Groundwater & Climate in Africa

an international conference

Kampala, Uganda

24 to 28 June 2008

conference programme & book of abstracts

edited by Richard Taylor & Callist Tindimugaya

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MINISTRY OF WATER AND ENVIRONMENT
P. O. BOX 20026
KAMPALA, UGANDA

The Republic of Uganda

June 2008

Dear *Groundwater & Climate in Africa* participants,

Welcome to Kampala!

We are delighted that you are able to participate in this unique event. The conference is one of the first conferences in the world to focus on the twin impacts of climate change and development on groundwater resources and groundwater-based ecosystems. As such, the conference firmly addresses one of the most persistent knowledge gaps recognised by the Inter-governmental Panel on Climate Change (IPCC) in both its 3rd (2001) and 4th (2007) Assessment Reports: "*further research on the impacts of climate variability and change on groundwater is needed*."

Approximately half of Africa's nearly one billion inhabitants rely upon groundwater for their daily water supply. Future adaptations in response to climate change and population growth in Africa will intensify dependence upon groundwater resources to meet domestic, agricultural, and industrial water demands. This dependence will also place considerable strain upon groundwater-based ecosystems and the services they deliver.

It is in response to this urgent need to improve our critically limited knowledge of how groundwater resources are affected by climate change and development in Africa that the *Groundwater & Climate in Africa* conference arose. The conference organisers, University College London, UNESCO and Ministry of Water and Environment together with relevant organisations, development partners and conference organising and scientific committees are to be congratulated for putting together a well structured programme that features 58 presentations from around the African continent and 34 presentations from the rest of the world.

Considerable effort has been made to bring new voices and the latest technical and policy-related research to this conference. With over 20 hours of dedicated discussion time culminating in a series of roundtable discussions, the conference represents a rare and exciting opportunity to translate current scientific and policy-related research into concrete technical and policy recommendations for national governments in Africa, regional, basin-wide and transboundary organisations as well as international fora and agenda (*e.g.,* AU Summit 2008, 5th World Water Forum 2009). The conference also represents a historic occasion for groundwater and climate scientists, managers and policy makers in Africa and their partners abroad to forge strategic new relationships upon which an improved capacity to understand and manage the impacts of climate change and development on groundwater resources may be developed in the near future.

The Ministry of Water and Environment in Uganda is proud to be a host and co-organiser of the *Groundwater & Climate in Africa conference*. I wish you a very successful and fruitful conference.

Have a nice stay in Uganda.

Maria Mutagamba,
Minister of Water & Environment
Republic of Uganda

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CONFERENCE RATIONALE

Current monitoring and assessments of the impacts of climate variability and change on water resources commonly exclude groundwater. This omission is of particular concern in Africa where current usage and future adaptations in response to climate change and rapid population growth, place considerable reliance upon groundwater to meet domestic, agricultural, and industrial water demands. The *Groundwater & Climate in Africa* conference brings together water and climate scientists from research/academic institutions, government departments, and private sector as well as policy makers and representatives from international agencies, donors and consortia in order to share knowledge and expertise, and thereby improve current understanding of the impact of climate and development on groundwater resources in Africa.

CONFERENCE STRUCTURE

The conference begins with a plenary sessions of opening addresses and keynote presentations that sets the agenda and structure of the conference. Subsequent oral and poster presentations will occur in sessions that contribute to each of the conference's 6 scientific themes. In each session, considerable time is dedicated to open discussion of the technical and policy-related issues that arise from oral and poster presentations. Session chairs and rapporteurs will include experts in both technical and policy issues to distil minuted discussions. To aid in this process, each presenter will be asked to submit, where possible, two key policy and scientific recommendations emanating from their presentation. A synthesis of the technical and policy-related issues raised in each session will be presented on the final day of the conference in advance of two plenary roundtable discussions during which key technical and policy-related recommendations will be debated and adopted. To facilitate this process, roundtable discussions will feature panels of senior water and climate scientists, policy makers, parliamentarians and other stakeholders. Technical recommendations will be published in the conference proceedings, forwarded to key scientific programmes (*e.g.* IPCC AR5, GEWEX, GWSP, GRAPHIC) and distributed widely via popular press (*e.g.* World of Science, EOS) and conference webpage (www.gwclim.org). Recommendations that assist the formulation of national and international policies related to groundwater and climate will be distributed for consideration by national governments via AMCOW (African Ministerial Committee on Water), regional bodies (*e.g.* SADC, ECOWAS) and international fora (*e.g.* AU Summit 2008, 5th WWF in Istanbul 2009, Copenhagen 2009). Finally, the conference will feature three side events that include: (i) building networks of groundwater and climate scientists in Africa, (ii) an invitation for African experts to join a global network of scientists in the UNESCO GRAPHIC Programme, and (iii) a workshop on groundwater monitoring and data management.

The conference will end with a field trip to Jinja, the source of the River Nile, which will include tours of HEP facilities and monitoring stations assessing interactions between groundwater and surface water.

Groundwater & Climate in Africa Conference - Programme Summary

		Day 1	Day 2	Day 3	Day 4		
	Monday 23 Jun	Tuesday 24 Jun	Wednesday 25 Jun	Thursday 26 Jun	Friday 27 Jun	Sat. 28 Jun	Sun. 29 Jun
08:00 - 09:00	arrival of delegates, registration	registration				field trip to Jinja: 'Source of the Nile', Nalubaale & Bugajali Dams	departure of delegates
09:00 - 10:10		**opening ceremony (Victoria Hall)**	**parallel sessions 1 and 2** (con't)	**parallel sessions 3 and 4** (con't)	**parallel sessions 5 and 6** (con't)		
10:30 – 11:00		*coffee/tea break*					
11:00 – 13:00		**opening plenary session (Victoria Hall)**	**parallel sessions 1 and 2:** *open discussion of technical and policy-related issues*	**parallel sessions 3 and 4:** *open discussion of technical and policy-related issues*	**parallel sessions 5 and 6:** *open discussion of technical and policy-related issues*		
13:00 – 14:00		*lunch break*					
14:00 – 15:00		**plenary keynote lectures (Victoria Hall) sessions 1 & 2**	**Plenary keynote lectures (Albert Hall) sessions 3 & 4**	**plenary keynote lectures (Albert Hall) sessions 5 & 6**	**plenary round-table discussions (Albert Hall)** ***technical issues***		
15:00 – 15:30		*coffee/tea break*			*coffee/tea Break*		
15:30 – 17:30		**parallel sessions** **session 1 – Victoria Hall:** Impact of climate variability and change on groundwater-based livelihoods **session 2 – Meera Hall:** Impact of climate variability and change on groundwater and groundwater-fed ecosystems	**parallel sessions** **session 3 – Albert Hall** Monitoring and modelling groundwater use and replenishment **session 4 – Meera Hall** Estimation of groundwater resources and demand under a changing climate	**parallel sessions** **session 5 – Albert Hall** *Groundwater management in sub-Saharan Africa under climate variability* **session 6 – Meera Hall** *Groundwater management in arid and semi-arid Africa*	**plenary round-table discussions (Albert Hall)** ***policy-related issues*** **closing ceremony (Albert Hall) 17:30 – 18:30**		
18:00 – 19:30		**special event:** *Networking African groundwater & climate scientists*	**special event:** *UNESCO GRAPHIC – call for African experts*	**special event:** *Groundwater monitoring & data management workshop*			
from 19:30	**ice breaker**	**opening reception** host: Minister of Water & Environment (Uganda)			**closing gala dinner from 19:00**		

Monday 23 June 2008

14:00 – 20:00	conference registration – Sapphire Hall
From 19:30	**Ice breaker – hosted by Conference Secretariat**

Tuesday 24 June 2008 Day 1

08:00 – 09:00	Registration – Sapphire Hall

OPENING CEREMONY (Victoria Hall)
chair: Permanent Secretary, Ministry of Water & Environment (Uganda)

09:00 – 09:10	Welcome remarks by the **Permanent Secretary, Ministry of Water & Environment** (Uganda)
09:10 – 09:20	Introductory remarks by the **Conference Chairs**
09:20 – 09:30	Address by the **Minister of Water & Environment** (Uganda)
09:30 – 09:40	Address by the **President, African Ministerial Committee on Water** (AMCOW)
09:40 – 09:50	Address by the **Danish Ambassador to Uganda**
09:50 – 10:00	Address by the **UNESCO Nairobi Director**
10:00 – 10:30	Opening address by the **President of Uganda**
10:30 – 10:50	*Coffee/Tea Break – common area (outside halls)*

OPENING PLENARY SESSION (Victoria Hall)
chair: Joseph Massaquoi (UNESCO, Kenya)

	Speaker	*Organisation/Institution*	*Title of presentation*
10:50 – 11:20	**Zbyszek Kundzewicz**	Polish Academy of Sciences, Poland	*Will groundwater ease the freshwater stress under climate change?*
11:20 – 11:50	**Laban Ogallo**	IGAD Climate Prediction and Applications Centre, Kenya	*Climate variability and change in Africa and potential impacts on terrestrial water resources*
11:50 – 12:10	**Jacob Burke**	Food and Agricultural Organisation (FAO) of the United Nations	*Agricultural demand for groundwater services in times of change; prospects for patterns and styles of groundwater use across Africa*

12:10 – 12:30	**Makoto Taniguichi**	Research Institute for Humanity and Nature, Japan	*GRAPHIC: Groundwater resources assessment under the pressures of humanity and climate change*
12:30 – 13:00	**AGWC Secretariat**	UNEP/UNESCO/UWC	*The AMCOW African Groundwater Commission (AGWC): roadmap & way forward*
13:00 – 14:00		*Lunch Break*	

PLENARY KEYNOTE LECTURES – SESSIONS 1 & 2 (Albert Hall)
chair: Willi Struckmeier (BGR, Germany)

14:00 – 14:30	**Keynote Session 1:** **Richard Carter**	Cranfield University, UK	*Climate change, population trends and groundwater in Africa*
14:30 – 15:00	**Keynote Session 2:** **Daniel Olago**	University of Nairobi, Kenya	*Holocene palaeohydrology, groundwater and climate change in the Central Kenya Rift*
15:00 – 15:30		*Coffee/Tea Break – common area (outside halls)*	

	SESSION 1 (Victoria Hall): *Impact of climate variability and change on groundwater-based livelihoods* *chair: Richard Carter (Cranfield University, UK)* *rapporteur: Albert Rugumayo (Makerere University, Uganda)*	**SESSION 2 (Meera Hall): *Impact of climate variability and change on groundwater and groundwater-fed ecosystems*** *chair: Daniel Olago (University of Nairobi, Kenya)* *rapporteur: Philip Gwage (Meteorology Department, Uganda)*
15:30 – 15:50	*Socially acceptable distributions of water in rural areas under conditions of climate variability for poverty alleviation: a case for Zambia* **Daniel Nkhuwa** (University of Zambia, Zambia)	*Oases in the apocalypse: the critical role of aquifer dependent ecosystems in mitigating climate change impacts in Southern Africa* **Christine Colvin** (CSIR, South Africa)
15:50 – 16:10	*What effect will climate change have on rural water supplies in Africa?* **Alan MacDonald** (BGS, UK), R.C. Calow, D.M.J. Macdonald, B. Dochartaigh, W.G. Darling	*National strategy for adaptation to climate change impacts on water resources in Uganda: status and way forward* **Florence Adongo** (DWRM, Uganda) and P.M. Gwage (Meteorology Department, Uganda)
16:10 – 16:30	*Climatic implications of groundwater recharge and discharge in parts of the escarpment areas of southern Nigeria* **Elisabeth Okoro** (Nnamdi Azikiwe University, Nigeria) and B.C.E. Egboka	*Preliminary assessment of the effects of climate change on groundwater resources in Cameroon* **T.M. Itie** (University of Buea, Cameroon) and V.E. Manga

16:30 – 16:50	*Groundwater resources mapping in Uganda: experiences and challenges* **Caroline Nakalyango** (DWRM, Uganda) and C. Tindimugaya	*Climate change, freshwater resources and access to safe water - the global response under the UNFCC* P.M. Gwage and **David Kabasa** (Makerere University, Uganda)
16:50 – 17:10	*Recent improvements of the geological and hydrogeological conceptual model for hard rock aquifers: application to their survey, management, modelling and protection* P. Lachassagne, Ahmed Sh., **Benôit Dewandel** (BRGM, France), N. Courtois, J.C. Maréchal, J. Perrin and R. Wyns	*Assessing the impacts of climate change and variability on water resources in Uganda: developing an integrated approach at the sub-regional scale* **Charles Basalirwa** (Makerere University, Uganda), G. Sabiiti, R. Taylor, A.W. Majugu, C. Tindimugaya
17:10 – 18:00	Open Discussion of Technical & Policy Issues	Open Discussion of Technical & Policy Issues

18:00 – 19:30 **Special event: Networking of African Groundwater and Climate Scientists**

discussants: Segun Adelana, Alan MacDonald (IAH), Emmanuel Naah, Yongxin Xu, Tamiru Alemayehu (AMCOW Groundwater Commission)

This informal session aims to improve networking and communication among African groundwater scientists and managers, and involves the **International Association of Hydrogeologists' (IAH) Burdon Network** and newly established **AMCOW African Groundwater Commission (AGWC)**.

From 19:30 **Welcome Reception**

Host: Hon. Maria Mutagamba, Minister of Water & Environment (Uganda)

Wednesday 25 June 2008 Day 2

	SESSION 1 (Albert Hall): *Impact of climate variability and change on groundwater-based livelihoods* *chair: Patrick Kahangire (African Development Bank)* *rapporteur: John Chilton (IAH)*	SESSION 2 (Meera Hall): *Impact of climate variability and change on groundwater and groundwater-fed ecosystems* *chair: Laban Ogallo (IGAD, Kenya)* *rapporteur: Patrick M'mayi (UNEP-DEWA)*
09:00 – 09:20	*Land-use impacts on gravity-fed community water supplies in southwestern Uganda* **Robert Mutiibwa** (FELS Consultants, Uganda)	*The relationships between groundwater and surface water in the upper Niger and Volta basins of West Africa* **Gil Mahé** (UMR Hydrosciences, France)
09:20 – 09:40	*A survey of the quality of groundwater drawn from boreholes in the Ashanti Region of Ghana* **Marian Nkansah** (KNUST, Ghana) and J.H. Ephraim	*Preliminary results from recent monitoring of groundwater / surface-water interactions in the Victoria Nile basin of Uganda* **Michael Owor** (Makerere University, Uganda), R.Taylor, J. Thompson, C. Mukwaya, C. Tindimugaya
09:40 – 10:00	*Increased risk of diarrhoeal diseases from climate change: evidence from communities supplied by groundwater in Uganda* **Richard Taylor** (UCL, UK), M. Miret-Gaspa, J. Tumwine, L. Mileham, R. Flynn, G. Howard, R. Kulabako	*Groundwater-surface water interaction as a component of the ecohydrology of arid regions* **Mohammed Messouli** (Semlalia Faculty of Sciences, Morocco), G. Messana, M. Yacoubi-Khebiza, A. El Alami El Filali, A. Ait Boughrous and M. Boulanouar

10:00 – 10:20

Spatial and temporal groundwater quality monitoring in rural Benin, West Africa: an example of collaboration with local populations
Stephen Silliman (University of Notre Dame, USA), P. Crane, M. Boukari, F. Azonsi

Impact of simulated extreme hydroclimatic conditions on groundwater resources
Richard Anyah (Rutgers University, USA), G. Miguez-Macho, Y. Fan and A. Robock

10:20 – 10:45 poster sessions – common area (outside halls)

POSTER SESSION 1: *Impact of climate variability and change on groundwater-based livelihoods*

Reliability of interview data for monitoring and mapping groundwater
Dale Lightfoot (Oklahoma State University, USA) N. Mavlyanov, D. Begimkulov and J. Comer

The challenge of climate variability and change to the sustainability of shallow groundwater supplies: a case study from Kabubbu Village, Uganda
Ronald Musiige (DWRM, Uganda)

The overburden aquifer and its potential contribution to reaching MDG targets of safe water coverage in northern Uganda
C. Mulder and **Ron Sloots** (WE Consult, Uganda)

Enhancing private sector participation in rural water supply
P. Baur, M. Woodhouse and **Richard Boak** (Water Management Consultants, UK)

The influence of hydrochemistry on the distribution of pathogenic strains of Escherichia coli in urban groundwater of Yaounde
Mireille Ebiane Nougang (University of Yaoundé, Cameroon), M. Nola, T. Njine, S. Hubert Z. Togouet, M. Djaouda and M. Djah

Correlations between hydrochemistry and faecal bacteria counts in urban groundwater underlying Ago-Iwoye, southwestern Nigeria
Olusola Fasunwon (Olabisi Onabanjo University, Nigeria), J. Olowofela, O. Akinyemi and O. Akintokun

POSTER SESSION 2: *Impact of climate variability and change on groundwater and groundwater-fed ecosystems*

Variations in the intensity of the monsoon-like flow from the tropical Atlantic and summer rainfall over equatorial and tropical southern Africa
Nicholas Vigaud (UCT, South Africa), Y. Richard, M. Rouault, N. Fauchereau

Simulation of Ethiopian Kiremt (summer) rainfall using NCEP Coupled Forecast System
Girmaw Bogale (National Meteorological Agency, Ethiopia) and W. Thiaw

Climate change impacts on groundwater recharge in Draa watershed, Morocco
Mohammed Messouli (Semlalia Faculty of Sciences, Morocco), M. Yacoubi-Khebiza, A. El Alami El Filali, L. Bouarab, B. Ghallabi, S. Rochdane, A. Ben Salem and F. E. Hammadi

Isotopic study and relationship between surface water and groundwater in the Souss-Massa basin of southwestern Morocco
Lhoussaine Bouchaou (Ibn Zohr University, Morrocco), T. Tagma, Y. Hsissou, M. Ikenne, S. Boutaleb, L. Bouragba and J. Mudry

Isotope techniques for the assessment of interactions between surface water, groundwater and wetlands in Uganda
Christine Mukwaya (DWRM, Uganda) and C. Tindimugaya

Detection of inhomogeneities in the national climate dataset (1902-2003) of Uganda
Lubega Fortunata (Meteorology Department, Uganda)

10:45 – 11:15	*Coffee/Tea Break - extension of poster sessions*	
11:15 – 11:45	Session 1 Open Discussion of Technical Issues *chair:* ***Abou Amani*** *(UNESCO)*	Session 2 Open Discussion of Technical Issues *chair:* ***Charles Basalirwa*** *(Makerere University, Uganda)*
11:45 – 12:30	Session 1 Open Discussion of Policy Issues *chair:* ***Patrick Kahangire*** *(African Development Bank)*	Session 2 Open Discussion of Policy Issues *chair:* ***Patrick M'mayi*** *(UNEP-DEWA)*
12:30 – 13:00	Session 1 Summary of Technical and Policy Issues *rapporteurs:* ***Abou Amani*** *(UNESCO) &* ***Patrick Kahangire*** *(African Development Bank)*	Session 2 Summary of Technical and Policy Issues *rapporteurs:* ***Laban Ogallo*** *(IGAD, Kenya) &* ***Patrick M'mayi*** *(UNEP)*
13:00 – 14:00	*Lunch Break*	

PLENARY KEYNOTE LECTURES - SESSIONS 3 & 4 (Albert Hall)
chair: Professor Stephen Foster, IAH President

14:00 – 14:30	**Keynote Session 3:** **Ken Howard** and A. Griffith	University of Toronto (Canada)	*Using transient models to confront the impacts of climate change on groundwater reserves in sub-Saharan Africa*
14:30 – 15:00	**Keynote Session 4:** **Petra Döll** and K. Berkhoff	University of Frankfurt (Germany)	*Diffuse groundwater recharge and groundwater withdrawals in Africa as estimated by global-scale water models*
15:00 – 15:30	*Coffee/Tea Break – common area (outside halls)*		

	SESSION 3 (Albert Hall): ***Monitoring and modelling groundwater use and replenishment*** *chair: Ken Howard (University of Toronto, Canada)* *rapporteur: Emmanuel Naah (UNESCO)*	**SESSION 4 (Meera Hall):** ***Estimation of groundwater resources and demand under a changing climate*** *chair: Petra Döll (University of Frankfurt, Germany)* *rapporteur: Nebert Wobusobozi (DWRM, Uganda)*
15:30 – 15:50	*Monitoring and modelling groundwater use in sub-Saharan Africa: issues and challenges* **Segun Adelana** (University of Ilorin, Nigeria)	*The impact of climate change on groundwater recharge: a case study from the Ethiopian Rift* **Tamiru Alemayehu** (Wits University, South Africa)
15:50 – 16:10	*The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment of Uganda* **Lucinda Mileham** (UCL, UK), R. Taylor, M. Todd, C. Tindimugaya	*Impacts of climate variability and change on groundwater in the humid tropics: a case study from the Ivory Coast* **B.T.A. Goula** (University of Abobo-Adjame, Ivory Coast), F.W. Kouassi, V. Fadika, K. E. Koff, B. Gnamien, K. Koffi, K. Bamory, D. Inza, I. Savane

16:10 – 16:30	*Estimating the effect of climate change on the hydrology of River Ssezibwa catchment, Uganda* **Philip Nyenje** (Katholieke Universiteit Leuven, Belgium) and O. Batelaan	*Global analogues of climate change effects on agriculture and groundwater between hydrologically similar regions of the world* **Timothy Green** (USDA-ARS, USA), B. Bates, S. Charles and E. Fathelrahman
16:30 – 16:50	*Application of a semi-distributed SWAT model to an Upper Nile catchment: implications for groundwater resources* **Max Kigobe** (Makerere University, Uganda)	*Modelling the freshwater availability in Africa with special attention to the current and future groundwater recharge* **Jürgen Schuol** (EAWAG, Switzerland), K. Abbaspour and H. Yang
16:50 – 17:30	Session 3 Open Discussion of Technical & Policy Issues	Session 4 Open Discussion of Technical & Policy Issues

18:00 – 19:30 **Special event: UNESCO GRAPHIC (Groundwater Assessment under the Pressures of Humanity and Climate Change) Programme – call for African experts**

discussants: Makoto Taniguchi (UNESCO GRAPHIC), Richard Taylor (UCL, UK), Tim Green (USDA, USA), Kevin Hiscock (UEA, UK)
moderators: Alice Aureli, Holger Treidel (UNESCO-IHP)
This evening meeting will feature a brief overview of the UNESCO's GRAPHIC programme and an open invitation to African water scientists and managers to engage in this global initiative assessing the impacts of development and climate change on groundwater.

Thursday 26 June 2008 Day 3

	SESSION 3 (Albert Hall): *Monitoring and modelling groundwater use and replenishment* *chair: Yongxin Xu (UWC, South Africa)* *rapporteur: Cheikh Bécaye Gaye (University of Cheikh Anta Diop, Senegal)*	**SESSION 4 (Meera Hall): *Estimation of groundwater resources and demand under a changing climate*** *chair: Engineer Mugisha Shillingi (DWRM, Uganda)* *rapporteur: Daniel Nkhuwa (University of Zambia, Zambia)*
09:00 – 09:20	*Groundwater recharge and flow in a small mountain catchment in northern Ethiopia* **Kristine Walraevens** (Ghent University, Belgium), I. Vandecasteele, K. Martens, J. Nyssen, W. Clymans, J. Moeyersons, T. Gebreyohannes, F. De Smedt, J. Deckers, M. Van Camp	*Systematic approach for groundwater management, under climate change in Benin, West-Africa* **Antoine Kocher** (University of Bonn, Germany) and B. Reicher
09:20 – 09:40	*Assessing changes in terrestrial water storage in Africa using GRACE satellite gravity data and JLG terrestrial water storage model* **Keiko Yamamoto** (Kyoto University, Japan), T. Nakaegawa, T. Hasegawa, Y. Fukuda and M. Taniguchi	*Climate variability and its impact on the Table Mountain Group aquifer in South Africa* **Anthony Duah,** (UWC, South Africa) and Y. Xu
09:40 – 10:00	*Design of a national groundwater monitoring network in Uganda* **Deborah Mwesigwa** (DWRM, Uganda) and C. Tindimugaya	*Groundwater recharge and salinization in coastal areas of Senegal: impacts of climate change* **Serigne Faye (**University Cheikh Anta Diop, Senegal) and A. Faye

10:00 – 10:20	*Improving groundwater monitoring networks in Africa: developing integrated approaches to the assessment of the impacts of climate and socio-economic change on groundwater resources in Africa* M.T.H. van Vliet and **Neno Kukuric** (IGRAC, Netherlands)	*Impact of climate change on the renewal of groundwater resources in the Chéliff-Zahrez basin of Algeria* **Mohamed Meddi** (University of Khemis Miliana, Algeria) and A. Boucefiane
10:20 – 10:45	poster sessions – common area (outside halls)	

POSTER SESSION 3: *Monitoring and modelling groundwater use and replenishment*

Using satellite-based solar insolation for estimating long-term regional evapotranspiration
Simon Paech (University of Alabama, USA), J.R. Mecikalski, D.M. Sumner and J.M. Jacobs

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Tenalem Ayenew (Addis Ababa University, Ethiopia)

10:45 – 11:15	*Coffee/Tea Break - extension of poster sessions*		
11:15 – 11:45	Session 3 Open Discussion of Technical Issues *chair: **Ken Howard** (University of Toronto, Canada)*		Session 4 Open Discussion of Technical Issues *chair: **Didier Pennequin** (BRGM)*
11:45 – 12:30	Session 3 Open Discussion of Policy Issues *chair: Science & Technology Committee (Uganda)*		Session 4 Open Discussion of Policy Issues *chair: SADC Parliamentary Forum*
12:30 – 13:00	Session 3 Summary of Technical and Policy Issues *rapporteurs: **Ken Howard** (University of Toronto, Canada) & **Disan Ssozi** (DWRM, Uganda)*		Session 4 Summary of Technical and Policy Issues *rapporteur: **Daniel Nkhuwa** (University of Zambia, Zambia) & **Sam Mutono** (World Bank)*
13:00 – 14:00	*Lunch Break*		

PLENARY KEYNOTE LECTURES - SESSIONS 5 & 6 (Albert Hall)
chair: H.E. Ato Asfaw (Ministry of Water Resources, Ethiopia)

14:00 – 14:10	**Vahid Alavian**	World Bank	*Opening Address*
14:10 – 14:30	**KEYNOTE SESSION 5:** **Stephen Foster**	World Bank GW/MATE & IAH	*Urban water-supply security in sub-Saharan Africa: making the best use of groundwater*
14:30 – 15:00	**KEYNOTE - SESSION 6:** **Youba Sokona**	OSS (Tunisia)	*Transboundary groundwater management and climate nexus in the Circum-Sahara*
15:00 – 15:30	*Coffee/Tea Break – common area (outside halls)*		

	SESSION 5 (Albert Hall): *Groundwater management in the humid tropics of sub-Saharan Africa under variable climates* *chair: Segun Adelana (IAH/University of Ilorin, Nigeria)* *rapporteur: Lister Kongola (Ministry of Water and Irrigation, Tanzania)*	**SESSION 6 (Meera Hall): *Groundwater management in arid and semi-arid Africa under variable climates*** *chair: Youba Sokona (OSS, Tunisia)* *rapporteur: Mohammed Messouli (Semlalia Faculty of Sciences, Morocco)*
15:30 – 15:50	*Impact of climate variability on groundwater in Dar es Salaam, Tanzania* **Praxeda Kalugendo** (Ministry of Water and Irrigation, Tanzania)	*Palaeohydrogeology of the Okavango Basin and Makgadikgadi Pan (Botswana) in the light of climate change and regional tectonics* J. Meier, **Thomas Himmelsbach** (BGR, Germany) and J. Böttcher
15:50 – 16:10	*Rationale and strategies for groundwater management in urban areas of Uganda* **Callist Tindimugaya** (DWRM, Uganda)	*Sustainable groundwater management in the East African Rift – the MAWARI Project experience* **Cheikh Bécaye Gaye** (University of Cheikh Anta Diop, Senegal), S. Kebede, F. Pinard

Time	Session 5	Session 6
16:10 – 16:30	*Simulating groundwater level fluctuations in the Quaternary aquifer of Bamako, Mali* **Hamadoun Bokar** (Ecole Nationale d'Ingenieurs, Mali)	*A decision support tool for sustainable groundwater management in semi-arid, hard-rock regions* **Benoit Dewandel** (BRGM, France), J. Perrin, S. Ahmed, S. Aulong, Z. Hrkal, P. Lachassagne, M. Samad, S. Massuel, A. Mukherji
16:30 – 16:50	*Groundwater exploitation and recharge rate estimation of a quaternary sand aquifer in Dar es Salaam, Tanzania* **Ibrahimu Chikira Mjemah** (Sokoine University of Agriculture, Tanzania), M. Van Camp and K. Walraevens	*Cooperation, conflict and adaptation to climate change in transboundary river basins in Africa* **Marisa Goulden** (UEA, UK) and Declan Conway
16:50 – 17:30	Session 5 Open Discussion of Technical & Policy Issues	Session 6 Open Discussion of Technical & Policy Issues

18:00 – 19:30 **Special event: Groundwater monitoring and data management**

chairs: Segun Adelana (Nigeria), Callist Tindimugaya (Uganda), Lister Kongola (Tanzania) & Neno Kukuric (Netherlands)

This evening session will focus on the development of groundwater monitoring networks and management of hydrogeological data and feature discussions involving senior water managers from around Africa who will discuss formally or informally case studies highlighting best practice in the design, construction and maintenance of monitoring networks.

Friday 27 June 2008 Day 4

	SESSION 5 (Albert Hall): *Groundwater management in the humid tropics of sub-Saharan Africa under variable climates* *chair: Phera Ramoeli (SADC)* *rapporteur: Rafik Hirji (World Bank)*	**SESSION 6 (Meera Hall): *Groundwater management in arid and semi-arid Africa under variable climates*** *chair: Ralf Klingbeil (BGR, Germany)* *rapporteur: Alex Magarigakis (UNESCO)*
09:00 – 09:20	*Groundwater management in non-urban areas under changes in climate variability* **Albert Tuinhof** (World Bank GW/MATE)	*Conceptualising transboundary groundwater management* **Waltina Scheumann** (DIE, Germany), E. Herrfahrdt and M. Alker
09:20 – 09:40	*Groundwater management in rural Ethiopia* **H.E. Ato Asfaw** (Ministry of Water Resources, Ethiopia)	*Water and food security in the Nile Basin: taking account of water resources beyond the river and the basin* **Tony Allan** (Kings College London, UK)
09:40 – 10:00	*Groundwater management in rural sub-Saharan Africa under conditions of climate variability* **Lister Kongola** (Ministry of Water and Irrigation, Tanzania)	*Tradeoff analysis between economic development and climate change adaptation strategies for the Nile river basin* **Eihab Fathelrahman** (USDA, USA), M. Babiker, K. Strzepek, J. Ascough II, and T. Green
10:00 – 10:20	*Groundwater management and drought preparedness in the SADC region* **Phera Ramoeli** (SADC)	*The role of parliamentarians in developing groundwater management policies under conditions of climate change* **SADC Parliamentary Forum** **Science & Technology Committee of the Ugandan Parliament**

10:20 – 10:45	poster sessions – common area (outside halls)	

POSTER SESSION 5: ***Groundwater management in sub-Saharan Africa under variable climates***

Challenges in enforcing water laws in water resources management in Uganda
Grace Namanda-Ssali (P.K. Hydroexperts Limited, Uganda)

Experimental GIS hydrogeological mapping of hard rock aquifers in Burkina Faso, to help groundwater management and planning
Nathalie Courtois (BRGM, France), R. Blanchin, P. Lachassagne, R. Wyns, F.D. Bougaïré, S. Somé and A. Tapsoba

Relict river channels in Uganda: potential corridors of preferential groundwater flow and storage
Graham Bradley (UCL, UK), C. Tindimugaya and R. Taylor

Geoelectrical characterization of aquifers in the basement complex / sedimentary transition zone around Ishara, southwestern Nigeria
Stephen Ariyo (Olabisi Onabanjo University, Nigeria) and G.O. Adeyemi

Groundwater governance in Asia: an innovative approach and platform for capacity building, research, and knowledge sharing on groundwater management
Karen Villholth (GEUS, Denmark), A. Mukherji, B.R. Sharma and J. Wang

POSTER SESSION 6: ***Groundwater management in arid and semi-arid Africa under variable climates***

Carbon-14, chlorine-36 and noble gases in deep groundwaters from the NE Sahara (Algeria) and their palaeoclimatic implications
Abdelhamid Guendouz (Blida University, Algeria), A.S.Moulla and J.L.Michelot

Compared analysis of variabilities and climatic changes impacts on the surface water and groundwater resources in Saharo-Sahelian zones
Youba Sokona (OSS, Tunisia), A. Dodo and M. Baba Sy

Climat et ressources en eau au Maghreb: tendances et impacts du changement global
Moulay Idriss Hassani (Université d'Oran, Algeria)

Conceptual model of basement aquifers in Limpopo province, South Africa
K.T. Witthüser, M. Dippenaar, **Theo Rossouw** (University of Pretoria, South Africa), M. Holland

Groundwater geochemical variations under a changing climate in the East African rift
Seifu Kebede (Addis Ababa University, Ethiopia)

10:45 – 11:15	*Coffee/Tea Break – extension of poster sessions*	
11:15 – 12:30	Session 5 Open Discussion of Technical & Policy Issues *chairs:* ***Segun Adelana*** *(IAH) &* ***Richard Carter*** *(Cranfield University, UK)*	Session 6 Open Discussion of Technical & Policy Issues *chairs:* ***Youba Sokona*** *(OSS, Tunisia) &* ***Ralf Klingbeil*** *(BGR, Germany)*
12:30 – 13:00	Session 5 Summary of Technical and Policy Issues *chair:* ***Vahid Alavian*** *(World Bank)*	Session 6 Summary of Technical and Policy Issues *chairs:* ***Mohammed Messouli*** *(Morocco) &* ***Ralf Klingbeil*** *(BGR)*
13:00 – 14:00	*Lunch Break*	

PLENARY ROUND-TABLE DISCUSSIONS I (Albert Hall)
Chair: Patrick Kahangire (ADB)

14:00 – 14:30 **Synthesis of technical and policy issues from conference sessions**
discussants: Richard Taylor (UK) / Callist Tindimugaya (Uganda) / Alice Aureli (UNESCO-IHP)

14:30 – 15:30 **Discussion of technical issues leading to specific outcomes and recommendations**
provisional panel: Zbyszek Kundzewicz (IPCC), Daniel Olago (Kenya), Youba Sokona (Tunisia), Philip Gwage/Stephen Magezi (Uganda), Didier Pennequin (BRGM), Willy Struckmeier (BGR), Brent Newman (IAEA), Patrick M'mayi (UNEP), DANIDA representative
potential foci:
- How does climate variability and change affect groundwater resources?
- What are the current constraints to improving our understanding of the relationship between groundwater and climate?

15:30 – 16:00 *Coffee/Tea Break*

PLENARY ROUND-TABLE DISCUSSIONS II (Albert Hall)
Chair: Hon. Maria Mutagamba (MWE, Uganda)

16:00 – 17:30 **Discussion of policy issues and recommendations for national and international policy formulations**
provisional panel: H.E. Ato Asfaw (MWR, Ethiopia),), Hon. Jennifer Namuyangu (MWE, Uganda), Aryamanya Mugisha (NEMA, Uganda) , Simon Thuo (NBI), SADC Parliamentary Forum, Science & Technology Committee (Uganda), Stephen Foster (World Bank, IAH), Manfred Konukiewitz (BMZ), Janot Mendler de Suarez (UNDP-GEF), Peter Akari (ADB/AWF), Tony Allan (KCL, UK)
potential foci:
- How can groundwater help communities in Africa mitigate or adapt to the impacts of climate change and increasing water demand?
- How can we best manage and regulate groundwater development to ensure long-term sustainability?

17:30 – 18:30 **Closing Ceremony**
Chair: Permanent Secretary, Ministry of Water and Environment

from 19:30 **CLOSING GALA DINNER**

Saturday 28 June 2008

09:00 – 18:00 **FIELD VISIT – Jinja**
Transboundary theme:
(1) Bujagali & Nalubale/Kira Dams; (2) Jinja groundwater / surface water monitoring facility; (3) 'Source of the River Nile'

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Groundwater management in arid and semi-arid Africa under variable climates

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PLENARY OPENING SESSION – KEYNOTE LECTURES

Will groundwater ease the freshwater stress under climate change?

Zbigniew Kundzewicz[1,2] *and P. Döll*[3]
1 Research Centre for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland
2 Potsdam Institute for Climate Impact Research, Potsdam, Germany
3 Institute of Physical Geography, University of Frankfurt/M., Frankfurt am Main, Germany

Groundwater, which provides drinking water for a large portion of the global population, in particular rural dwellers, is subject to stress with respect to both water quantity and quality. Hence, it is of utmost importance to examine climate change impacts on groundwater and to discuss where and under what circumstances groundwater may ease freshwater stress under a changing climate. Under climate change, reliable surface water supply is likely to decrease due to increased temporal river flow variations that are caused by increased precipitation variability and decreased snow/ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and increase groundwater withdrawals but this option is only sustainable where groundwater withdrawals remains well below groundwater recharge. Thus, groundwater is not likely to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge (e.g. Northeastern Brazil and the Mediterranean). Climate change will affect groundwater recharge, i.e. long-term average renewable groundwater resources, via increases in mean temperature, precipitation variability and sea level, as well as via changes in mean precipitation (increasing in some areas and decreasing in others). Over many areas groundwater recharge is projected to increase in the warming world (but less than the river runoff), but many semi-arid areas that suffer from water stress already today may face decreased groundwater recharge. A sea level rise that is likely to occur during the 21st century might leave many flat coral islands without a reliable groundwater source. However, in coastal areas with a land surface elevation of a few metres or more, groundwater availability is more strongly impacted by changes in groundwater recharge than sea level rise.

Climate variability and change in Africa and potential impacts on the terrestrial water resources

Laban Ogallo
IGAD Climate and Applications Centre, Nairobi, Kenya

The climate of large areas of Africa can be classified as arid and semi arid that experience recurrent and severe droughts. The livelihoods of the society are largely nomadic pastoralist. The economies of many states in areas that receive reliable rainfall, rely heavily on rain-fed agriculture. The Intergovernmental Panel on Climate Change (IPCC) assessment indicates that both droughts and floods have increased in frequency and severity in the recent years, and are projected to increase in the future at many locations world wide, with far reaching implication on the demand and availability of quality fresh water resources. Increased recurrences of droughts in the future will force agriculture in Africa to place new demands upon groundwater for increased irrigation for sustainable agricultural production. IPCC 4AR argues that the African continent is the most vulnerable continent to climate change. Other future challenges to fresh water availability in Africa include pollution by human activities together with the ever increasing demand of clean water by the fast increasing population of the continent. Climate change will thus introduce new challenges to sustainable fresh water availability, conflicts / security and the general sustainable development of the continent of Africa in the 21st century. This paper provides some highlights of the climate variability and change in Africa, and some of the potential impacts on terrestrial hydrology. Lessons and experiences from the African regional climate centers in integrated climate risk management for coping with current climate variability and adaptation to future climate changes are highlighted.

Agricultural demand for groundwater services in times of change; prospects for patterns and styles of groundwater use across Africa

Jacob Burke
Food and Agriculture Organization of the United Nations

Groundwater use for irrigated agriculture still reflects a North Africa / Sub-Saharan Africa divide. Within these regional contrasts, use is also differentiated across a public / private divide - a legacy of land and water administration. As competition for land and water resources intensifies and

agricultural markets change, some groundwater development options may close while others open up. A review of these prospects needs to be seen in the light of changing patterns of recharge and socio-economic demand as well as trends in natural resource regulation. Equally, comparisons with groundwater dependant economies in Asia should not be invoked without appreciation of actual economic costs and benefits.

GRAPHIC: Groundwater resources assessment under the pressures of humanity and climate change

Makoto Taniguichi[1], A. Aureli[2] and J. L. Martin[2]
1 Research Institute for Humanity and Nature, Kyoto, Japan
2 UNESCO-IHP, Paris, France

The UNESCO-IHP initiated project, *Groundwater Resources Assessment under the Pressures of Humanity and Climate Change* (GRAPHIC), project promotes and advances sustainable groundwater management in the face of climate change and linked human effects. GRAPHIC provides a platform for exchange of information through case studies, thematic working groups, scientific research, and communication. In this paper, the vision/aims/structure/theme/methods of the GRAPHIC are outlined and some case studies in Tokyo and use of satellite GRACE data are introduced. There are urgent and ongoing needs to address the expected coupled effects of human activities and climate change on global groundwater resources.

SESSION 1 IMPACT OF CLIMATE VARIABILITY AND CHANGE ON GROUNDWATER-BASED LIVELIHOODS

As groundwater is the primary source of safe water for dispersed rural communities and low-cost urban water supplies in Africa, papers in this session explore the susceptibility of groundwater-fed water supplies in both rural and urban areas to climate variability and change, and the ability of communities to adapt to changing groundwater availability.

KEYNOTE: Climate change, population trends and groundwater in Africa

Richard Carter
Cranfield University, Cranfield, Bedford, UK

Global climate change is affecting Africa, as it is every other continent and region of the world. The absolute poverty of a large proportion of the continent's people renders them highly vulnerable to changes in climate. Mitigation of climate change is a global imperative yet numerous other changes continue apace, notably population growth, natural resource degradation, loss of natural ground cover, and rural-urban migration. Probably 50% or more of the continent's population rely on groundwater. This paper explores the relative impacts of changes in climate, demography and land use/cover on groundwater resources and demands. It concludes that the climate change impacts are likely to be significant, though uncertain in direction and magnitude, while the direct and indirect impacts of demographic change are not only known with far greater certainty, but are also likely to be much greater. The combined effects of urban population growth, rising food demands and energy costs, and consequent demand for fresh water represent real cause for alarm, and these dwarf the likely impacts of climate change on groundwater resources, at least over the first half of the 21st century.

The role of appropriate water supply mechanism for poverty alleviation in rural areas of Zambia

Daniel Nkhuwa
School of the Built Environment, Copperbelt University, Kitwe, Zambia

Despite Zambia investing significantly in rural water supply since the early 1970s, the actual number of people effectively provided with safe drinking water remains very low. In a recent (2000) census, only 37% of the population was estimated to have access to safe water supply, a deprivation that has characterised and entrenched poverty in Zambia's rural areas. Attempts to alleviate this poverty must be supported by a policy that favours a shift of emphasis from provision of safe water supplies to that encompassing productive water to enable families to increase generation of income. This income will, in turn, increase the affordability of healthcare services for water-related illnesses. Gains in income generation will also enable communities to address their safe water needs and improve the sustainability of rural water supply programmes. Such developments ultimately create a favourable environment in which rural communities are able to enjoy a life of quality and dignity.

What effect will climate change have on rural water supplies in Africa?

Alan MacDonald[1], R.C. Calow[2], D.M.J. Macdonald[2], B.É.Ó. Dochartaigh[1] and W.G. Darling[2]
1 British Geological Survey, Edinburgh, UK.
2 British Geological Survey, Wallingford, UK

One of the key uncertainties surrounding the impacts of a changing climate in Africa is the effect that it will have on the sustainability of rural water supplies. Many of these water supplies abstract from shallow (< 50 m) groundwater and are the sole source of safe drinking water for the majority of Africa's population. This paper discusses the possible implications of climate change on rural water supplies: most recent climate predictions are for an overall reduction in rainfall but increase in the intensity of high-rainfall events across much of northern and southern Africa, and a corresponding likely increase in the number of people who could be experiencing water stress in these areas by 2055. The approach taken in this study is to use current knowledge of source and resource behaviour during extended dry seasons and drought to examine the potential impact of climate change. This suggests that under a changing climate, and increasing frequency of droughts, there will be two main impacts: an increase in demand for groundwater as surface water sources fail; and changes to groundwater recharge. Studies across sub-Saharan Africa, backed up by numerical modelling of source behaviour, indicate that an increased demand towards the end of the dry season could lead to many sources having insufficient water to meet demand, or failing altogether. This reduction in supply will effectively limit the access of communities to available groundwater resources. Demand for groundwater for irrigation is also likely to increase markedly if rainfall becomes more unpredictable and may pose more of a threat to long-term sustainability of the resource than any change in domestic demand. Existing recharge studies, in conjunction with new information emerging from measurements of residence time indicators from community water supplies in Tanzania, suggests that the effect of a changing climate on recharge will be highly variable. However, an annual recharge of 10 $mm \cdot a^{-1}$ is sufficient to sustain a rural water supply equipped with hand pump. Using the latest climate predictions and current understanding of recharge, it is likely that significant impacts on the absolute availability of groundwater for domestic supplies will be restricted to a few marginal areas. In most areas, gaining access to water rather than its physical scarcity will continue to determine the water security of rural populations. In summary, climate change is likely to have a serious impact on rural water supplies across Africa, but not from a catastrophic reduction in recharge. Rural water supplies are likely to become under increasing pressure as surface sources become unreliable, this could lead to reduced access to groundwater. In marginal areas, and where groundwater is used for irrigation, problems will arise as demand exceeds the available groundwater resources. Due to the complexity of these inter-relationships, there is a pressing need for interdisciplinary studies which focus on the increasing demand for groundwater, access to groundwater and absolute resource availability.

Groundwater recharge and discharge in the escarpment areas of southeastern Nigeria

Elisabeth Okoro, B.C.E. Egboka and A.G. Onwuemesi
Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria

Groundwater resources in southeastern Nigeria are influenced by changes in climate. During the rainy season, water levels in aquifers rise with resultant geotechnical implications of gully erosion and landslides. The high rate of these ecological phenomena along Awka-Umuchu-Orlu escarpment is exacerbated by heavy rainfall, fast runoff and groundwater discharges. The geomorphic characteristics of the escarpment are major controlling factors in flood flow, groundwater recharge and discharge. The major geology of the area includes the Nanka Sands and Imo Shale. Whereas productive unconfined and confined aquifers are found in Nanka Sands, the Imo Shale forms aquitards except in the sandstone members. This study shows that an understanding of recharge sources and pathways is required in order to assess the impacts of climate change on groundwater resources in the region.

Groundwater resources mapping in Uganda - experiences and challenges

Caroline Nakalyango and C. Tindimugaya
Directorate of Water Resources Management, Entebbe, Uganda

Groundwater development in Uganda has traditionally been done with very little information on the hydrogeological conditions and groundwater potential of various areas of the country. This lack of knowledge resulted in significant financial losses due to development of unsuccessful water sources. In addition, very expensive water supply technologies were often employed where maps now show cheaper and more sustainable ones are possible. In order to significantly improve water supply coverage in the country using low – cost, water supply technologies, Uganda initiated a groundwater resources mapping program to prepare maps representing groundwater resources in terms of their quantity and quality that summarises this information spatially. The purpose of the maps is to guide planning and implementation of groundwater development activities. Six types of maps have been produced at the district level. To date, mapping activities have been completed in 17 out of 82 districts in the country. In order to improve the pace of preparation of groundwater maps, local groundwater consultants were engaged to prepare groundwater resources maps for 16 additional districts. A number of lessons have been learned in the preparation of the maps. Although all the maps are principally produced using borehole drilling data, the quality and availability of data vary greatly across the country and this variability poses a substantial challenge to the production of reliable maps. Similarly, the capacity for preparation of groundwater mapping using among others GIS technologies is still low but is slowly being developed. It is hoped that the whole country will be mapped over the next 5 years through increased collaboration with the private sector.

Recent improvements of the geological and hydrogeological conceptual model for hard rock aquifers: application to their survey, management, modelling and protection

P. Lachassagne[1], Ahmed Sh.[2], Benôit Dewandel[1], N. Courtois[1], J.C. Maréchal[1], J. Perrin[3] and R. Wyns[4]
1 BRGM, Water Division, Resource Assessment, Montpellier, France
2 National Geophysical Research Institute, Indo-French Centre for Groundwater Research, Hyderabad, India
3 BRGM, Water Division, Resource Assessment, Indo-French Centre for Groundwater Research, Hyderabad, India
4 BRGM, Geology Division, Orléans, France

Hard rocks (granites, metamorphic rocks) occupy large areas throughout the world, particularly in Africa and India. Groundwater resources located in hard rock aquifers are modest in terms of available discharge per well (from 2-3 up to ~20 m^3/h), compared to those from other types of aquifers. However, these resources are geographically widespread and therefore well suited to scattered settlement and small to medium size cities. They largely contribute to the economic development of such regions, especially in arid and semiarid areas where the surface water resource is limited. Significant advances have recently been made about the genesis, geometry and functioning of hard rock aquifers, particularly in India. The hydrodynamic properties of these aquifers appear to be mainly related to weathering processes. The weathering profile, up to more than 100 m thick, is mainly composed of two stratiform and superimposed layers, the saprolite, playing a storage role, and the underlying fissured layer that assumes the transmissive function of the aquifer. Where saturated with groundwater, these two layers constitute an integrated aquifer. The spatial distribution of such weathering profiles, or their remains after erosion, can be mapped at the catchment scale. As a result, the 3-D aquifer geometry and the spatial distribution of the hydrodynamic properties of hard rock aquifers can also be mapped. These new geological and hydrogeological concepts that enable a regional-scale understanding of hard-rock aquifer properties, find numerous practical applications: the mapping of groundwater potential on a regional scale, through borehole sitting techniques and methods increasing the success rate in terms of exploitable discharge at the local scale; sustainable water resources management at the watershed scale. This insight is crucial in areas where groundwater is the only water resource. In India, for example, this resource is often overexploited. A Decision Support Tool specially devoted to hard rock aquifers in the semi-arid context has been developed. These new concepts also allow the use of multilayer mathematical modelling tools to simulate their functioning. The experience gained in Indian for the management of hard rock overexploited aquifers may be of particular interest to anticipate the problems Africa might face in the future decades; the management of groundwater quality issues, particularly when dealing with non-point source pollutions and the question of the increase in fluoride content in hard rock aquifer groundwater; and also various other applications such as town and country planning, quarries, and tunnels.

Land-use impacts on gravity-fed community water supplies in southwestern Uganda

Robert Mutiibwa
FELS Consultants, Kampala, Uganda

"*Halving the number of people living without access to safe drinking water*" by 2015 is target 2 of the Millennium Development Goal (MDG) 8: Ensure Environmental Sustainability. Achieving the goal and target requires much more than logistical support. Appropriate and timely interventions may be our greatest challenge. In Mbarara and Ibanda towns of south-western Uganda, a reduction in the discharge of springs supplying gravity-fed community water systems has been observed. Although our understanding of variability in spring discharges is limited by insufficient monitoring records, the human influence on catchment areas sustaining spring discharge has yet to be fully considered. Recent clearing of spring catchment areas for cultivation and settlement has affected the spring's 'recharge zone' by reducing infiltration and increasing surface runoff. This paper highlights the importance of appropriate interventions such as protection of spring catchments to promote the sustainability water sources long after 2015.

A survey of the quality of groundwater drawn from boreholes in the Ashanti Region of Ghana

Marian Nkansah[1] and J.H. Ephraim[2]
1 Department of Chemistry, Kwame Nkrumah University of Science and Technology-Kumasi, Ghana
2 Catholic University of Ghana-Fiapre, Ghana

We assessed the chemical quality of groundwater sampled from 21 water wells from 13 communities in the Ejisu-Juaben District and 17 boreholes from 11 communities of the Bosomtwi - Atwima - Kwanwoma District within the Ashanti Region of Ghana (West Africa) from November 2004 to June 2005. Water samples were analysed for pH, EC, TDS, SO_4^{2-}, Cl^-, PO_4^{3-}, NO_2^-, Fe, Mn, Cu, Zn, Cd, Na, K and Pb. UV-Visible spectrophotometry was used to determine minor-ion (SO_4^{2-}, PO_4^{3-} , NO_2^-) concentrations. Atomic absorption spectrophotometry was used to determine metal (Fe, Mn, Cu, Zn, Cd, Pb, Na, K) concentrations and titrimetry was employed to measure alkalinity, hardness and chloride concentrations. We observe significant variations in the hydrochemistry of groundwater: pH 3.95 to 7.95, EC 44 to 1110 $\mu S \cdot cm^{-1}$, Turbidity 0.1 to 45 NTU, colour <5 to 60 HU, TDS 31 to 779 $mg \cdot L^{-1}$, hardness 3 to 402 $mg \cdot L^{-1}$, alkalinity 10 to 365 $mg \cdot L^{-1}$, Cl^- 5 to 92 $mg \cdot L^{-1}$, SO_4^{2-} 0.5 to 17 mg/L, PO_4^{3-} <0.01 to 2.4 mg/L and NO_2^- 0.01 to 0.08 $mg \cdot L^{-1}$. Metal concentrations are Fe 0.06 to 3.4 $mg \cdot L^{-1}$, Mn <0.01 to 1.65 $mg \cdot L^{-1}$, Cu 0.01 to 1.30 $mg \cdot L^{-1}$, Zn <0.01 to 3.3 $mg \cdot L^{-1}$, Cd <0.01 to 0.006 $mg \cdot L^{-1}$, Pb 0.01 to 0.04 $mg \cdot L^{-1}$, Na 4 to 87 $mg \cdot L^{-1}$ and K 0.2 to 80 $mg \cdot L^{-1}$. With the exception of isolated cases of trace-metal contamination and turbidity, groundwater from the boreholes in the two districts is of acceptable chemical quality for domestic use.

Increased risk of diarrhoeal diseases from climate change: evidence from communities supplied by groundwater in Uganda

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The incidence of diarrhoeal diseases rises dramatically during the rainy season in the humid tropics where there is considerable reliance upon unpiped, groundwater-fed sources including wells and springs for domestic water supplies. Interruption of faecal-oral transmission of pathogenic microorganisms is problematic in rapidly urbanising areas of sub-Saharan Africa where access to adequate sanitation is critically limited and there are a range of contaminant pathways to water sources drawing groundwater from weathered crystalline rock aquifers. In the city of Kampala (Uganda), our high-frequency sampling of protected springs shows gross but ephemeral contamination by thermotolerant (faecal) bacteria in response to heavy rainfall events (> 10 $mm \cdot day^{-1}$). Through dynamical downscaling of future climates predicted by the HadCM3 general circulation model (SRES

A2 forcing scenario) using the regional climate model, PRECIS, we show further that the frequency of heavy rainfall events is projected increase substantially over the 20th century in Uganda. Strong correlations between sanitary risk scores and bacteriological contamination of groundwater-fed sources stress, however, the importance of improved community hygiene in mitigating the increased risk of diarrhoeal diseases posed by climate change.

Spatial and temporal groundwater quality monitoring in rural Benin, West Africa: an example of collaboration with local populations

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Experiences in developing regional and local water-quality data for rural Bénin are presented. This work represents collaboration among a number of participants including the local populations impacted by the studies. Regional (spatial) sampling was performed by the technical partners with sufficient spatial resolution to allow geostatistical analysis at the scale of hundreds of kms. Local (temporal) sampling was completed by teams from the local population trained to measure nitrate and associated parameters using test strips and colorimetry. The local monitoring program has allowed collection of reliable, weekly water-quality data for a period of more than three years. Difficulties overcome have involved issues of language, logistics, and reliability of field equipment. Results illustrate that collaboration among diverse participants can result in collection of high-value, water-quality data. In particular, the efficacy of relying on a local population with minimal formal education to collect reliable data on water quality has been demonstrated.

Reliability of interview data for monitoring and mapping groundwater

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Groundwater levels are falling in many areas of the world though we often lack sufficient data to assess the magnitude of this decline. Monitoring wells can track these changes but are not always available where needed. People who maintain personal or village wells are familiar with local groundwater conditions and can provide details where scientific data are absent. The reliability of these interview data is uncertain. In this research, the accuracy of interview data is assessed by comparing water table depths reported by users of traditional wells to data recorded independently by nearby monitoring wells for 1985, 1995, 2000 and 2005. In all cases, the correlation between well water depths is at least 0.9 and the regression coefficient is between 0.797 and 0.867, indicating that estimation of depths to the water table can be reliably made based on oral reporting from traditional wells in the absence of hydrological well monitoring.

The challenge of climate variability and change to the sustainability of shallow groundwater supplies: a case study from Kabubbu Village, Uganda

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Shallow wells which dry up during the dry season, highlight the delicate balance between groundwater recharge and demand. In Kabubbu Village of Wakiso District (Uganda) some wells, which are meant to serve the community, fail after some time during to the dry season. Seasonal variability in shallow water tables must be considered when constructing water sources. The following must be addressed properly considering the climatic aspects to provide reliable water sources throughout the year: Institutional and funding option; social cultural dimension; participatory implementation and including all stakeholders when implementing these projects; flexibility of design option; climate concern education; environment concern; and land requirements. In conclusion, if all stakeholders come on

board to address the climatic aspect this will solve the problem of seasonal water sources which fail to supply communities throughout the year.

The overburden aquifer and its potential contribution to reaching the MDG targets for safe water supply coverage in Northern Uganda

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The paper discusses the experience of the authors in the implementation of a NGO-funded shallow borehole drilling programme in Apac and Lira Districts of Northern Uganda. The shallow aquifer is often forgotten as a sustainable water resource. The paper discusses the often unjustified poor image of the shallow borehole with policy makers, development partners, contractors and NGOs due to a misconception on restricted aquifer sustainability, water quality, and presence. The advantage of shallow boreholes over deep boreholes is summarised in terms of related costs for the different activities for successful water sources. The relationship between overburden aquifer behaviour and climate change is discussed. The results of the shallow well drilling programme indicate that shallow boreholes are a cost-efficient way to serve a large part of the rural population with a sustainable good quality water source. The authors give their view on how the shallow borehole's image can be improved, and how the implementation environment can be optimised through targeted promotion of shallow borehole drilling with local governments and the use of technological option maps. The authors argue that a strong focus on shallow boreholes as preferred technological option in areas similar to the programme area will aid in attaining targets for safe water provision, specifically focusing on the rural poor.

Enhancing private sector participation in rural water supply

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The number of people without an improved water supply in rural Africa is many times greater than that of the urban population. Alongside a process of decentralization of government powers, the rural water sector in Africa and elsewhere is in transition. The private sector and NGOs are increasingly seen as providers of skills and labour to communities whereas local authorities oversee the design, construction and maintenance of water supplies. We report on efforts in Zambia, Tanzania and Ghana, to enhance the participation of the small-scale rural-based private sector in rural water supply provision through the dissemination and uptake of best practice guidelines. The work was undertaken with local partners, under the Knowledge and Research programme funded by the Department for International Development (DFID), UK.

The influence of hydrochemistry on the distribution of pathogenic strains of *Escherichia coli* in urban groundwater of Yaounde

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Bacteriological and hydrochemical studies have been carried out on the water of 10 springs, 4 wells and 13 surface waters in Yaoundé (Cameroon) with a view to characterize the pathogenic strains of *Escherichia coli* by hemagglutination tests. Microbiological analyses were carried out by membrane filtration; physico-chemical analyses used standard analytical techniques. The concentration of thermotolerant coliforms, *E.coli* and pathogenic *E.coli* exhibit spatial and temporal fluctuations. The relationship between abundances of these microorganisms and physico-chemical factors such as temperature, electrical conductivity, pH or suspended matters are weak and of varied nature on the whole. The distribution of these bacteria in these aquatic environments depends upon numerous environmental parameters. The presence of the pathogenic strains in analysed water points exposes their users to short-term health risks for which basic precautions (e.g. boiling) must be considered.

Correlations between hydrochemistry and faecal bacteria counts in urban groundwater underlying Ago-Iwoye, southwestern Nigeria

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The study evaluates some functional parameters of well water in a densely populated university town, Ago-Iwoye, in southwestern Nigeria. Well-water samples were collected at 10 sites and analysed for coliform counts, Salmonella counts, standard-plate counts, and physico-chemical properties (14 elements and 2 physical parameters). 40 % of the well samples were contaminated with coliform whereas 20% were contaminated with salmonella indicating a faecal source of contamination. Further analysis revealed that most of the wells have their chemical concentrations within tolerable ranges according to WHO standards. Unacceptable concentrations of lead and nitrate were observed at one site. Microbiological analyses confirmed the presence of faecal bacteria; 3 sites (30%) were contaminated with excessive concentrations of iron (Fe); and 4 sites possessed excessive concentrations of copper (Cu).

SESSION 2 IMPACT OF CLIMATE VARIABILITY AND CHANGE ON GROUNDWATER AND GROUNDWATER-FED ECOSYSTEMS

Papers in this session seek to improve the currently limited understanding of how climate variability and change affect: (1) interactions between groundwater and surface waters including lakes, river and wetlands; (2) groundwater storage; and (3) ecosystem services provided by these aquatic habitats.

KEYNOTE: Holocene palaeohydrology, groundwater and climate change in the Lake Basins of the Central Kenya Rift

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The Central Kenya Rift contains small soda lakes such as Nakuru, Elmenteita and Bogoria, freshwater Lake Naivasha, and partially freshwater Lake Baringo. The hydrology of this area is controlled mainly by climate, rift-controlled morphological and volcanic barriers, faults, and local water table variations. Much of the area relies on groundwater for human and industrial use though there are widespread quality issues particularly in relation to fluoride. Despite the huge demand for the resource, little is known about the highly complex groundwater systems due to a number of constraints including lack of basic and monitoring data. Significant hydrological changes have taken place in the region over the last 10,000 years as a result of global, regional and local changes, but the impacts on groundwater resources are still largely unknown. IPCC projects a 10 to 15% increase in rainfall in the area but it may not necessarily result in a concomitant increase in groundwater recharge. High groundwater recharge periods appear to be anchored on a decadal cycle.

Oases in the apocalypse: the critical role of aquifer dependent ecosystems in mitigating climate change impacts in Southern Africa

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Climate change in Southern Africa is predicted to generally increase temperatures, increase CO_2 deposition, decrease precipitation and potentially decrease carbon uptake. Aquifers will be impacted by a change in recharge rates, influenced by changes in precipitation input and bio-physical properties of the unsaturated zone. Aquifer discharge zones are widely used by ecosystems in Southern Africa, and their specific eco-hydrology results in dependent ecosystems which often have a special function as keystone ecosystems and significant ecological ‘multiplier effects’ or trophic subsidies. Aquifer dependent ecosystems (ADEs) are likely to become eco-hydrologically more significant under climate change conditions, as they are reliant on groundwater with greater landscape reserves (storativity) and slower transfer times (permeability) than rain-fed and surface water sources. Aquifers will therefore be

a more reliable source of water for ecosystems under conditions of increased extreme events and co-efficient of variation for precipitation. ADEs are expected to act as refugia habitats during times of drought and confer greater eco-hydrological resilience to broader ecosystems and biomes as a result of their oasis effect. Increased aridity in the currently semi-arid areas of Southern Africa is predicted to have a significant ecological impact, with significant losses of biodiversity. The viable extent of South Africa's semi-arid biomes is predicted to halve with climate change. This region has the lowest rate of mean annual precipitation (MAP) conversion to mean annual runoff in the world. Studies in this region have also shown that groundwater recharge varies with greatest sensitivity in the 200 to 600 mm MAP range. Shifts in this range could therefore have the greatest effect on discharge rates to ecosystems and the depth of the water table. This will affect groundwater use by ecosystems and people, particularly in rural areas where communities are more dependent on the local water and ecological resource base. Hydrogeologists need to assist ecologists in recognising aquifer discharge zones and dependent ecosystems, and to work with catchment managers in protecting groundwater environmental flow requirements. We will need to improve our confidence in groundwater eco-hydrology to support informed decision making on water allocation in increasingly stressed conditions.

Preliminary assessment of the effects of climate change on groundwater resources in Cameroon

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Analysis of recent climatic trends in Cameroon reveals significant warming trends in recent decades. Warming trends have already had significant effects on water resources in Cameroon - most significantly in terms of groundwater resources. The effects of climate change on groundwater resources of Cameroon include changing precipitation and temperature regimes, coastal flooding, urbanization, woodland establishment and changes in cropping and rotation. A subjective ranking of key effects and vulnerabilities due to climatic change in Cameroon identifies water resources and hydropower as being of the highest priority in terms of certainty, urgency, and severity of impact, as well as the importance of the resource being affected. The focus of the present paper is to carry out preliminary assessment of the effects of climate change on groundwater resources of Cameroon.

Climate change, freshwater resources and access to safe water - the global response under the UNFCC

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Freshwater is finite, limited and in great demand. In recent decades, global consumption of freshwater has risen dramatically and far outstrips population growth. A number of environmental problems associated with increased demand placed upon accessible freshwater resources in groundwater, rivers, and lakes are emerging around the world. The vulnerability of countries to climate change varies enormously. In sub-Sahara Africa, rainfall-fed agriculture accounts over 70% of employment and is especially vulnerable to climate change impacts on hydrology. Global warming is predicted to lead to more frequent and severe droughts that destroy crops on marginal agricultural land and place additional stress on limited freshwater resources and its infrastructure. Drought-prone areas are likely to increase in extent. Heavy precipitation events, which are likely to increase in frequency, will increase flood risks, leading to water pollution and therefore serous health problems. Access to clean and safe water is and will be one of the greatest challenges for sustainable development. The United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol is our current basis for tackling climate change and its associated problems. The UNFCCC commits parties to reduce or avoid the emission of greenhouse gases and to find ways of coping with the negative impacts of climate change. Paragraph 1(e) of Article 4 commits Parties to "*cooperate in preparing for adoption to the impacts of climate change; develop and elaborate appropriate integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods*". Climate change is a global problem so are the problems resulting therein. Access to clean and safe water is therefore a global concern and indeed a development concern.

Assessing the impacts of climate change and variability on water resources in Uganda: developing an integrated approach at the sub-regional scale

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A one-year project to enhance indigenous scientific capacity to undertake integrated assessment of the sub-regional impact of climate change and climate variability on water resources in Uganda was sponsored by SysTem for Analysis, Research, and Training (START). Through a programme of training and collaborative research, a PC-based regional climate model (RCM), using PRECIS (Providing Regional Climates for Impact Studies) of the UK Meteorological Office, driven with lateral boundary conditions from the HadCM3 (GCM) simulations of future climate (SRES A2 sceanrio for 2071-2100) was used. RCM outputs were used to drive soil-moisture balance models of the terrestrial water balance for water resource management applications. The START project also provided an opportunity for focused dialogue in Uganda between those engaged in the management of water resources and those engaged in the study and assessment of climate variability and change. Preliminary results in the validation of PRECIS model outs using 1991-1994 data indicate that the PRECIS model was able to simulate both seasonal and monthly rainfall values that showed a positive correlation trends of $0.35 < r < 0.9$ when compared with actual observations. However, there was a tendency for the model to overestimate rainfall amounts in some climatologically homogeneous zones and to underestimate rainfall amounts in others.

The relationships between groundwater and surface water in the upper Niger and Volta basins of West Africa

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The upper Niger and Volta rivers exhibit substantial and very different variability. The Bani river, largest tributary to the Niger river in Mali shows a dramatic decrease of runoff after the 1970's whereas the Nakambe river (upper Volta basin) shows increasing runoff over the same period. As variations in groundwater discharge (baseflow) might play an important role in influencing this surface discharge variability, we examined water table data from the national groundwater networks of two countries, Mali and Burkina-Faso, and compared them to surface runoff. The results are that the variability of the Bani low flows is well correlated to a decrease of the water table. Concerning the Volta basin, the runoff increase is not supported by a water table increase but is due to the land degradation which reduces the water holding capacity.

Preliminary results on the monitoring of the groundwater - surface water interactions in the Victoria Nile basin of Uganda

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The role of groundwater in maintaining surface water levels during periods of low or absent rainfall on low relief surfaces of Eastern and Southern Africa has received little attention and remains very poorly understood. Neither a clear conceptual nor numerical representation of the interaction between surface water and groundwater in this terrain exists. In the Lake Victoria and Victoria Nile basins of Uganda, interactions between groundwater and surface waters (lakes, wetlands) are commonly ignored and groundwater is excluded from estimations of the lake-water balance. Our research seeks to characterise the interface and hence pathways between groundwater and surface water and, ulitamtely, to assess the contribution of groundwater to surface waters under variable climatic conditions. We find recent regional changes in groundwater storage indicated by borehole hydrographs at 10 stations in central Uganda correlate well ($r^2 = 0.6$) with large-scale, satellite (GRACE) observations of changes in total water storage. We also report of preliminary efforts to charatcerise the lithological interface and

dynamic hydrological gradients between groundwater and surface water at two sites of Lake Victoria at Jinja and Entebbe, and Lake Kyoga at Bugondo. Most of the groundwater interacting with the surfaces waters flows within saprolite underlying a relatively thin (<5 m) lacustrine sand. Daily observations of the hydraulic gradient between groundwater and Lake Victoria at Entebbe since 1998 indicate that the groundwater primarily discharges to the lake. The magnitude and direction of this flux appears to be strongly influenced by variations in precipitation and dam releases at Jinja.

Groundwater-surface water interaction as a component of the ecohydrology of arid regions

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Ecohydrology is more than just hydrology and ecology combined. It is understood best if science, engineering and construction, public administration and political decision assist each other in an integrated scheme and on a common scale. The Biosphere Reserve “Tafilalt Oasis”, in south of Morocco, is dependent upon all four of these aspects for its sustained existence. Based on four years of observations in a small aquifer in the Ziz River (Tafilalt Oasis), the dynamics of a groundwater system are analysed. Changing spatial and temporal flow patterns during differing hydrological situations were examined using a combined hydraulic and hydrobiogeochemical approach. Major changes in the management of groundwater (GW) downstream of the oasis were associated with problems related to clogging processes in the river bed as well as with general improvement of water quality. Climate has a strong influence on the structure and functioning of hyporheic areas by controlling temperature, precipitation, evapotranspiration, and runoff.

Impact of simulated extreme hydroclimatic conditions on groundwater resources

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A fully coupled regional climate-hydrologic modeling system (RAMS-Hydro) that incorporates surface, sub-surface and groundwater processes, is applied to investigate the impact of groundwater reservoir on the simulated extreme hydroclimatic conditions. Based on the ready availability of model evaluation and validation data, the present study focuses on two most extreme drought and flood conditions experienced over Midwestern parts of the United States in 1988 and 1993, respectively. However, preliminary progress in adapting RAMS-Hydro to study extreme hydro-climatic anomalies over the Nile sub-basins is also described. Two parallel simulations are performed, with or without water-table dynamics (i.e., changes in groundwater storage). It is shown that the inclusion of water table dynamics in one of the soil drainage schemes leads to significantly altered simulated land-atmosphere responses and feedbacks, compared to the scheme that allows free drainage at the bottom of the soil column. It is further shown that with groundwater storage the simulated precipitation is more consistent with observations in the semi-arid, water-limited regions of the western United States. In these areas, our current research suggests that groundwater introduces a stronger vertical interaction (coupling) between the land surface and overlying atmosphere. However, in the relatively humid areas, where the water table is also shallow evidence of water table influence on the temporal and spatial variability of root-zone soil moisture that is reflected in the variability of evapotranspiration, surface heat fluxes and, to some extent, precipitation is not obvious. Instead, both lateral and vertical moisture transport appear to play complementary (at times competing) roles in setting up feedbacks associated with regional soil moisture, evapotranspiration and precipitation variability/anomalies. It is also evident from our simulations that by including groundwater reservoir the temporal pattern of the soil moisture are consistent with the temporal evolution of the 1988 drought and 1993 flood conditions. The temporal changes in water table depth appear strongly related with temporal changes in both soil moisture and cumulative precipitation in simulations, especially in regions where the extreme anomalies were more severe.

Variations in intensity of the westerly monsoon-like flow from the tropical Atlantic and summer rainfall over equatorial and tropical southern Africa

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An empirical orthogonal function (EOF) of the onshore flow of moisture along the west coast of southern Africa using NCEP-DOE AMIP-2 re-analyses suggests two dominant modes of variability that are linked to (a) variations within the circulation linked to the mid-latitude westerlies and the South Atlantic anticyclone, (b) the intensity of the westerly flow from the tropical Atlantic. The second mode, referred as the Equatorial Westerly mode, contributes the most to moisture input from the Atlantic onto the subcontinent at tropical latitudes. This mode appears to be associated with large-scale rainfall anomalies over the upper lands surrounding the Congo basin in January-February, with potential impacts on land hydrology persisting until April-May to the east of the Great Rift valley. It is preceded in November-December by a strengthening/weakening of the South Atlantic anticyclone. Enhanced (reduced) advection of moisture over the Congo basin is accompanied by increased (inhibited) convection processes. In the positive phase of this mode, the excess water vapour is channelled from the Congo basin to the east and southeast at surface, while the southern extension of the African Easterly Jet (AEJ) could play a role in transporting more moisture southwards at mid-tropospheric levels, leading to above-normal rainfall. During its negative phase, often related to ENSO, an eastward shift of the ascending branch of the Walker-type circulation is found to reduce convection and thus rainfall over the upper lands surrounding the Congo basin. In conclusion, the study of water vapour transport may help in explaining southern African rainfall variability and thus, more globally, in assessing issues such as climate predictability as well as potential impacts on the hydrological cycle over the continent, in particular for tropical regions which are less documented.

Simulation Ethiopian Kiremt (summer) rainfall using NCEP Coupled Forecast System (CFS)

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Significant Sea Surface Temperature (SST) modes are identified using principal component analysis. Northern Atlantic and northern Indian Ocean is the main mode of variability while the tropical eastern Pacific Ocean appeared as second mode of variability. The main rainy season of Ethiopia is highly correlated with second mode of variability rather than the first mode of variability specifically with northern part of the country. The ensemble simulation rainfall forecasts over Ethiopia for July-September (JAS) using NCEP coupled forecast system (CFS) were evaluated with the observations for the period 1981-2003. Results revealed that CFS simulation well captured the interannual variability of JAS Ethiopian rainfall though a little deviation is depicted by varying the initial conditions period. The correlation coefficient between the observations and CFS hindcast is high. However, CFS simulation failed to capture the observed rainfall over northern and eastern Ethiopia. The results further revealed that the rainfall belt for JAS season was shifted southwards by CFS simulation. The source of error for the shifting of the rainfall belt was examined by correcting the systematic SST error and by studying the main rain-producing system during JAS season. The simulation, which was made after the systematic SST error was corrected, revealed that the JAS season rainfall belt shifted towards north as compared to the CFS simulation. This simulation also indicated that the main rain-benefiting systems represented their position close to the reanalysis in comparison with the CFS simulation. The feedback of soil moisture is also investigated in this study. The comparison of CFS and reanalysis of soil moisture for the first 10 cm in volume indicated that the soil moisture is underestimated by the CFS simulation over northern and eastern parts of the country.

Climate change impacts on groundwater recharge in Draa watershed, Morocco

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In Morocco the examination of the last three decades shows revealing signs of climate change including: the frequency and intensity of droughts, unusually devastating floods, the decrease in the snow cover period on the peaks of the Rif and the Atlas mountains, the modification of spatial and

temporal rainfall distribution. An integrated approach is described from Draa watershed, south of Morocco, to identify the main factors that affect groundwater recharge including changed precipitation and temperature regimes, urbanization, water diversion, and changes in cropping and rotations.

Isotopic study and relationship between surface water and groundwater in the Souss-Massa basin of southwestern Morocco

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This paper summarises the results from stable isotope studies that have recently been carried out in the Souss-Massa basin of Morocco in order to improve the management of groundwater resources. Stable isotope ratios (^{18}O:^{16}O, ^{2}H:^{1}H) in waters range from -8‰ to -5.2‰ for oxygen and from -52‰ to -34‰ for hydrogen. These isotope signatures indicate recent recharge from the Atlas Mountains and infiltration of surface water along the Oueds in the alluvial cones at the margin of the Atlas Mountains. The upstream watershed features waters depleted in their heavy isotope as a result of altitude and continental effects. Enrichment of groundwaters in heavy isotopes (^{2}H, ^{18}O) observed towards the sea, reflect evaporation effect near the condensation source or irrigation returns. Isotopic ratios in precipitation suggest that the recharge derives mainly from the Atlas Mountain whereas the contribution of the local rains is negligible downstream.

Isotope techniques for assessment of interactions between surface water, groundwater and wetlands in Uganda

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Hydrogeological, hydrochemical and isotopic techniques have been employed to assess interactions between surface water, groundwater and wetlands around Lake Victoria in Uganda. Comparison of responses of groundwater levels in a monitoring well constructed in an alluvial aquifer 140 m from Lake Victoria and surface water levels in Lake Victoria since 1999 shows similar responses until July 2005 after which the two water level curves deviate from each other. The groundwater level rises while the lake level falls suggesting that although the lake and groundwater are both recharged by rainfall, they are not well connected and are impacted differently by variations and changes in climatic factors. Had the two been well connected and impacted similarly by climatic variations, the continued and drastic drop in the lake level would have corresponded to similar but probably subdued drop in groundwater level. Electrical conductivity and stable isotope results show that there is interaction between groundwater and wetlands at 4 sites suggesting that the wetlands are groundwater-fed. Similarly, the results show that there is interaction between lake water and wetlands at 2 sites suggesting that these wetlands are lake-fed. As expected, lake water is highly enriched in stable isotopes while the groundwater in the monitoring well lies along the local meteoric line suggesting that the groundwater is not recharged by lake water. These preliminary results show that there is no interaction between groundwater and surface water around the Ugandan part of Lake Victoria. However, there are interactions between groundwater and surface water with the wetlands but these vary spatially. The results suggest that the variations in both groundwater and surface water resources due to climate variability or change will impact wetlands around the lake differently.

Detection of inhomogeneities in the national climate dataset (1902-2003) of Uganda

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Climate data are a key component of water resource management. This fact has recently been emphasized by the superimposition of human-induced climate change on natural climate variability. Detection of meteorological trends associated with climate change requires the elimination of errors associated with observations and record keeping. Since excessive rainfall raises the water table and excessive drought lowers it, accurate records of Maximum Annual Rainfall (MAR) and Consecutive (zero) Dry Days (CDD) are critical to assessments of climate impacts on groundwater. The WMO together with the climate scientists are keen to see that inhomogeneities within the climate datasets are removed. As recgonised by Yadowsun Boodhoo at the *4th seminar on Homogenisation and Quality*

Control in Climatological Databases in Budapest (2004), homogenization of the climate datasets is not within the reach of all member countries. This paper reviews quality control efforts performed under the Hydroclimatic Study (2001) in Uganda that addressed errors and inhomogeneities within the national climate dataset. The detection of errors and inhomogenities in climatological datasets using metadata and quality control measures was undertaken through an inter-disciplinary study carried out by the Uganda Meteorological Department (UMD) and Water Resource Management Department (WRMD). 597 rainfall and 30 temperature stations which were digitized using CLICOM software, generated 16,363 and 1,500 records of rainfall and temperatures, respectively, that span the years 1902 to 2003. Different types of errors and their relationship were identified. Checking logics (nature of checking algorithm) was employed both by automatic computer programs and manual checks. The check tests used varied in accordance with the characteristic of logical operations, the element and the type of data being checked, daily, monthly or annual data type and also suspicious zeros. Suspicious values were compared to their neighbours and available metadata was checked to prove the worthiness of the record. As a result of these quality control techniques, inconsistent records and extreme rainfall events were identified. Inhomogenities were discovered in Mbarara, Buvuma and within estates stations where management had changed abruptly.

SESSION 3 MONITORING AND MODELLING GROUNDWATER USE AND REPLENISHMENT

Papers in this session address the critical shortfall in Africa of sustained monitoring of hydrogeological parameters (*e.g.,* groundwater levels, abstraction) as well as the storage and use of monitoring data that are presently available.

KEYNOTE: Using transient models to confront the impacts of climate change on groundwater reserves in sub-Saharan Africa

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Burgeoning cities and a changing climate pose extraordinary stresses on the management of water supplies in Africa. Groundwater flow models can greatly assist pre-emptive decision-making but their use is largely limited to steady state scenarios that ignore aquifer storage The importance of storage is well illustrated by “fossil” hydraulic gradients in the sedimentary basins of North Africa and, on a smaller scale, by the basement aquifers of sub-Saharan Africa which often rely on water released from storage in the regolith. In future, aquifer models will prove invaluable for optimising the use of groundwater resources and confronting the impacts of climate change, but they must be run in “transient mode” that fully incorporates time-variant inflows and outflows. This requirement will impose additional data demands in the form of reliable specific yield values, together with good temporal information on precipitation, potential evaporation, groundwater levels and stream flows. Lack of adequate field data to “fuel” predictive models is emerging as the greatest constraint on tackling the climate change problem.

Monitoring and modelling groundwater use in sub-Saharan Africa: issues and challenges

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In the last 5 decades, there has been a growing demand for freshwater, creating water shortages across the world. The need for predictions of groundwater flow and contaminant transport in the sub-surface (over large distances and long-term periods) has imposed extraordinary demands on the field of hydrogeology. Such a need arises from projected population growth, with Africa producing the highest growth rate, and a changing climate. The limited knowledge of temporal distribution of groundwater quality on a national scale has hampered adequate development and the judicious use of the resource in many countries of Africa. Effective management of Africa's groundwater resources is constrained by a critical shortfall of sustained monitoring of basic hydrogeological parameters. This paper reflects on the shortfalls in the designs, construction and maintenance of groundwater databases and presents case studies that employ monitoring data with current challenges in modelling groundwater use in

Africa. Prior to identifying possible strategies and cost-effective techniques for groundwater monitoring, cognizance of constraints and considerations such as responsibility and funding were taken in this study. Proposed strategies consider such aspects as the level of information required at country- and continent- scale, available resources, monitoring frequencies, funding and the use of a pilot-scale study to initiate national or continent-wide monitoring network.

The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment of Uganda

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Predicted future warming in equatorial Africa, accompanied by greater evaporation and more frequent heavy precipitation events, may have substantial but uncertain impacts on terrestrial hydrology. Quantitative analyses of climate change impacts on catchment hydrology requires high resolution (<50 km) climate data afforded to Regional Climate Models (RCMs). In this study we use validated precipitation and temperature data from the RCM PRECIS (Providing Regional Climates for Impact Studies), to quantify the impacts of climate change on groundwater recharge and runoff, in the River Mitano catchment (2 100 km^2), south-western Uganda, using a semi-distributed soil moisture balance model (SMBM). SMBMs explicitly account for changes in soil moisture and partition effective precipitation into groundwater recharge and runoff. Increases in catchment precipitation of 14 % and potential evapotranspiration of 53 % under the A2 emissions scenario (2070-2100), result in increases in recharge and runoff of 66 % and 123 % respectively.

Estimating effects of climate change on groundwater: case of Ssezibwa catchment in Uganda

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This paper investigates the effect of climate change on the groundwater system of Ssezibwa catchment in Uganda. The anticipated effects are analysed in relation to groundwater recharge and groundwater flow or base flow. WetSpa, a physically-based distributed hydrological model is used to simulate the hydrology of the catchment. Climate change predictions are obtained from the UK Hadley Climate model and downscaled to the local climate using a statistical downscaling model, SDSM. The downscaled climate is extracted for the current period (1960-1990) and three future periods 2020’s (2010-2039), 2050’s (2039-2069) and 2080’s (2070-2099) and used as inputs in WetSpa to investigate the changes in groundwater recharge and baseflow conditions. A trend analysis is also performed to examine whether climate change is actually taking place in the study area. The results generally show an increase in recharge and baseflow for the future conditions. These changes become more pronounced from the 2050s onwards. The simulated changes in rainfall are shown to be the major factor affecting the predicted changes in flows and recharge.

Application of a semi-distributed SWAT model to an Upper Nile catchment: implications for groundwater resources

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Uganda, like many other developing countries, is faced with escalating challenges of raising sufficient resources to meet its water supply needs. The abstraction of groundwater for water supply, especially for rural communities, requires the assessment of its quantity and quality. Recent hydrological research has focussed on using spatially distributed hydrological information. This move has been largely due to the wide development and testing of distributed hydrological models, which have also been applied in developing countries. In this study, groundwater recharge is estimated using a semi-distributed hydrological model (SWAT), which is applied to a catchment in Uganda. The model was calibrated against observed stream flow for the Mpologoma basin over the period 1970 – 1974. The results, in terms of simulated stream flow, recharge and groundwater flow, clearly demonstrate

reduced groundwater storage in the valleys. The results show that groundwater storage volumes are predominantly controlled by two recharge seasons per year.

Groundwater recharge and flow in a small mountain catchment in northern Ethiopia

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Management of groundwater resources requires a well developed understanding of the hydrodynamics of related aquifer systems is accomplished. Water balances are a key element in understanding and quantifying the water cycle components. Subsurface water balance components can be estimated from field measurements and observations, or can be obtained from a groundwater flow model. In the latter case, the conceptual model that is used must include the relevant hydrologic processes like recharge and discharge mechanisms. For a small catchment in North Ethiopia in the Tigray region groundwater recharge and flow is investigated. To obtain a subsurface groundwater balance, in this study a groundwater flow model is combined with a runoff model and a soil moisture balance model to estimate aquifer recharge. The method is applied on a small catchment in northern Ethiopia, a region characterized by a climate with distinctive wet and dry seasons. Results of the three model components are combined to produce an overall water balance including surface runoff, soil moisture storage, aquifer recharge, storage in the phreatic aquifer, groundwater seepage and spring discharges. The result is a transient water balance for the period 1995 until 2006 with monthly averages for the different balance components.

Assessing changes in terrestrial water storage in Africa using GRACE satellite gravity data and JLG terrestrial water storage model

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In Africa, large-scale drought has occurred in recent years and the shortage of water is one of the serious problems. Hence, it is very important to study current and future landwater movement in Africa. The variations in the temporal gravity field revealed by dedicated gravity mission GRACE (Gravity Recovery and Climate Experiment), which can be interpreted as surface mass changes, have been widely employed for studies of landwater movements. One of the advantages to use GRACE data for the study of landwater movements is that GRACE can detect total terrestrial water storage variations including groundwater and it is directly useful for the current monitoring of the large-scale landwater movement. On the other hand, for the discussion on the securing and the effective use of the water resource, it is also important to investigate movement of each landwater component separately as well as the total terrestrial water. In this respect, numerical landwater models which consider physical storage processes and can be forced by atmospheric objective analysis data, are useful. Numerical models are also useful for the future prediction of the landwater storage. However, at this stage, most of numerical models have considered the groundwater components insufficiently. Thus, in this study, for the purpose of obtaining more reliable knowledge of current and future landwater movement from landwater model, we employed GRACE data to improve the landwater model. As mentioned above, GRACE data gives a constraint to total landwater variation and it is also useful to improve landwater model. We used Japan Meteorological Agency JLG (JRA-JCDAS LDA and GRiveT) model, which consists of soil moisture, snow water equivalent, river water storage and groundwater storage. By comparing the GRACE results with the outputs of the model, we tuned river discharge and groundwater storage for each river basin. On the basis of the results of current landwater monitoring by GRACE and the simulation results of improved landwater model, we finally discuss the effective current and future securing of water resources in Africa.

Design of a national groundwater monitoring network in Uganda

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A national groundwater monitoring network of 15 monitoring stations was established in Uganda in 1998 based on existing boreholes. The objective of the network is to monitor changes in groundwater quantity and quality resulting from natural (climatic) and human impacts as a basis for national strategy for groundwater resources development and management. This network is a starting point of groundwater monitoring and is regularly reviewed so that additional sites are added to meet future monitoring requirements or to replace some sites that are found to be unsuitable. The monitoring network has undergone continuous reviews in order to address the key water resources issues in the country. Systematic design of an issue-based monitoring network of surface water, groundwater and water quality was undertaken through a participatory process of identification of issues nationally and at sub-basin level. Of the 93 water resources issues identified, those relevant to groundwater include impact of abstraction, long-term climatic change, seasonal variations, poor water quality, pathogenic contamination, pesticide pollution, nitrate pollution, and state of water resources. Issues identification was followed by classification of monitoring sites in terms of whether they will be basic, specific or temporary networks. This classification was followed by prioritisation and ranking of the proposed sites based on three major factors namely; water resources issues, geology and spatial distribution. Each issue was given a weighting factor depending on its level of importance in a particular area. A prioritized issue-based groundwater monitoring network consisting of 47 wells of which 25 are basic and 22 are specific stations was designed and is undergoing phased establishment. Network review is a systematic and continuous process since the priority of water resources issues is bound to change as the impact of these issues themselves changes, as political priorities change and as the documentation level of the issues is improved.

Improving groundwater monitoring networks in Africa: developing integrated approaches to the assessment of the impacts of climate and socio-economic change on groundwater resources in Africa

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Groundwater is an important primary source for agriculture, domestic and industrial water supply in many African countries. The demand for groundwater in Africa is likely to increase in the future, primarily due to population growth. Additionally, groundwater demand may increase in some regions because of the need to offset declining summer surface water availability due to climate change. Hence, groundwater can be considered as buffer resource, coping with climate change. On the other hand, groundwater is - as part of the hydrological cycle - also affected by climate and its changes. In comparison to surface water impacts, there has been little research on the potential effects and vulnerability of groundwater systems to climate change, because of the invisibility of acting processes and complexity in the evaluation of responses, which are generally indirect and slow. In this paper, we review the main climatic drivers and major effects on groundwater resources, paying special attention to Africa. The structure proposed by UNESCO’s initiative GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Change) is used as basis for this overview. In addition, the methods used to evaluate climate induced changes in groundwater-related variables are discussed. At regional scale, remote sensing and modelling are very valuable tools for estimating current and future groundwater-related parameters. However, ground observations and systematic monitoring of changes in groundwater-related parameters are necessary for calibration and verification of these techniques. Together with its partners, IGRAC is establishing a sustainable global groundwater monitoring system (GGMS). The GGMS will be integrated with remote sensing observations and global groundwater models, in order to attain the ultimate purpose of assessing and predicting effects on global groundwater resources under climate change conditions. The paper focuses on implementation of GGMS for Africa.

Using satellite-based solar insolation for estimating long-term regional evapotranspiration

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Incoming short-wave solar radiation (insolation) data are used to formulate net radiation, and subsequently, evapotranspiration (ET). This paper highlights a satellite-based capability towards monitoring ET on 2 to 20 km scales across large geographical regions. As an example of what may be performed over Africa, we present a study performed over the state of Florida in the United States. Estimates of solar insolation from GOES satellite over a 10-year period (1995-2004) have been produced at 2 km spatial resolution. Model validation and calibration of the daily insolation product was undertaken using pyranometer data. Pre-calibration results indicated good performance, with a model error of 2.2 MJ $m^{-2}day^{-1}$ (13%). Calibration reduced errors to 1.7 MJ $m^{-2}day^{-1}$ (10%), and also removed time- and season-related biases. The final dataset will be used by State of Florida Water Management Districts to produce 2 km resolution ET estimates. The authors seek the feasibility of performing such an effort over African regions.

Climate change impacts on groundwater recharge in northeastern Uganda and potential role of groundwater development in livelihood adaptation and peace building

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The delicately balanced livelihoods of the people of northeastern (NE) Uganda are under increasing pressure due to the dynamic conditions of both the natural and socio-political environments of the region. The climate record for NE Uganda during the 20th century shows patterns of air surface temperature change that mirror those observed in global datasets, with post WW2 cooling giving way to a strong warming trend since the 1960s. While no such trends are observed for precipitation in the record, the latest IPCC report indicates the possibility of future increases in precipitation. Preliminary groundwater recharge simulations are presented which reproduce observed groundwater level fluctuations and give best estimates for groundwater recharge decreasing from 140 $mm{\cdot}a^{-1}$ in Teso region to less than 30 $mm{\cdot}a^{-1}$ in the semi-arid Karamoja plain. The underlying models and the available data strongly suggest that recharge occurs predominantly through indirect or localised mechanisms. If so, effects caused by higher temperatures may be more than offset by the predicted increase in future precipitation leading, overall, to an increase in the available groundwater resource. Adaptive strategies for the people of NE Uganda may depend on future groundwater use to an increasing extent if current environmental and socio-political trends continue unabated. Thus, further research is essential to confirm the mechanisms of recharge in the region and the sustainability of such developments. Given the role of natural resources within the current conflict dynamics, groundwater science may have a significant role to play in peacebuilding within the region in years to come.

Groundwater recharge mechanisms and water management in a coastal sedimentary basin of Benin

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Groundwater resources constitute the principal source of water supply of the large cities of the coastal sedimentary basin of Benin. In the current context of climate change, it is important to understand aquifer recharge mechanisms in order to adapt water demand to its availability in this basin. Groundwater recharge is estimated by the method of water-level fluctuations in response to rainfall variability. This study shows that, in the coastal sedimentary aquifer of Benin, groundwater recharge is related to direct infiltration of rainwater, lateral infiltration and vertical ascending leakage through the semi permeable and incidentally impermeable geological layers. Annual fluctuations in groundwater levels are in order of 1 to 3 m. Decreasing recharge and intensive pumping of water involved today induces saltwater intrusion from the Lake Nokoue and water quality deterioration. Under these

conditions, it is essential to reinforce water supply strategies contributing towards an integrated and sustainable management of groundwater.

An assessment of the response time of groundwater levels to climate change

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This paper assesses trends and variations in groundwater levels in response to variable precipitation (increased precipitation or prolonged droughts) in selected areas of Uganda. Three observation wells located in the Districts of Pallisa (Basement geology), Wakiso, Entebbe (Buganda-Toro geology) and Mbarara (Karagwe-Ankolean geology) have been selected as source wells. Water levels are treated as non-stationary time series and I examine trends and periodic components of well hydrographs in order to investigate human and climate influences. In addition, I assess the relationship between the amount of rainfall (mm) and recharge to the groundwater table (mm) and the time lag between the event and recharge. A cross comparison over the different geologies will also be done and representative response-time derived.

Ground water resources seasonal variability and vulnerability of rural communities in middle Nzoia River catchment, Kenya

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This paper assesses seasonal variability in discharges from springs and shallow wells in the Nzoia River Catchment of Kenya. A total of 28 springs were georeferenced and mapped using GIS; sixteen of which were randomly selected for water yield measurements along with eight shallow wells. The spring-water yields were measured using a stop watch and measuring cylinder. Water yields in shallow wells were estimated by depth measurement using a weighted cord. Land use was also assessed using GIS techniques. Results showed that at the onset of rainfall, the highest discharging spring is rated 5th class (0.63 to 6.3 $L \cdot s^{-1}$), which falls far below what may be considered as a 1st class spring (2 800 $L \cdot s^{-1}$). Majority (59 %) of the studied springs were in the 6th class (0.063 to 0.63 $L \cdot s^{-1}$). However, following heavy rains in August, spring discharges increased so that the majority (77 %) of the springs were rated as 5th class. In case of shallow wells, shallow groundwater levels rose by more than 1 m after the onset of rainfall. This rise highlights the dependence of the groundwater recharge events on rainfall intensity and, thus, their vulnerability to extreme rainfall variability arising from climate change. Suggestions are made for integrated water resource management to lessen vulnerabilities and to ensure sustenance of livelihoods for the rural communities in the study area.

Groundwater quality and the sustainability of abstraction from weathered and fractured granite aquifers in the Lake Kyoga Basin of Uganda

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The sustainability of abstraction from weathered and fractured granite aquifer systems in the Lake Kyoga Basin is under threat from population growth. Uganda's freshwater is a key strategic resource which is vital for sustaining life, promoting development and maintaining the environment. The collection and analysis of water resources related data and information, is therefore one of the priority areas for the water resources management sub-sector. In this study, a hydrochemical evaluation of groundwater from the weathered (unconsolidated regolith) and fractured crystalline rock aquifers was undertaken in Pallisa District; groundwater samples were analysed for minor and major elements. This survey was done to assess the quality of groundwater presently pumped from the fractured bedrock aquifer with that of the unconsolidated regolith aquifer. The results showed that electrical conductivity values (degree of mineralisation) are significantly lower for springs than for dug wells drawing from weathered (unconsolidated regolith) granite. Sampled boreholes drawing from the fractured bedrock clearly show the highest degree of mineralization, with relative enrichment of nearly all tested elements. The above trends do not apply to nitrates and suggest that non-geological factors influence their concentration. Both regolith and bedrock groundwaters are calcium-bicarbonate type indicative of relatively short flowpaths. Overall, our survey shows that the boreholes in Pallisa District are safe for drinking purposes except for a few sources with high iron concentrations.

Fluoride hydrochemistry of regional crystalline rock aquifers: a case study from southern Sri Lanka

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The estimated health impact of naturally occurring fluoride is considered to be more widespread than arsenic. Although fluoride is beneficial to bone and dental development in humans, the consumption of high fluoride (above the WHO limit in drinking water of 1.5 mg·L^{-1}) may cause severe health hazards such as dental mottling, skeletal fluorosis, and more rarely skeletal radiculomyopathy. From the known global distribution of endemic fluorosis, the most affected regions are in arid to semi-arid climatic zones; such areas are likely to be at greater risk of contamination as a result of climate change. Fluoride (F^-) in its most common form is found in several geological environments including igneous, sedimentary and metamorphic rocks and leaching of F^- into surface, soil and ground waters is the most common cause of fluoride endemics worldwide. High fluoride concentrations in groundwaters are found in many parts of the world such as the volcanic East African Rift System of Kenya and Tanzania, Ghana, China, India and Pakistan, and also in Sri Lanka where fluoride is associated with high-grade metamorphic rocks. To investigate the regional distribution of high-F^- groundwaters in the Uda Walawe Basin in the dry zone of southern Sri Lanka and to assess the main geochemical factors controlling F^- mobilisation in the crystalline rock aquifers of this and similar areas, a detailed hydrochemical survey was completed. Groundwater in wells that are used for drinking water is vulnerable to poor quality with measured F^- values ranging from 0.1 to 6.1 mg·L^{-1} in shallow dug wells and 0.2 to 9.2 mg·L^{-1} in deep tube wells. Fluoride in groundwater was found to be predominantly from a geological source, mainly fluorine-bearing silicate minerals such as biotite and hornblende. Specific hydrogeological conditions, mainly rock-water interactions and groundwater recharge and discharge patterns, were found to determine the distribution of F^-. Concentrations of F^- are higher in areas where there is limited recharge that promotes longer residence times and greater rock-water interaction. The prevalence of HCO_3^- with high PCO_2 values suggests that H_2CO_3 is responsible for silicate weathering and the release of major cations (Ca^{2+}, Mg^{2+} and Na^+) and F^-. The occurrence of accessory minerals such as carbonates, apatites and fluorite is limited and are not considered an important F^- source given that groundwaters in discharge areas are saturated with respect to these accessory minerals. Of secondary importance is high evapotranspiration in the downstream catchment areas where F^- is concentrated in shallow groundwaters, whereas in upstream areas F^- concentrations are additionally controlled by dilution in those areas that have been developed under an irrigation scheme.

Hydrogeochemistry of fluoride and salinisation of groundwater in Singida, central Tanzania

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The study focused on the determination of factors controlling high fluoride groundwater and salinization in basement aquifers of a semi-arid area in central Tanzania. Water samples were collected from productive dugouts, shallow wells and boreholes. ^{18}O, ^{2}H, and major cation and anion chemistry, including fluoride, was determined using standard analytical techniques. A sodium-bicarbonate type of water dominates the study area. ^{18}O - ^{2}H relationships suggest that infiltrating water and groundwater has undergone evaporation. Shallow wells and dugouts were found to have higher concentrations of both fluoride and chloride and this is partly attributed to effect of evapotranspiration. The main mechanism for fluoride input into groundwater as well as salinization is attributed to leaching of surface and near surface soil salts. No clear relationship was observed between depth of wells/boreholes and fluoride concentration. A more detailed investigation is needed, however, to determine the effect of sampling depth on fluoride concentration and salinization.

SESSION 4 ESTIMATION OF GROUNDWATER RESOURCES AND DEMAND UNDER A CHANGING CLIMATE

Papers in this session examine current methods of estimating groundwater resources and demand under conditions of climate variability and change in Africa.

KEYNOTE: Diffuse groundwater recharge and groundwater withdrawals in Africa as estimated by global-scale water models

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The WaterGAP Global Hydrology model (WGHM) computes groundwater recharge at a spatial resolution of 0.5º x 0.5º based on data on climate, land cover, soil, relief and a number of other physio-geographic data. WGHM is tuned against observed river discharge at 1235 stations worldwide, which arguably leads to better groundwater recharge estimates than can be obtained without such tuning. For semi-arid and arid regions, WGHM is additionally tuned against independent estimates of groundwater recharge that have mostly been derived from chloride profiles. This leads to an unbiased estimation of groundwater recharge in semi-arid and arid regions. A best estimate of long-term average 1961-90 groundwater recharge (renewable groundwater resources) for Africa will be presented, as well as possible changes in groundwater recharge due to climate change. In addition, first estimates of groundwater withdrawals in Africa will be shown. These estimates are based on, among other data, new estimates of irrigation water requirements as computed by the Global Crop Water Model GCWM, which distinguishes 26 crops.

The impact of climate change on groundwater recharge: a case study from the Ethiopian Rift

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The amount of water stored in an aquifer can be estimated through different methods that may result in the mean values. Some of the methods are through direct measurement, tracer techniques, Darcian approach, empirical formulae, soil-water balance, and hydrograph analysis. Application of the methods to estimate the groundwater resources depends on the availability of historical records but do not consider the effects of climatic changes on input variables. In Ethiopia, mean values of hydrometeorological data are used to determine the water resource of an area in order to manage the resource for future use. The use of single or mean values of climatic elements such as precipitation, temperature, humidity, sunshine and wind speed could lead to mean value or underestimate or overestimate the existing storage amount if appropriate climatic prediction is not done. The climate of Ethiopia ranges from equatorial desert to hot and cool steppe and from tropical savannah and rainforest to warm temperate. However, in recent days strong and unexpected rain is causing flooding in different parts of the country and long dry season is observed in the low lands which should be considered in recharge estimations. This changing climate produces precipitation that varies widely in the country. In almost all basins, over 80% of the runoff results from annual precipitation that falls between June and September. Due to variable geological cover and physiography, climate and physical characteristics of drainage basins, the amount of water in the rivers and runoff in the basins are directly related to effective recharge. Climatic factors are locally variable based on altitude and globally varies based on climate changes. Therefore, application of prediction methods like Precipitation-Runoff Modelling System (PRMS) which considers climate changes in an area could result in more reasonable values in runoff and recharge to an aquifer. In this paper, we develop a method of recharge estimation that takes into account climate change and variability in the Meki River Basin of the main Ethiopian Rift.

Impacts of climate variability and change on groundwater in the humid tropics: a case study from Cote d'Ivoire

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As elsewhere in Africa, rainfall in Côte d'Ivoire experiences significant inter-annual variability with alternating humid and dry periods. This variability in precipitation impacts groundwater resources. The current survey assesses the response of groundwater during dry periods over four watersheds exposed to different climates. For this, the drying up coefficient of Maillet improved by dichotomous resolution and the water volumes mobilized by aquifers, are calculated. The fluctuation of annual rainfalls has been characterized by the method of centred and reduced variables. The deficit periods 1970-1996, 1967-1997, 1969-1996, 1995-1997 and 1981-1997 are respectively pointed out in Ouangolodougou under the influence of the transitory tropical climate, Man in the west under mountain climate, Dimbokro in the centre under transitory mitigated equatorial climate, Tabou and Grabo in the south west where prevails a transitory equatorial climate. Groundwater reflects this precipitation decrease through reduced recharge and an increase of the depletion coefficient. Recharge decreases during the periods 1971-1999 for the Comoe in Yendere and Aniassue, 1980-1993 for the N'zo in Kahin on the Sassandra basin, 1971-1994 for the N'zi in Dimbokro on the Bandama, 1982-2000 for the Tabou in Yaka and 1991-2002 for the San Pedro at the pumping station which are western coastal watersheds. The calculated deficits for groundwater are 54, 47, 40, 31, 46 and 46% respectively.

Global analogues of climate change effects on agriculture and groundwater between hydrologically similar regions of the world

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Large regions of the world are heavily dependent upon groundwater for domestic water and irrigation. The impacts of climate change and modified climate variability on groundwater resources, soil water, agriculture, and human life are relatively unknown in most areas, and key sensitivities need to be explored. One low-cost approach is to identify and analyze geographical analogues between hydrologic/climatic regions. For example, hydrological similarities between Australia and South Africa have been identified previously and recently a bilateral partnership was formed between countries to collaborate on climate change adaptation. Here, recent simulation results from the Mediterranean and humid subtropical regions of Australia are related to potential counterparts in Africa. Soil and vegetation play important roles in the imbibition, storage, and evapotranspiration of rainfall, which control the drainage of water beneath the root zone. In this way, the near surface biophysical system acts as a highly nonlinear transfer function of rainfall to groundwater recharge. Both the direction and magnitude of change in soil water and groundwater recharge may vary with projected climate change. Subtropical climate change likely will lead to pronounced increases in groundwater recharge. This could increase the amount of groundwater available for domestic and agricultural use, which may be needed to offset the increased demand for groundwater, especially if drought durations increase as projected in such regions. In addition to changes in the mean recharge rate, predicted climate change is expected to affect the temporal persistence of soil water content and interannual amounts of groundwater recharge. These subsurface responses to projected changes in regional climates have profound implications for water resources management and soil-water availability to agro-ecosystems. Likewise, results of a new investigation of climate change effects on agricultural systems in the semi-arid to subhumid Great Plains of the USA will provide analogues to similar regions around the world. Thus, international scientific partnerships between countries with regions of hydroclimatic similarity are recommended. In addition to simulation studies of the potential effects, long-term soil and groundwater monitoring should be encouraged for ground-truthing of the climate effects across geographical analogues.

Modelling the freshwater availability in Africa with special attention to current and future groundwater recharge

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On a continental and annual basis, Africa has abundant water resources but the problem is that many people and large areas are suffering from insufficient water supply because of large spatial and temporal variability within and between African countries and river basins. Considering this variability, the continent can be seen as dry with pressing water problems. Though of critical importance, detailed information on water resources and water scarcity is in Africa still limited. By applying a semi-distributed hydrological model SWAT (Soil and Water Assessment Tool), the freshwater components blue water flow (i.e., water yield plus deep aquifer recharge), green water flow (i.e., actual evapotranspiration) and green water storage (i.e., soil water) were estimated with a monthly resolution for the whole African continent by dividing the area into 1496 subbasins. Using the program SUFI-2 (Sequential Uncertainty Fitting Algorithm), the model was calibrated and validated at 207 discharge stations and the uncertainty is quantified and presented for all temporally and spatially aggregated monthly and annual, subbasin and country based, blue and green water resources. The presented model and its results can be used in various advanced studies on climate change, water and food security, and virtual water trade, among others. Climate change analyses will be performed under different scenarios and their effect on various water balance components quantified.

Progressive approach for groundwater model development as a water management tool under climate change in Benin

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Since the late 1970s the occurrence of drought years increases in Northwest and West Africa presenting a major constraint to the future development of these regions. According to the IPCC conventions, a general decrease in rainfall together with a prominent surface heating can be expected for sub-Saharan Africa and north of the Sahara until 2050, with the implication of a decreasing fresh water availability opposed to an increasing water demand. In this context IMPETUS ('An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa') was initiated to offer management options to the already pressing water problems in West Africa, focusing on the hydrological cycle as determining process for water availability. With an interdisciplinary approach, IMPETUS identifies and quantifies its different system components and their complex interaction within two river catchments in West Africa (Wadi Drâa, Morocco; River Ouémé, Benin). In order to solve possible future problems of water availability, IMPETUS offers tangible ways of translating scientific results into science-based strategies and model-based operational tools. Since groundwater is a major drinking water resource and very important for irrigation, an efficient assessment tool for the groundwater resources is a central task in basin wide integrated water resource management. Hydrogeological research in Benin has been developed progressively from local to sub-regional to regional scale. Thus, the first project phase was dedicated to the comprehensive assessment of the main hydrogeological processes in a sub catchment of around 30 km^2, resulting in a sound hydrogeological conceptual model. In the course of the second step, a regional (14 500 km^2) finite element hydrogeological model was developed for the Upper Ouémé catchment. Current task is to develop a reliable numerical ground water model for the whole Ouémé catchment. As large scale models have to reach the best balance between spatial resolution and heterogeneity, different discretization methods are applied to hydrological and hydrogeological parameters. Consequently, the Precambrian fractured basement splits into connected zones with a remote sensing analysis and recharge is calculated through sub-basin ground properties. Other characteristics like transmissivity and storage capacity are attributed to specific geological settings using field experiments and official database sources. Furthermore, ongoing groundwater characterisation by means of groundwater chemistry and isotopic content will result in a more detailed numerical model.

Climate variability and its impact on the Table Mountain Group aquifers in South Africa

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The Table Mountain Group (TMG) formation lies within the southwestern Cape (SWC) region of South Africa that is characterised by winter rainfall brought mainly via cold fronts and by substantial interannual variability. The TMG regional aquifer is fractured, deep-seated, and well exposed along mountainous ranges and ridges. The TMG is considered a potential source for bulk water supply to meet both agricultural and urban needs. Previous work has found evidence that the interannual variability in SWC winter rainfall may be related to sea surface temperature (SST) in the South Atlantic Ocean and to large-scale ocean-atmosphere interaction in this region. Predictions based on results from international climatic change research indicate considerable impacts on climatic patterns of southern Africa. As a result significant changes in the rainfall distribution can also be expected over the next few decades. The impact of these changes on groundwater conditions is poorly understood. An application of Cumulative Rainfall Departure (CRD) on rainfall time series and the Standard Precipitation Index (SPI) have been used to correlate groundwater level datasets. These time scales reflect the impact of drought or otherwise on the availability of the groundwater resources. Groundwater reflects long-term precipitation anomalies hence SPI for longer time scales have been compared. This knowledge is used to estimate recharge for the sustainable development and management of the groundwater resources for present and future generations in the light of our changing climate.

Groundwater recharge and salinization in coastal areas of Senegal: impacts of climate change

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It has long been known that natural climate variability and climate change affect groundwater levels. One can predict groundwater resources will be impacted by climate change in relation to the nature of recharge, interactions between groundwater and surface water systems, and changes in water uses. Decreased precipitation will not only affect groundwater recharge (water storage), but may also impair water quality. One potential impact includes altering the equilibrium in coastal aquifers, and reducing the volume of water stored. Evaluation of these likely direct impacts is therefore essential for long-term water resource management especially in semi-arid regions where limited water resources may be the key constraint on economic development. In Senegal, one of the most serious impacts associated with a negative water budget occurs in coastal estuarine rivers where saline surface water can contaminate adjacent shallow groundwater. The Saloum and the Casamance rivers located south are both actually tide influenced inverse estuaries where hypersalinity occurs upstream to levels much greater than seawater values. As they are hydraulically connected to shallow aquifers, groundwater is greatly affected by saltwater contamination up to 120 km and 200 km, respectively, from the coast. For the Senegal River prior to 1985 (building of the Diama dam), salinization occurred up to 150 km inland. Recent studies on some aquifers (Senegal River, North Coast littoral, Saloum delta and the Casamance delta) reveal high sensitivities to climate variability and climate. These studies utilise both hydrochemistry of major and minor elements, isotopes of the water molecules together with numerical groundwater flow and water table fluctuations methods to provide information on the regional picture of recharge and groundwater flow in the context of semiarid conditions. The model approach using a sensibility analysis on the recharge values (reduced by 10 to 25%) reveal very little difference in the general appearance of the water table patterns; despite this fact the difference is still more pronounced (-1.5 to 3 m) in high water level zones whereas in lower water table region it tends to nil. In the Casamance catchment, seasonal recharge deduced from water table records indicates that climate change will inevitably impact the system and the magnitude will variably depend on the geomorphologic areas.

Impact of climate change on the renewal of groundwater resources in the Chéliff-Zahrez basin of Algeria

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The aims of our work are to study the impact of climate changes on the renewal of the groundwater in the Chéliff-Zahrez watershed. It is based on analysis of the relationship between the evolution of rainfall and the piezometric heads. The relationship between rainfall patterns and fluctuations of piezometric levels of the groundwater were analyzed. The aquifers of Upper Chellif, Middle Chellif, Lower Cheliff and Mina are the most important in the studied area. Groundwater is the most important resource used in the watershed Cheliff-Zahrez. The renewal of the resource depends on the groundwater recharge which is a function of rainfall and evapotranspiration. An increase in evaporation and evapotranspiration, due to temperature increases would lead to a decrease in recharge which would in turn have a direct impact on the levels and quality of groundwater. Several recent studies have shown that the climatic trends are well correlated with changes in the groundwater levels. The studied area encompasses two watersheds: the basin of Cheliff in the North and the basin of Zahrez-Sersou in the south. The climate of the region is semi-arid to temperate. The rainfall pattern has undergone a change from the seventies that has led to the emergence of a rainfall deficit from 1970 and the continuation of this diminution in precipitation over the last decade of the last century. The rain diminishes with distance from the Mediterranean Sea, with a little degradation of rainfall from east to west. The wettest region is in the northeast of the basin, characterized by important elevations that are exposed to the wet winds to the north. The annual average rainfall varies from 600 to 700 mm. On the plains the rains are less than 500 mm while in the south of the Cheliff-Zahrez basin, High-plateaux and Zahrez, the annual averages rainfall varies from 100 to 300 mm. A filter of moving averages over 3 years has been applied to highlight the main trends. The results show that the periods 1980-1994 and 1998-2001 are characterized by a significant deficit in rainfall recorded in the various stations. Thus, the annual average rainfall recorded was below the average reported for the period 1968-2001. Generally, the piezometric analysis shows that the variations of the piezometric levels in the Chelif valley closely reflect the pluviometric evolution recorded in the rainfall stations of Ghrib, El Khemis, Chlef and Relizane. The response of the water levels to the climatic variations show lag times that depend on the hydraulic conductivity, the storage of the aquifers, and also on the distance between the recharge zones and the observation points. We have seen a marked decrease in the levels of the groundwater since 1997 with a decline of 0.5 to 1 m.

Episodic recharge to the Quelo-Luanda aquifer: anticipating the impacts of climate change

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Quelo-Luanda hydrogeological system (2 000 km^2) underlies Luanda and is bordered by the Atlantic Ocean and Rivers Bengo and Kwanza. It has a maximum depth of 500 m and comprises detrital formations of Middle Miocene to Pleistocene age. Mean annual precipitation is 370 mm and is highly variable. Recharge is estimated to be 250 mm per decade. Groundwater levels (60-70 m), low hydraulic gradients (0.001 to 0.005) and high salinity of the water (800 $\mu S \cdot cm^{-1}$ in recharge areas, up to 6 000 $\mu S \cdot cm^{-1}$) have been determined. Quelo-Luanda system can be considered as a useful aquifer yet further development is constrained by salinity. Although the aquifer system is currently able freshwater, longer periods of absent recharge, as a result of climate change, may severely restrict future groundwater use.

Quantifying the impact of predicted climate change on groundwater recharge to fractured rock aquifers

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This study investigates the potential impact of climate change on groundwater recharge to fractured bedrock aquifers. A case study area in Canada is used to demonstrate the methodology, but the methodology has been applied in other areas and may provide a means to estimate recharge under scenarios of climate change in other regions. The HELP (USEPA) hydrological model was used. This model derives estimates of vertical flux (recharge) at the base of a vertical percolation column. Different vertical percolation profiles, representative of the different combinations of soil type and thickness, depth to water table, and vadose zone fractured media- were developed. Average estimates of media properties (thickness, hydraulic conductivity, field capacity, wilting point, and porosity), surface slope, leaf area index, etc. were mapped in ArcGIS for generating recharge zones, which allowed spatial and temporal integration of the recharge results. The recharge model is driven by daily weather data downscaled from current and future global climate model (here CGCM1) predictions using SDSM and LARS-WG stochastic generator that is calibrated to the observed local climate data. Recharge in the study area varies from 180 to 540 $mm \cdot a^{-1}$ and is shown to increase progressively in the future.

The movement and occurrence of groundwater in the Ethiopian volcanic terrain: Implications for exploration and development

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Being one of the largest and thickest volcanic sequences in the world, the Ethiopian volcanic terrain has long held the attention of geoscientists. Although detailed geological, tectonic, and seismic investigations have been carried out, very little research has been conducted, to date, on the hydrogeology. This work aims at filling this gap by converging evidences from hydrogeological mapping, hydrochemistry and satellite spectral data analysis under GIS environment. Selected regions with distinct hydrogeological regimes are identified. The study starts from the regional conceptualization to a more focused analysis of the occurrence and movement of groundwater including aspects of water quality in the areas representing: highland thick Trap volcanic sequence, intermountain graben field with thick sediments, fractured rift boarded by steep high altitude plateau, and vast flood plain covered with alluvial sediment with adjoining piedments in a tectonically active rift floor. The results reveal extreme variations in aquifer hydraulic characteristics. Recharge, flow and occurrence of groundwater strongly controlled by the geomorphological setting of highland-rift transition as well as the structure and lithology of the volcanics and associated sediments. Groundwater recharge varies in a wide range between a few tens of mm to 400 $mm \cdot a^{-1}$. Groundwater flow in the rift and escarpment areas is largely controlled by normal regional faults. Despite high recharge and permeable rocks some highlands adjacent to steep escarpments have lower groundwater levels as a result of flow through large open faults. Wide basic and acidic volcanics, alluvio-colluvial and lacustrine deposits form shallow unconfined aquifers, with transmissivity of 27 to 135 $m^2 \cdot d^{-1}$. Deep groundwaters are localized often in weathered basalts and ignimbrites interbeded with river gravels in the highlands locally forming artesian conditions. The thick intermountain graben fills and the rift flood plain sediments associated with fractured volcanics form the largest aquifers dominantly under water table and semi-confined conditions. Well yields in the deeper basaltic aquifers are directly related to the existence of faults and interbedded sediments. A broad survey of the hydrochemistry indicates large spatial variations. Chemically, groundwaters are dominated by alkaline earths (Ca and Mg) and HCO_3 in the highlands and Na, Cl and SO_4 become more important in the rift. The salinity increases dramatically from the highlands towards the rift following the regional groundwater flow direction. The highland waters are predominantly fresh with low Total Dissolved Solids (50 to 1 200 $mg \cdot L^{-1}$). The rift waters have high salinity and fluoride, which is the major national water quality problem. The complex geohydrological conditions unravelled in this study clearly signify the importance of understanding the plateau-rift hydrogeological architecture in finding proper well sites and developing sustainable groundwater management rather than looking only at the permeability and recharge of aquifers. This issue has far-reaching implications for groundwater development in the entire East African Rift System.

SESSION 5 GROUNDWATER MANAGEMENT IN THE HUMID TROPICS OF SUB-SAHARAN AFRICA UNDER CLIMATE VARIABILITY

Papers in this session discuss groundwater management strategies in both urban and rural areas of sub-Saharan Africa under conditions of climate variability and considerable hydrological uncertainty.

KEYNOTE: Urban water-supply security in sub-Saharan Africa: making the best use of groundwater

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In Sub-Saharan Africa the rate of urban population growth places heavy pressure on water-supply provision – a pressure that is likely to be exacerbated by reduced reliability of surface-water sources under most climate change scenarios. Where suitable aquifers are present, expansion of groundwater development is usually the preferred response, in terms of time taken, capital outlay and drought reliability. This is widely occurring both by urban water utilities (at a variety of scales) and through the rapidly-growing phenomenon of 'community and private self-supply'. This paper provides an overview primarily from World Bank experience of the social benefits, economic implications and quality hazards of urban groundwater use, as a stimulus for discussion of the role of groundwater in improving urban water-supply security, together with the policy issues arising and the most pressing of management approaches required.

Impact of climate variability on groundwater in Dar es Salaam, Tanzania

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Tanzania, like other countries in sub-Saharan Africa, is experiencing water shortages due to climate variability. Increased demand for water combined with lower and more variable rainfall reduce per capita availability of freshwater that impairs local livelihoods. This paper focuses on Dar es Salaam and areas along Tanzanian coast to the extreme east, covered by the Wami Ruvu River Basin, one of the institutions responsible for water resources management. Dar es Salaam depends on surface water as a major source of water supply for its growing population of about four million people. The Ruvu River being the major source of portable water, originates from springs in the Ulugulu Mountains northwest of the city and local rainfall. Climate variability has led to a decrease in river flows and substantial uncertainty in this supply of freshwater to Dar es Salaam. During the prolonged draught period of 1996/97, a large number of Dar es Salaam residents shifted to groundwater sources since the water supply became insufficient and unreliable for different uses. Aquifers in the region are found from the (Holocene) shallow floodplain deposits underlying the urban area. Since 1997, groundwater has been explored and exploited both by public bodies and privately. This emergency supply, however, became permanent because of supply shortages. Presently, groundwater development is unplanned, well construction inadequately regulated, and the shallow aquifers have experienced saline water intrusion and groundwater pollution. There is, furthermore, no groundwater monitoring network in Dar es Salaam region. A network is under consideration for the whole Wami/Ruvu River Basin. Inconsistency in monitoring means that it is uncertain whether current shallow groundwater abstraction is sustainable with respect to both quantity and quality. A permanent and reliable water source for Dar es Salaam City is being sought under which framework a study was carried out with the World Bank Support. The results indicated that there is a great and extended potential aquifer of up to 1000 meters deep located in the coastal areas to the north and south of the City. Before development of this resource, it is essential to understand the groundwater dynamics of the region to uncover its sustainability. This exercise requires, however, a well planned pilot well field with a proper monitoring network.

Rationale and strategies for groundwater management in urban areas of Uganda

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Groundwater development for urban water supply in Uganda has been ongoing since early 1990 through construction of deep boreholes in weathered and fractured-bedrock aquifers. This has, however, been done with very limited understanding of groundwater flow and storage in the aquifers making it difficult to develop strategies for sustainable groundwater development and management. This problem is compounded by high dependence on on-site sanitation systems in form of septic tanks and pit latrines which are likely to pollute groundwater. In order to improve understanding of the hydrogeological characteristics of aquifers and develop appropriate groundwater development and management strategies, groundwater monitoring and assessment studies have been undertaken in various towns in the country underlain by different geological formations. These studies show that fairly high well yields are obtained from the weathered and fractured-bedrock aquifers and intensive abstractions are sustained by leakage of groundwater from the high storage weathered aquifer to the underlying fractured-bedrock aquifer, both of which form a hydraulically connected system. Similarly, higher well yields are obtained from alluvial aquifers found along former river channels and groundwater abstraction is sustained by the wide extent of the aquifers. Abstraction in such aquifers becomes unsustainable due to continued abstraction and when the extent of the aquifers reduces due to erosion. The continued abstraction and erosion of alluvial aquifers as observed in Rukungiri town in western Uganda has lead to groundwater level decline of the order of 2.5 m a^{-1} resulting in unsustainable groundwater development. Based on results of various studies, groundwater management strategies in form of regulation of groundwater abstraction and boreholes drilling, continued groundwater monitoring and assessment, and zoning of protection areas have been instituted.

Simulating groundwater level fluctuations in the Quaternary aquifer of Bamako, Mali

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There is an urgent need for information on the hydrogeology and hydraulics of groundwater flow in urban aquifers of sub-Saharan Africa. Increased potential evapotranspiration under warmer temperatures serves to reduce the rate of groundwater recharge. Contamination of the Quaternary aquifer in Bamako City has been discussed in many fora but with respect to groundwater flow, characterisations have largely been limited to piezometric maps. Sporadic groundwater level monitoring by the Geological Department of the School of Engineers does not permit prediction of hydraulic-head distributions. Numerical flow models (e.g., MODFLOW) are thus indispensable for aiding planning and decision-making processes involved in groundwater management. Flow modelling confirms the conceptual model of groundwater flow, indicated before the piezometric maps, including: head contours are parallel to the river; hydraulic-head fluctuations are dependent upon the recharge rate, the Niger River stage and the evapotranspiration. The model also permits predictions of long-term temporal head distributions.

Groundwater exploitation and recharge rate estimation of a quaternary sand aquifer in Dar-es-Salaam, Tanzania

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The water supply of Dar-es-Salaam City derives from surface water and groundwater. Groundwater is used to supplement surface water supply and has increasingly become a major source of water supply in the city. The study area comprises three major parts: the central coastal plain with Quaternary fluviatile-deltaic sediments, the deltaic Mio-Pliocene clay-bound sands and gravels in the northwest and southeast and the Lower Miocene fluviatile sandstones of Pugu Hills in the west of the study area. The main objective of this study was to quantify the integrated water balance. The major source of renewable groundwater in the aquifer is rainfall. Hence, the long term average recharge of 240 $mm \cdot a^{-1}$ to the aquifer was estimated using the water balance method of Thornthwaite and Mather and is equal to 93 $hm^3 \cdot a^{-1}$ for the whole alluvial aquifer. This value was balanced with total groundwater abstraction of 8.6 $hm^3 \cdot a^{-1}$, baseflow to rivers of 76 $hm^3 \cdot a^{-1}$ and discharge into the sea (9.1 $hm^3 \cdot a^{-1}$).

Groundwater management in non-urban areas under changes in climate variability

Albert Tuinof
World Bank GW/MATE

Groundwater is the critical underlying resource for rural water supply and economic development in large parts of Africa, including in the extensive drought-prone areas of south-eastern, eastern and western Africa These areas occupy 70 % of the Sub-Saharan land area as a whole and are extensively underlain by two broad aquifer classes:

- weathered crystalline basement forming a shallow, patchy, minor aquifer system of low storage
- consolidated sedimentary rocks which form generally deeper, but less extensive and geologically more complex, aquifers.

Traditionally throughout the Sub-Saharan Africa Region it was the accessibility of groundwater through dug wells, shallow drilled wells at springheads and in seepage areas that controlled the extent of human settlement beyond the major river valleys and riparian tracts – and this groundwater was usually developed through community initiative. Under economic growth, technology development and population increase, the use of groundwater in non-urban areas has sharply increased, causing a number of management challenges related to water availability, water quality and allocation of groundwater. Climate variability and change (flood events, prolonged drought periods, sea level rise) will pose an additional burden to secure water to the rural population (village water supply, small town water supply and agricultural water use) and to maintain important non-productive uses of groundwater (providing river baseflows and sustaining wetlands). Climate change scenarios will give insight into the impacts of changes in rainfall patterns and the possible responses through management interventions. The paper will identify the main (technical, hydrological, institutional and knowledge) issues and challenges to be addressed to improve and maintain the access to water for rural Africa under the impacts of climate change. Examples will be provided of good practices to illustrate some of key issues.

Groundwater management in rural sub-Saharan Africa under conditions of climate variability

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Tanzania is endowed with an estimated 40 km^3 of groundwater which is available throughout the country under different geological and hydrogeological settings and varying quantity and quality. Much of groundwater that has been developed for domestic use is of appreciable quantities to form reliable source for water supply and is of acceptable quality. It is the most dependable source of water for the rural population in Tanzania who form about 80% of the total population. Groundwater is finding new uses such as small-scale irrigation creating potential competition amongst the different water uses. Climate variability is another complication to competition for water use especially in areas that are totally dependant on groundwater. Despite insignificant direct effect of climate variability to groundwater availability, there have been reported cases of drying up of shallow wells and severe decline in water levels in boreholes from several parts of the country. Of recent are the droughts of 1997/8 and 2005/6 which had devastating effects not only to the population but more so to the National economy. Published figures showed that the drought of 2006 caused a decline of between 2 to 3% of the NGDP. There is a clear link between availability of water and the economic growth of countries. For the rural population of Tanzania and indeed of many other sub-Saharan Africa countries, reliable, adequate, clean and safe water supply means life and livelihood. They depend on rain to grow crops for their livelihood and sell any excess agricultural produce as a source of family income. Safe drinking water is insurance to life especially for young children who are vulnerable to waterborne and water-related diarrhoeal diseases including cholera. Rural populations cannot afford expensive medication which usually is required to treat such diseases. There is need for deliberate effort by governments to invest in water resources assessments including groundwater, establishment of monitoring networks especially in areas with substantial abstractions of groundwater and construction of infrastructure for water storage for domestic and other uses. Private and public partnership where possible, should be encouraged.

Challenges in enforcing water laws in water resources management in Uganda

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Uganda is well endowed with water resources which are unevenly distributed both in space and time, and are threatened by rapid population growth, increased industrial activities, environmental degradation due to soil erosion, drainage of wetland and population of rivers and lakes. Other problems include increasing competition between and within sectors, trans-boundary conflicts, unequal distribution or access and increased frequency and severity of droughts. Water laws and institutions provide a framework and guidance to the development, management, allocation, utilization and conservation of the country's water resources. This paper reviews the challenges of enforcing Uganda's water statue of 1995 which has 4 fundamental objectives: to promote the rational management and use of the waters of Uganda; to promote provision of a clean, safe and sufficient supply of water for domestic purposes and to all persons; to allow for the orderly development and use of water resources for commercial purpose, like watering of stock, irrigation, and agriculture; and to control pollution and promote safe water, storage, treatment, discharge and waste water disposal.

Experimental GIS hydrogeological mapping of hard rock aquifers in Burkina Faso, to help groundwater management and planning

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BF-GS ("Burkina Faso, Geo-resources and Society") is a scientific project in collaboration with BRGM and BUMIGEB (Office of Mines and Geology of Burkina Faso). It aims at developing tools to help to manage geo-resources (metals, industrial rocks and minerals, water resources, etc.). As a prerequisite, the project aims at developing maps of the potential of geo-resources, among which is groundwater. In the framework of this project, experimental numerical (GIS based) hydrogeological maps of hardrock aquifers (granite and metamorphic rocks that constitute a large part of the African continent), have been generated at the country scale (1:1 000 000). The methodology developed relies on the evaluation and prioritizing of their hydrodynamic properties. It is based on recent results obtained in such hydrogeological contexts that allow the linking of hydrodynamic parameters (transmissivity, storativity) to both their lithology and the geometry of the various layers constituting their weathering profiles. Different hydrogeological maps have been generated (e.g. mean expected discharge, thickness of aquifers, recharge potential, etc.) that can be combined to help in groundwater management and planning. This methodology was implemented in Burkina Faso, where use of the recent 1:1 000 000 scale numerical geological map and about 16 000 water-wells database have been used to elaborate several methodologies combining among others statistical treatment and geo-statistics.

Relict river channels in Uganda: potential corridors of preferential groundwater flow and storage

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Deeply weathered crystalline rock aquifer systems that underlie 40% of sub-Saharan Africa and the entire Great Lakes Region of Africa, commonly exhibit low transmissivity and storage that constrain the development of groundwater. Previous research in Uganda demonstrates that the regional-scale hydrogeological properties of these aquifers systems are a function of the tectonically controlled cycles of deep weathering and stripping (i.e. tectono-geomorphic model). Using this model, we argue that corridors of preferential groundwater flow and storage occur in relict river channels reversed by tectonic activity associated with the development of the East African Rift System (EARS). In the mid-Miocene, westward flowing rivers in Uganda, headwater basins of the River Congo, were truncated by the western arm of the EARS. By the mid-Pleistocene, uplift parallel to the rift escarpment exceeded the rate of river incision and led to the reversal of surface flow. On surfaces of low relief east of the upwarp, coarse-grained sediments in these channels were overlain by low-energy fine-grained deposits that currently support extensive wetlands. Obscured by papyrus filled swamps, the aquifer potential of the underlying coarse-grained relict channel fills have yet to be examined. Recently developed aquifer test analysis techniques including diagnostic log-log derivative plots are used to improve our understanding of newly identified anomalously high yields in wells that draw from coarse-grained fluvial deposits west of the upwarp. This ongoing programme of research is currently examining the relict channels of the Katonga drainage basin to the east of the surface water divide in a region which avoided the post mid-Pleistocene erosion. The overall aim is to characterise the hydrology and hydrogeology of the Katonga channel in order to understand the groundwater resource potential and facilitate wetland management. The proposed research methods include: 2D electrical resistivity survey; minimal disturbance sediment sampling; state-of-the-art aquifer test analysis; isotope ratio analysis; and long term groundwater head monitoring. If sustainability of these relict channel aquifers is confirmed they will provide improved water management options and increased capacity to enable adjacent communities to adapt to future freshwater scarcity.

Geoelectrical characterization of aquifers in the basement complex / sedimentary transition zone around Ishara, southwestern Nigeria

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Marked local and regional geomorphologic changes often accompany movement from basement to sedimentary terrain and these, in turn, affect the occurrence of groundwater. Reliable data on the hydrogeology of southwestern Nigeria are currently unavailable. This project work is thus meant to determine the groundwater occurrence and the aquifer characteristics in this geological transition zone around Ishara, southwestern Nigeria. To achieve these aims, geophysical investigation involving Vertical Electrical Sounding (VES) were carried out in the study area. Forty (40) soundings were carried out using the Schlumberger electrode configuration. Most of the field curves obtained from resistivity survey in the basement complex show three (3) layers, consisting of the topsoil with resistivity ranging between 116 and 448 ohm-m, a fairly conductive intermediate weathered layer (clayey sand/ sandy clay layer) with resistivity values ranging from 35 to 154 ohm-m underlain by fractured/ fresh bedrock. The sedimentary terrain has three (3) to six (6) subsurface layers consisting of topsoil with resistivity ranging between 53 and 801 ohm-m, sandy/ sandy clay, underlain by sandstones of varying composition. The values of resistivity of the aquiferous layers in the basement complex and sedimentary terrains vary between 383 and 2960 ohm-m and 629 and 12 503 ohm-m while depth to bedrock varies from 2.3 to 11.9 m and 3.2 to 76.9 m respectively. Findings from this work show that groundwater occurs at shallower depth in the basement complex area than in the sedimentary area.

Groundwater Governance in Asia: an innovative approach and platform for capacity building, research, and knowledge sharing on groundwater management

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It is increasingly recognized that human capacity is a major shortfall when it comes to addressing pressing challenges of groundwater management in Asia where groundwater is primarily abstracted for irrigation with extensive, but increasingly threatened, poverty alleviation benefits. This paper describes a half-year training and research program for the capacity building of professionals involved in water management in two major river basins under water stress, the Indo-Gangetic and Yellow River Basins in south Asia and China, respectively, specifically addressing the five countries of India, China, Bangladesh, Pakistan and Nepal. The objective of the program, which is run by the International Water Management Institute and supported by the CGIAR Challenge Program on Water and Food, was to enhance the capacity of practitioners to contribute to a more informed, integrated and sustainable management of groundwater resources of the region through integrated, interactive and inter-disciplinary training and research. The program was successful in developing a comprehensive understanding of the contemporary issues related to groundwater use across the vastly different parts of the river basins and increasing the awareness and understanding of the participants with respect to the inter-linkages of groundwater use with socio-economics, legal, policy and institutional aspects and the physics of the resource. The program is one in a series of two annual cycles and though major investment and experiences will be taken advantage of in the second round there is a need to think in longer-term sustainability of these efforts and how best to cater to future capacity building needs of the region within topics related to groundwater governance.

SESSION 6 GROUNDWATER MANAGEMENT IN ARID AND SEMI-ARID AFRICA UNDER CLIMATE VARIABILITY

Papers in this session discuss groundwater management strategies in arid and semi-arid regions of Africa that consider development of transboundary aquifers, use of fossil groundwater, and conditions of increased climate variability and considerable hydrological uncertainty.

KEYNOTE: Transboundary groundwater management and climate nexus in the Circum-Sahara

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As Africa braces itself for climate change, the main players in the continent are growing more aware of the key issues of vulnerability and adaptation. However, momentous challenges persist and include the need for solid Africa-focused climate science and stronger adaptation capacity. Comprehensive observational systems are crucial in tackling the crippling dearth of data and information which afflicts Africa's capacity to shield its vulnerable natural resources from the adverse impacts of climate change. The stakes are particularly high in circum-Saharan Africa—the Sahara and Sahel Observatory's zone of action— where the acute drought of the 1970s left an indelible mark in the Sahel. Groundwater resources, "unseen" and too often overlooked, have a strategic role to play in climate change adaptation: they are less affected by climate variability, and abundant in a region where surface water is a rarity. Furthermore, groundwater, through its complex links with surface water, plays a key role in mitigating the impacts of extreme climatic events, such as drought and floods. Its availability in huge amounts, however, should not distract attention from the risks threatening it. Besides, its transboundary nature—the geology of most African aquifers ignores geopolitics—makes their sustainable use and management a complex but nonetheless essential affair. The approach that the Sahara and Sahel Observatory (OSS) takes to transboundary aquifers, combines the improvement of scientific knowledge and the mustering of political will with a view to entrench concerted management of these shared resources in the circum-Saharan region. By doing so, OSS contributes to preserving these hidden—and still underestimated—"treasures" whose sheer strategic importance will, rather ironically, become crystal clear as they are increasingly considered through the lens of climate change.

Groundwater evolution and palaeoclimate in Africa: implications for future management

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Groundwaters of known age contained in major aquifer systems in the African sedimentary basins enable low resolution (±1000 a) characteristics of past climates to be determined, specifically palaeotemperature, air mass origins, humid/arid transitions and rainfall intensity. Results from both northern and southern Africa indicate the predominance of a westerly Atlantic air flow during the Late Pleistocene. Greater aridity during the LGM is recorded over most of northern Africa by the absence of dated groundwaters. An intensification of the African monsoon during the Early Holocene is apparent from isotopically light groundwaters found especially over Sudan. Maximum cooling around the LGM of 5-7°C is recorded in the noble gas recharge temperatures from Africa. Modern recharge can be readily identified from the chemical and isotopic signatures (Cl, $\delta^{18}O$ and ^{3}H) in the unsaturated zone and in shallow groundwaters. The results indicate the non-renewability of many groundwater sources now being exploited across the arid and semi-arid regions of Africa. Extreme events in the past, noted from the groundwater record, may have lessons and implications for adapting to future climate change. Small but finite amounts of renewable groundwater may be estimated using chloride mass balance and other tracer techniques. These renewable waters form the basis of sustainable development in areas such as the Sahel. Based on the field evidence of water scarcity, new approaches are needed in management and education to adapt to the current limited resources in the face of changing climates.

Palaeohydrogeology of the Okavango Basin and Makgadikgadi Pan (Botswana) in the light of climate change and regional tectonics

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In Southern Africa, large intra-continental depressions form the base level of huge hydrological catchments which are dewatered by mostly ephemeral streams and few persistent rivers. Being former basins of large freshwater lakes and representing therefore ancient recharge areas, these large depressions are receiving an increasing interest as they may have the potential to contain groundwater resources that could be used as drinking water for an increasing population. To understand the recent, and sometimes surprising discoveries of deep, fresh groundwater resources, it is necessary to investigate geological structures, palaeo-hydrogeological conditions and the palaeo-hydrology of these lakes. This research needs to consider not only climatic change but also regional tectonic events. In the late Pleistocene the Okavango Delta and the Makgadikgadi Pan in Botswana were covered by lakes reaching levels of 945 m, 936 m, 920 m and 912 m asl which corresponds to water depths of locally more than 60 m. Accordingly, the analysis of drill cores in the vicinity of the lakes revealed the occurrence of calcretes, indicating that former groundwater levels must have been much higher than in the present. In a first approach all lake levels cited in the literature were compared with results obtained by a digital elevation model (DEM) and transferred into a GIS. During a second step the different lake levels in combination with their barrier beaches and large sand dunes were localised on satellite images (Landsat TM 5). They are clearly visible and correlate quite well with literature data. At a few locations, a false-colour analysis of the satellite images revealed doubtful boundaries between lake sediments and the barrier beaches on their fringes. The different soil types can be identified clearly on these satellite images and show sharp boundaries between salt soils in the Nwetwe und Sua Pan, which lies in the Makgadikgadi Pan, and sediments outside the pan. Finally, all ^{14}C – dating of calcretes cited in the literature were compiled and transferred into a GIS. During the early Pleistocene, tectonic movements formed a depression which led to the current Makgadikgadi Pan. The palaeo-hydrology was controlled by the Okavango and Zambezi and the high level stage on 945 m asl developed between 40 and 35 ka BP, before the connection with the prominent Zambezi water course was disrupted. Tectonic displacements along NE – SW trending faults led to a down-warping of the Okavango Delta and split the lake into two basins. One of these lakes was the Thamalakane on 936 m asl, which later developed slowly into the present deltaic system. The other remnant lake was located in today’s Makgadikgadi Pan and oscillated between 920 m and 912 m asl. Both lakes were fed by the Okavango and were connected by the Boteti River overflow. During the Holocene both lakes dried up gradually. Since a direct correlation of the lake levels with South African palaeo-climate records is difficult, the influence of over-regional tectonic movements for the history of the lakes becomes more and more evident. The ancient lakes had obviously a vast catchment which was gradually cut off with time. As the groundwater levels in the past were up to 100 m above the present levels the influence of the ancient lakes on the groundwater recharge was important.

Sustainable groundwater Management in the East African Rift – the MAWARI Project experience

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The Management of Water Resources in East African Rift (MAWARI) project is a multi-counterpart regional project on the assessment of volcanic aquifers of the East African Rift in Djibouti, Ethiopia and Kenya. It is a French initiative to support investigations aimed at improving the knowledge base and the understanding of the hydrodynamics of the aquifer systems of the East African Rift Valley. Groundwater in the East African Rift is characterised by discontinuous aquifers with low storage. These characteristics are the function of disruption on lithologies by rift faults and rift bounding faults.

These characteristics make the groundwater storage in aquifers of East African Rift vulnerable even to short lived climate shocks. Drilled wells often dry following wet seasons or following short lived drought events. Decadal-scale climate change events related to El Niño, SST changes are coupled with groundwater storage and depth to water table. In such conditions, obtaining groundwater with sustainable yield under prolonged drought depends on obtaining rift aquifers with high storage that are connected to sustained recharge sources. One sustained recharge source being the mountains bounding the rift aquifers. In Ethiopia, a group of groundwater professionals from the Addis Ababa University and the Ethiopian Geological Survey are conducting integrated research in understanding groundwater recharge and flow between the rift bounding mountains and the rift floor aquifers. The result show that the occurrence of sustained groundwater sources in the rift depends on the configuration of the interface between the high rainfall mountains and the arid rift valleys. High groundwater storage that can absorb the shocks of short-lived climate variations can be obtained in alluvial filled marginal grabens bounding the rifts and in tectonic windows where the rift faults are cut by transverse faults. Sustained recharge alone cannot guarantee sustainable groundwater development. In the rift, fresh groundwater bodies are often underlain by salt waters or high fluoride ground waters. Extracting the good quality waters without obliterating the stratification requires the development of groundwater flow models of accurate performance. The state-of-the-art review of fluoride occurrence in the East African Rift ground waters has been prepared and preliminary investigations for building of experimental de-fluoridation units are underway. In Djibouti, scientists from the "Centre d'Etudes et de Recherches de Djibouti" (CERD) are carrying experiments on the so-called Hydrogeological Experimental Site at Atar near the town of Djibouti to understand and model the groundwater flow in volcanic aquifers. This groundwater reservoir has been identified from more than thirty boreholes used for the water supply of Djibouti. A set of boreholes (9) at depths ranging from 40 to 50 metres, equipped with dippers and various measuring devices are being pumping tested and the aquifer properties have been recorded. The first results show that the aquifer is replenished through the adjacent oued Atar and the depth of the seawater – fresh water interface is localized. Low storage, shallow circulating ground waters are also most vulnerable to pollution from anthropogenic sources. In Kenya investigation is being made on mapping the vulnerability of the volcanic aquifers to pollution. Effort is being made on understanding the role of fracturing and faulting on the vulnerability of the volcanic aquifer systems. In parallel with the investigations being carried out and to support the capacity building in the three countries, a large portion of the funds is used for training purposes including support for approximately 50 students to pursue PhD (10) and MSc (40) degrees. A series of workshops on ''hydrogeological modelling'', geochemistry and isotope hydrology methods and remote sensing have been organized.

A decision support tool for sustainable groundwater management in semi-arid, hard-rock regions

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Until recently, aquifers located in hard rock formations (granite, gneiss, schist) were considered as highly heterogeneous media, and adequate methodologies for groundwater management or borehole siting were non existent. Recent studies showed that a typical hard rock aquifer is made of two main hydrogeological units characterized by quite homogeneous specific hydrodynamic properties; namely the saprolite and the fissured layers. Therefore, hard rock aquifers can be considered as a multi-layered system. Based on this research work, the Indo-French Centre for Groundwater Research (BRGM-NGRI located in Hyderabad, Andhra Pradesh, India) has developed an operational Decision Support Tool (DST) designed for groundwater management in hard rock areas under variable agro-climatic conditions. This DST focuses on the impact of changing cropping pattern and artificial recharge on the groundwater levels at the scale of small watersheds (up to 100 km^2). The DST is based on the groundwater balance and the 'Water Table Fluctuation Method', well-adapted methods in hard rock and semi-arid contexts. It is a semi-automatic program developed under a MS-Excel Interface. The model integrates the natural characteristics of hard rock aquifers such as the variation in specific yield with depth, the respective thicknesses of the fissured and saprolite layers, as well as variations in both natural and artificial aquifer recharges with respect to climatic conditions. In addition to the hydraulic model, the DST includes a module dedicated to future scenarios including socio-economic indicators: scenario "business as usual", implementation of supply and demand measures to mitigate over-exploitation, impact on farmer incomes, etc. During its scientific development, the DST has been implemented in a representative south Indian watershed (53 km²) characterised by a granitic basement, semi-arid climatic conditions, rural context, and groundwater irrigation. For this watershed, the DST models the basin-scale piezometric levels with an average error of less than ±0.6 m from 2001 to 2005 (calibration period); this shows the robustness of the model. Due to groundwater overexploitation (more than 700 bore wells in use), the model results showed that if no measures are taken, the water table depletion will run dry about 50% of the pumping bore wells by the year 2010. Simulations of mitigation measures with the DST show that a realistic change in cropping patterns could rapidly reverse the tendency and lead to a sustainable management of the resource. Presently the DST and the related methodologies are being tested at an operational scale for Policy Makers and Planners in the Gajwel watershed (80 km^2) under the project SUSTWATER sponsored by the European Commission (Asia ProEco programme). This project is carried out in close collaboration with the Andhra Pradesh Rural Development Department and Groundwater Department.

Cooperation, conflict and adaptation to climate change in transboundary river basins in Africa

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We review current knowledge of the potential impacts of climate change on water resources in Africa and the possible limits, barriers or opportunities for adaptation to climate change in transboundary river basins. Africa faces significant challenges to water resources management in the form of high variability and regional scarcity, set within the context of generally weak institutional capacity. Management is further challenged by the transboundary nature of many of its river basins. Climate change, despite uncertainty about the detail of its impacts on water resources, is likely to exacerbate many of these challenges. The complex drivers of cooperative and conflictual interactions between riparian states influence water resource management in transboundary basins and are likely to influence adaptation to climate change. Further research to examine the factors and processes that are important for cooperation to lead to positive adaptation outcomes and the increased adaptive capacity of water management institutions is suggested.

Conceptualising transboundary groundwater management

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Considering that many of Africa's groundwater resources are transboundary by nature and are stored in the estimated 40 transboundary aquifer systems, cross-boundary coordination, cooperation and management will become imperative in order to safeguard equitable and sustainable use of these groundwater resources. At present, cooperation on transboundary groundwater resources in Africa is rather weak if compared to international rivers and lakes; unilaterally use and management are the dominant features, and few initiatives exist for coordinated activities. The transboundary dimension of groundwater management poses additional challenges to an issue which is already complex at the national level. A research and consultancy project addressed this particular issue by trying to identify typical riparian constellations and interstate cooperation problems on the basis of specific hydrogeological attributes of the aquifers. Based on the actual stages of management and cooperation, we present a step-by-step approach starting from sharing data and expertise to working out agreements on use scenarios and joint management of the resource, and discuss management forms.

Water and food security in the Nile Basin: taking account of water resources beyond the river and the basin

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The purpose of the paper is to highlight the water resources of the ten Nile riparians. It will also track the "virtual water" trade within the basin and with global trading partners. It will be shown that the basin is a major net importer of virtual water. Water traded as virtual water can be freshwater or soil water. The analysis shows that the majority water in the basin overall is soil water. Southern economies export significant volumes of virtual water to Egypt - mainly in tea and coffee. The issue of the productivity of the southern Nile Basin soil water resources will be discussed.

Note: virtual water is the water embedded in food commodities. It requires about 1000 m3 (tonnes) of water to produce a tonne of wheat. A water scarce economy avoids the economic and political stress of mobilizing 1000 m3 if it imports of a tonne of wheat.

Tradeoff analysis between economic development and climate change adaptation strategies for the Nile river basin

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Recent Intergovernmental Panel on Climate Change (IPCC) briefings have declared that the growing population in the Nile river basin region (about 160 million, or 57% of the entire population of the basin's ten riparian countries) is at risk of water scarcity. Adjustment strategies in response to climate change involve either changes in water allocation or structural adjustments in both the upper and lower basin management schemes. These potential strategies may contradict existing economic development plans in this region. General Circulation Models (GCMs) show widely diverging pictures of future river flows (from a 30% increase to a 78% decrease), and any reductions over 20% may result in major social and economic impacts. The large uncertainty in climate change projections makes it difficult for policy makers and basin managers to adopt any specific response policy. Furthermore, there is a significant lack of data collection on surface water runoff and groundwater discharge/recharge in the Nile basin countries despite research efforts in this area. Integration of climate change, water balance, and economic models contributes towards filling such large gaps of information. This research will use economic input-output (I-O) tables, social accounting matrices (SAMs), surface and groundwater hydrology information (e.g., groundwater discharge, recharge, storage; and surface runoff), and the USDA ARSAT (Agricultural Risk Screening and Analysis Tool) software program to analyze tradeoffs between economic development and environmental mitigation strategies in the Nile basin region. This study describes the nature and limitations of the tradeoff analysis, uses existing projected climate change scenarios, and integrates the results of these scenarios with hydrological information and economic consequences. Climate change modelling scenarios will be derived from the Geo-Physical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO), and the Goddard Institute of Space Studies (GISSA) models. Specifically, this study summarizes surface and groundwater hydrology impacts due to changes in precipitation, temperature, solar radiation on selected Nile sub-basin zones and the economic implications in selected Nile sub-basin regions. The I-O tables, SAMs tables, and model-generated hydrological information will be used to quantify economic and environmental impacts due to existing and proposed development plans and projects on one hand and strategies for climate change adaptation on the other. The tradeoff analysis utilizes a stochastic dominance (stochastic efficiency with respect to a function) approach with economic (e.g., net present value of on-going and proposed development projects in the region) and environmental indicators (e.g., groundwater storage) to quantify impacts of climate change adaptation strategies versus economic development plans and projects in the Nile basin region. Finally, this research will tabulate the tradeoff results and provide discussion of possible implications for policy and the decision-making processes at regional and sub-regional levels.

Carbon-14, chlorine-36 and noble gases in deep groundwaters from the northeastern Sahara of Algeria: palaeoclimatic implications

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The deep "Continental Intercalaire" (C.I.) is a large aquifer system that extends over an area of approximately 1 000 000 km^2 in the northern part of Sahara Desert. This resource, vital in an arid region, is considered to be "fossil" (i.e. mainly inherited from previous climatic conditions, more humid than at present). Sampled groundwaters show a quite wide range of ^{36}Cl contents, ranging from 8 to 99 10^{-15} $at.at^{-1}$, expressed as $^{36}Cl/Cl$ atomic ratio. The spatial distribution of ^{36}Cl contents fits fairly well with what is known about the piezometric contours of the aquifer: a decrease is observed from recharge to discharge zones. If this decrease is radioactive decay, it can be interpreted in terms of groundwaters transit time. Maximum time intervals of about 3 half-lives (900 ka) may be computed using ^{36}Cl specific activities ($at.l^{-1}$). The residence times determined on the main flow line where the radio decay is observed are expressed in terms of minimum ages (16 to 500 ka) and maximum ages (25-1200 ka). Noble-gas data are presented to improve the palaeoclimatic and residence time interpretation for the CI aquifer system. The groundwater recharge temperatures (RT) were estimated from the averaged amounts of noble gases (Ne, Kr, Xe) corrected for the excess air effect. The RT's for most groundwaters are generally lower than the present day recharge temperatures. Along the main flow direction the CI Paleowaters (ages 20 to 40 ka BP) have an average RT of 16.9°C which is some 5°C cooler than at the present day. Recharge temperatures calculated in four samples from the CI aquifer (30-150 m depth) average 19.7°C, close to the present day mean annual temperature of 21°C.

Compared analysis of variabilities and climatic changes impacts on the surface water and groundwater resources in Saharo-Sahelian zones

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Investigations carried out in West Africa and Sahara often omit to report the drought period which settled at the beginning of the 1970's and still continues nowadays. However, the analysis of the rainfall series of the semi-arid and arid areas of Western Africa and the Sahara has shown a clear downward trend in the heights of precipitations recorded during decades of 1970 and 1980, corresponding to the limits of the dry phase. In the Niger basin, the observation series from 1950 to 2001, distinguished one "wet" period before 1970 and one "dry" period from 1970 to the end of the 1980's. The beginning of a new wet period is perceptible from the beginning of the 1990's. The climate records collected in Guinea, Mali (Koulikoro, Diré), Niger (Niamey) and the area of the Lake Chad, highlight a rainfall deficit beginning from the year 1969-1970, of about 20 to 30 % compared to the wet period. This deficit appears very clearly even in areas recognized to be wetter, particularly the forested areas of Côte d'Ivoire, which are justified by the observations of the station of Odienné. This tendency for the dryness to recur since the beginning of 1970 is not specific to Western Africa. This phenomenon is also found in North-Western Africa and was clearly monitored over one century of measurements (1874 to 1988) at the rainfall station of Djelfa on the Saharan Atlas in Algeria. This reveals that in this area of the Sahara, the period from 1926 to 1950 would appreciably correspond to the average pluviometric section over the period of observations. The period from 1885-1908 is wet with weaker annual rains extending from 1973 to 1988. In addition, in the Southern Tunisia (Remada), the period from 1973 to 1984 is characterized by a succession of dry years. This rainfall deficit generated the progressive evolution of the isohyets towards the south in the order of 100 km in West Africa within the Niger river and Tchad basins. This deficit, which translates into increasing aridity, had a significant impact on the Niger River flow and Lake Chad. Indeed, in the first case for example, the flows decreased from about 20 to 50 % with sometimes severely low water levels leading to dry beds, in Douna (Mali) in 1983, 1984 and 1987, while in Niamey in 1985 the Niger River dried up. Moreover, this climatic variability (decrease of rain and river flows) led to increasing pressure on groundwater. These two combined effects generated a decrease in the aquifer water levels as was the case in a sub-basin of Bani in upper Niger, Mali from 1983 to 1987 where the piezometric heights recorded their lowest levels. Regarding the hydrogeologic aspects, the Saharan and sub-Saharan Africa impacted by these climatic variabilities and changes contains large aquiferous basins: the basins of Senegalo-Mauritanian, Taoudenni, Iullemeden and Lac Chad in Western Africa; and the basins of the North Western Sahara, Nubian sandstones and Mourzouk in North western Africa. These climatic variabilities and changes may result in a great variability in the aquifer recharge. Two types of water resources were thus identified in these two areas: renewable resources, and a little or non-renewable resources. The renewable resources are contained in the non-confined aquifers. These are recharged by the effective rain and the infiltration of surface waters. This type of aquifers reacts to the variation of precipitation. These renewable water resources closely follow climatic variability. Piezometric fluctuations recorded in Mali and Niger show the response of the aquifers during the decade 1990-2000. The non-renewable resources especially represent the climatic changes recorded during the Quaternary period. This period is particularly characterized by the Holocene (10000 years BP) or the postglacial period and by Pleistocene (12000 - 45000 years BP). In the North Western Sahara, the behaviour of the aquifers was simulated with the model of the NWSAS (North Western Sahara Aquifer System) over a period of 10000 years (Holocene) with zero recharge conditions. These aquifers are considered as fossil and hence, the piezometric levels observed nowadays would be only result in complete depletion. The depletion of the aquifer from the "Continental Intercalaire" (of North Western Sahara basin) to the outcrops of the Saharan Atlas in the north-west, and Adrar Ben Drich in the south, was simulated by this model. This depletion which represents a generalized fall of the hydraulic heads in the whole area, shows that these levels have regularly dropped during the last 10000 years. In this case at the end of the last 4000 years, there was a fall of 10 mm/year on average in the Saharan Atlas in the North-West of the basin, and 7 mm/year in Adrar Ben Drich in the south of the basin.

Climat et ressources en eau au Maghreb: tendances et impacts du changement global

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Dans la région du Maghreb, les ressources en eau se sont toujours caractérisées par leur rareté. Ces dernières décennies, la région a été affectée par une augmentation des températures et une accentuation de la variabilité climatique en relation avec le réchauffement climatique global. Cette situation risque de s'accentuer, en effet les projections des modèles climatiques globaux concordent quant aux scénarios futurs prédisant pour la région, à l'horizon 2050, une baisse du régime pluviométrique de l'ordre de 10 à 24 %. Ceci entraînera une aggravation des déficits actuels en ressources en eau renouvelable. Si plusieurs mesures d'adaptation ont déjà été incorporées dans les pratiques de gestion des ressources en eau pour faire face aux sécheresses précédentes, l'accentuation prévisible des impacts induits par le changement climatique, dans la région comportera des défis nouveaux et nécessitera une gestion stratégique de la ressource en eau.

Conceptual model of basement aquifers in Limpopo Province, South Africa

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The geology of Limpopo Province (South Africa) is dominated by two lithostratigraphical units in the Basement Complex: the Hout River Gneiss underlying the larger part of the western Limpopo water management area (WMA), and the Goudplaas Gneiss underlying the larger part of the Luvuvhu/Letaba WMA. Conceptual models for the two WMAs were developed based on available geological data and analysis of over 1000 pumping test and over 300 hydrochemical datasets from a national groundwater database. Determined transmissivities follow a log-normal distribution, with higher transmissivities observed in boreholes targeting alluvial aquifers or the composite regolith aquifer in closer vicinity to the Hout river shear zone on the southern side of the Limpopo Belt. No spatial relation of transmissivities to the prevailing neotectonic stress field is apparent in the dataset, indicating an overriding influence of preferred weathering along structurally weakened zones under paleo or current stresses.

Groundwater geochemical variations under a changing climate in the East African rift

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The East African rift features primarily closed drainage basins. These hydrological characteristics make the volume and levels of lakes and wetlands highly sensitive to short-lived or millennial-scale changes in climate. The volcanic and volcano-clastic materials occupying much of the rift valley are bounded by lacustrine sediments formed by shrinking lakes. Within these sediments evaporitic salt deposits such halite, gypsum and carbonate minerals have accumulated. Elements such as Li, F, As which can be remobilized from these lacustrine sediments, are a major threat to water quality. Research under the MAWARI project assesses the relative importance of climate change, geothermal activities, and leaching of volcanic materials in determining the geochemistry of groundwaters in the East African rift. .