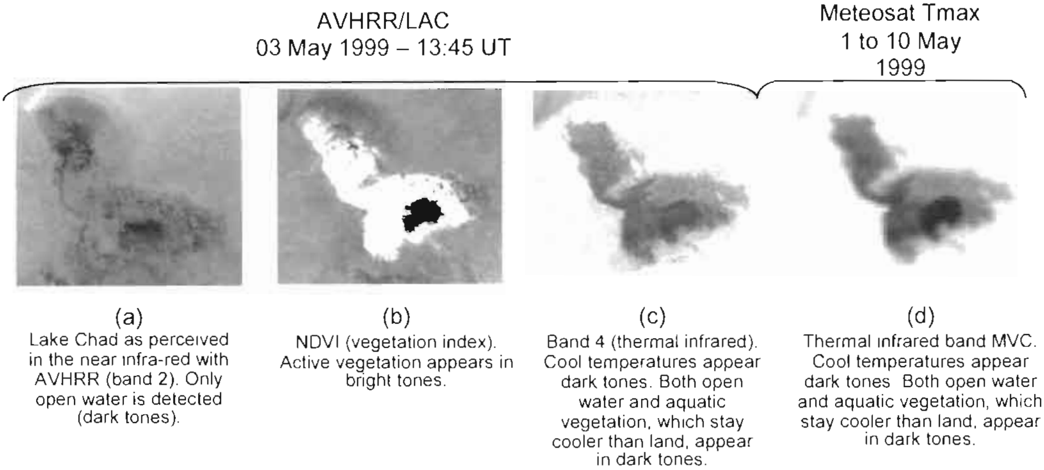

Fig. 3 Thermal inertia of Lake Chad waters.

groundwater model was important because of: (a) the high spatio-temporal variability of Lake Chad; and (b) the fact that not only a recharge area disappears with Lake Chad but a discharge area (evaporation) is created, which amplifies the effect on the water table. The application of the transient groundwater model reveals that the impact of Lake Chad's shrinkage on the water table is strong, but limited in space to a relatively small area around the north pool and the south-eastern and south-western extremities of the Lake. Satellite images show a recent improvement of the hydroclimatic situation with, for example, the north pool being flooded all year long in 1999.

The technology applied in this study is not new, but it is the scale and the scope with which remote sensing and GIS were used to enhance the groundwater modelling which is something that has not often been exploited. Now is an appropriate time for hydrologists and hydrogeologists working in semiarid regions to reconsider the use of satellite data because of the increase in hardware and software capacity, the launch of new sensors and the willingness of satellite operators to offer readily accessible data.

Acknowledgements The authors show gratitude to the Universities of Glamorgan (UK) and Poitiers (France) who funded this research. We wish to thank the NOAA Satellite Active Archive system for AVHRR/LAC data and the CMS and the IRD (Lannion, France) for Meteosat Tmax data. We are grateful to the Lake Chad Basin Commission and the DHA (Department for Hydraulics and Water Treatment) in Chad and the DDH (Department of Hydraulics) of Diffa in Niger for their support.

REFERENCES

Bonnet, M. & Meurville, C. (1995) Mise en place d'un système de suivi et de gestion de la nappe phréatique du Chari-Baguirmi. Direction de l'Hydraulique et de l'Assainissement. N'Djamena, Tchad.

Carter, J. D., Barber, W., Tait, E. A. & Jones, D. G. (1963) The geology of parts of Adamawa, Bauchi and Borno Provinces in NE Nigeria. *Nigeria Geological Survey Bulletin*.

Eberschweiler, C. (1993) Monitoring and management of groundwater resources in the Lake Chad Basin: mapping of aquifers water resource management. Final report. R 35 985, CBLT - BRGM, Orléans, France.

FAO, Schroeter, P. & Gear, D. (1973) Etude des ressources en eau du bassin du lac Tchad en vue d'un programme de développement. FAO-PNUD-CBLT, Rome, Italie.

Favreau, G. (2000) Caractérisation et modélisation d'une nappe phréatique en hausse au Sahel: dynamique et géochimie de la dépression piézometrique naturelle du Kori de Dantiandrou (sud-ouest du Niger). Thèse de Doctorat. Université de Paris XI, Orsay, France.

Herdendorf, C. E. (1982) Large lakes of the world. *J. Great Lakes Research* **8**, 379-412.

Lahuec, J.-P. & Guillot, B. (1994) Satellite monitoring of the climate, climatic monitoring atlas: 1986–1994 (Africa and the intertropical Atlantic). ORSTOM, Météo-France, Ministère de la coopération. IRD Editions.

Leblanc, M. (2002) The use of remote sensing and GIS for water resources management in large semi-arid basins. Case study of the Lake Chad Basin, Africa. PhD thesis, University of Glamorgan, UK, and University of Poitiers, France.

Leduc, C., Taupin, J. D. & Le Gal La Salle, C. (1996) Estimation de la recharge de la nappe phréatique du Continental Terminal (Niamey, Niger) à partir des teneurs en tritium. *C. R. Acad. Sci. Paris* **323**, 599–605.

Leduc, C., Favreau, G. & Schroeter, P. (2001) Long-term rise in a Sahelian water-table: the Continental Terminal in south-west Niger. *J. Hydrol.* **243**, 43–54.

Lemoalle, J. (1979) Etude des potentialités du bassin du lac Tchad. Hydrologie: Utilisation de la télédétection pour l'évaluation des surfaces inondées. ORSTOM, Paris.

Lemoalle, J. (1991) Eléments d'hydrologie du lac Tchad au cours d'une période de sécheresse (1973–1989) In: *Rapport sur les pêches. no. 445.* Food and Agriculture Organization (FAO). Rome, Italy.

Lerner, D. N., Issar, A. S. & Simmers, I. (1990) *Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge.* International Association of Hydrogeologists. Verlag Heinz Heise.

L'Hôte, Y. & Mahé, G. (1995) Carte des précipitations moyennes annuelles en Afrique de l'Ouest et Centrale (période 1951–1989). IRD Editions.

Olivry, J. C., Chouret, A., Vuillaume, G., Lemoalle, J. & Briquet, J. P. (1996) Hydrologie du lac Tchad. ORSTOM, IRD, Paris, France.

Rosema, A. & Fiselier, J. (1990) Meteosat-based evaporation and thermal inertia mapping for monitoring transgression in the Lake Chad region and Niger delta. *Int. J. Remote Sens.* **11**, 741–752.

Schneider, J. L. & Wolff, J. P. (1992) *Carte géologique et carte hydrogéologique au 1/1 500 000 de la République du Tchad, mémoire explicatif.* BRGM, Orleans, France.

Simmers, I. & Hendrickx, (1997) *Recharge of Phreatic Aquifers in (Semi-) Arid Areas.* A. A. Balkema, Rotterdam, The Netherlands.

Travaglia, C., Kapetsky, J. & Righini, G. (1995) Monitoring wetlands for fisheries by NOAA AVHRR LAC thermal data. *RSC Series no. 68.* FAO, Rome, Italy.

UNESCO-PNUD-CBLT (1972) Study of water resources in the Lake Chad Basin 1966-1970. UNESCO, Paris, France.

IAHS Publication no. 278
ISSN 0144-7815

Hydrology of Mediterranean and Semiarid Regions

Edited by

Eric Servat, Wajdi Najem, Christian Leduc & Ahmed Shakeel

Hydrology of Mediterranean and Semiarid Regions

Edited by

ERIC SERVAT
IRD, UMR HydroSciences Montpellier (CNRS, UM2, IRD, UM1), Maison des Sciences de l'Eau, BP 64501, F-34394 Montpellier Cedex 5, France

WAJDI NAJEM
ESIB, Faculté d'Ingénierie de l'Université Saint-Joseph, BP 1514, Beyrouth, Liban

CHRISTIAN LEDUC
IRD, UMR HydroSciences Montpellier (CNRS, UM2, IRD, UM1), Maison des Sciences de l'Eau, BP 64501, F-34394 Montpellier Cedex 5, France

AHMED SHAKEEL
Indo-French Centre for Groundwater Research, National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India

Papers selected for the international conference on:
Hydrology of the Mediterranean and Semi-Arid Regions
held in Montpellier, France, from 1 to 4 April 2003.

This conference was jointly convened by:
UNESCO (United Nations Educational and Cultural Organization)
IAHS (International Association of Hydrological Sciences)
WMO (World Meteorological Organization)
FRIEND AMHY (Flow Regimes from International Experimental and Network Data, Alpine and Mediterranean Region)
IFR ILEE (Institut Fédératif de Recherche, Institut Languedocien de Recherche sur l'Eau et l'Environnement)

IAHS Publication no. 278
in the IAHS Series of Proceedings and Reports

Published by the International Association of Hydrological Sciences 2003
IAHS Press, Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK
IAHS Publication no. 278
ISBN 1-901502-12-0

British Library Cataloguing-in-Publication Data.
A catalogue record for this book is available from the British Library.

The papers included in this volume have been peer reviewed and some were extensively revised before publication.

IAHS is indebted to the employers of the Editors for the invaluable support and services provided that enabled them to carry out their task effectively and efficiently.

The papers were checked, formatted and assembled by Cate Gardner and Penny Farnell at IAHS Press, Wallingford, UK.

Publications in the series of Proceedings and Reports are available *only* from:
IAHS Press, Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, UK
tel.: +44 1491 692442; fax: +44 1491 692448; e-mail: jilly@iahs.demon.co.uk

Printed in The Netherlands by Krips BV, Meppel.