ATLAS OF
ISOTOPE HYDROLOGY
AFRICA

IAEA
International Atomic Energy Agency

ATLAS OF ISOTOPE HYDROLOGY

— AFRICA

IAEA

Water Resources Programme

EDITORIAL NOTE

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For further information, please contact:

Isotope Hydrology Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna
Austria
tel.: + 43 1 2600 21736
fax.: +43 1 26007
ihs@iaea.org
http://www.iaea.org/water

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CONTENTS

FOREWORD

At the core of all efforts for sustainable human development lies an adequate supply of freshwater. With increasing population numbers and economic growth, it is imperative that we reach a balance between demand and the availability of freshwater, protect available resources in rivers, lakes and aquifers, and prevent disputes over shared resources. Although a significant portion of the Earth's freshwater is renewed by the hydrological cycle, freshwater is still a finite resource and, unlike many other strategic resources, it has no substitute in most of its uses. Nearly half of all freshwater used for drinking and irrigation worldwide is groundwater, on which irrigation and the world's food supply are dependent. Yet, the world's groundwater resources are not well understood.

Water resources management and related policy development require widely acceptable scientific information on the hydrology of water bodies. Naturally occurring isotopes in water provide unique hydrological information and the associated techniques are highly cost effective. The applications of isotopes in hydrology have been part of the IAEA's programmes related to the peaceful applications of nuclear energy from the very beginning. The focus of the IAEA's work has been to develop appropriate methods for use in water resources management and to assist its Member States in using those methods.

The IAEA has helped create a large body of isotope data on the world's rivers, lakes and aquifers that can be used for resource assessment and management on a local, regional and continental scale. I am pleased to see that a number of isotope hydrology atlases are now being produced using these data from nearly one hundred countries. By making the data easily available to scientists worldwide, I hope that we can facilitate the integration of isotope hydrology into the practice of water resources management.

Vienna, August 2007

Mohamed ElBaradei

Director General
International Atomic Energy Agency

PREFACE

Although there are abundant water resources in Africa — about 17 large rivers and 160 lakes greater than 27 km^2 — most of these resources are located in the humid and sub-humid regions around the equator. The surface runoff in Africa, on average, is much lower than average precipitation as a result of high evaporation and evapotranspiration, resulting in endemic drought in parts of the continent. Consequently, groundwater is a very important resource for Africa, providing nearly two-thirds of drinking water on the continent, and an even greater proportion in northern Africa.

Despite the importance of groundwater for many societies, there is a lack of corresponding public concern about its protection, perhaps because the extent and availability of groundwater are not easily measured. The impact of increasing degrees of temporal and spatial climatic variability on water resources is also an important consideration, and groundwater to some extent provides an opportunity to mitigate the impacts of climate change.

Applications of isotopes in hydrology are based on the general concept of "tracing", in which naturally occurring or environmental isotopes (either radioactive or stable) are used to study hydrological processes on large temporal and spatial scales through their natural distribution in a hydrological system. Thus, environmental isotope methodologies are unique in regional studies of water resources to obtain integrated characteristics of groundwater systems. The most frequently used environmental isotopes include those of the water molecule, hydrogen (^{2}H or D, also called deuterium, and ^{3}H, also called tritium) and oxygen (^{18}O), as well as of carbon (^{13}C and ^{14}C, also called radiocarbon or carbon-14) occurring in water as constituents of dissolved inorganic and organic carbon compounds. ^{2}H, ^{13}C and ^{18}O are stable isotopes of the respective elements, whereas ^{3}H and ^{14}C are radioactive isotopes.

Among the most important areas where isotopes are useful in groundwater applications are aquifer recharge and discharge processes, flow and interconnections between aquifers, and the sources, fate and transport of pollutants. In particular, under arid and semi-arid climatic conditions, isotope techniques constitute virtually the only approach for the identification and quantification of groundwater recharge. Pollution of shallow and deep aquifers, by anthropogenic contaminants is one of the central problems in the management of water resources. Environmental isotopes can be used to trace the pathways and predict the spatial distribution and temporal changes in pollution patterns for assessing pollution migration scenarios and in planning for aquifer remediation.

This first isotope hydrology atlas focuses on projects in the IAEA's African Member States, where environmental isotopes were used to assess water resources in terms of quantity or quality. It presents location maps of study areas, summary statistics and relevant data plots. Nearly 10 500 isotope records from 79 projects between 1973 and 2007 in 26 African States are included. For each country, a digital elevation map is provided that shows major water bodies, locations of stations in the IAEA/WMO Global Network of Isotopes in Precipitation (GNIP) and the project study areas. For each project, a higher resolution map of the study area is provided, together with data tables and plots for median and mean values of $\delta^{18}O$ and $\delta^{2}H$, average annual precipitation and air temperature, tritium values, and radiocarbon.

The Isotope Hydrology Information System (ISOHIS), maintained by the the IAEA, has been the source of the hydrological and isotope information used in the compilation of this atlas. Data presented here, as well as additional hydrochemical and isotope data obtained in other studies conducted in Africa, are available through the on-line application WISER at http://www.iaea.org/water. A number of present and former IAEA staff contributed to ISOHIS.

The following IAEA staff were responsible for the preparation of the atlas: P.K. Aggarwal, L. Araguás-Araguás, S. Dogramaci, E. Izewski, K.M. Kulkarni and T. Kurttas.

DESCRIPTION OF PLATES

The countries in this atlas are listed alphabetically. The projects are arranged chronologically: first national projects and then regional projects, with each country having a group of plates in the Atlas. The first plate in each group contains a physiographic map of the country showing the project area(s). This plate also includes a brief background of each project. The following plate(s) provides a detailed map of each project area, a summary table of isotope data, and relevant isotope plots.

Physiographic maps for countries and study areas were taken from commercial GIS software [1]. Country boundaries have been taken from the United Nations Geographical Information Working Group [2].

Project types and codes

Each IAEA technical cooperation project as well as research contract has a unique code number that appears on the plates of the Atlas. National projects include investigations at the national or local level, whereas regional projects comprise investigations in a group of Member States. Research contracts form a part of more focused coordinated research projects (CRPs) on selected research themes.

The codes for the three categories of projects mentioned above are described below.

National projects: The code consists of a three-letter string for the country, followed by the number 8, which stands for the thematic field of the project (i.e. water resources and industrial applications). Finally, a three-digit sequential code is assigned (e.g. ALG8001, BEN8002, etc.). These codes are used on the plates describing national projects. Multiple study areas investigated in a project are shown on different plates with details. In such cases, an arbitrary letter is placed after the project code, for example, ZAM8005K and ZAM8005L.

Regional projects: The code consists of a three-letter string RAF, followed by the thematic field area number (8) and a three-digit sequential code (e.g. RAF8012, RAF8029, etc.). A three-letter code identifying the participating country is added after this code. The regional project plates show a code such as, for example, RAF8012–SEN or RAF8022–SUD, etc. When multiple study areas are investigated in a given country, they are shown on different plates with details. In such cases an arbitrary letter is placed after the project code, for example, RAF8022Q–EGY and RAF8022W–EGY.

Research contracts: The research contract code consists of a three-letter country code, followed by the assigned number of the contract (e.g. GHA–12954).

Study areas

The approximate spatial distribution of the study areas of all the projects is shown in Fig. 1. Project codes and study areas are listed in Table 1.

FIGURE 1. Map of Africa showing the areas covered by the IAEA projects on water resources that are included in the Atlas.

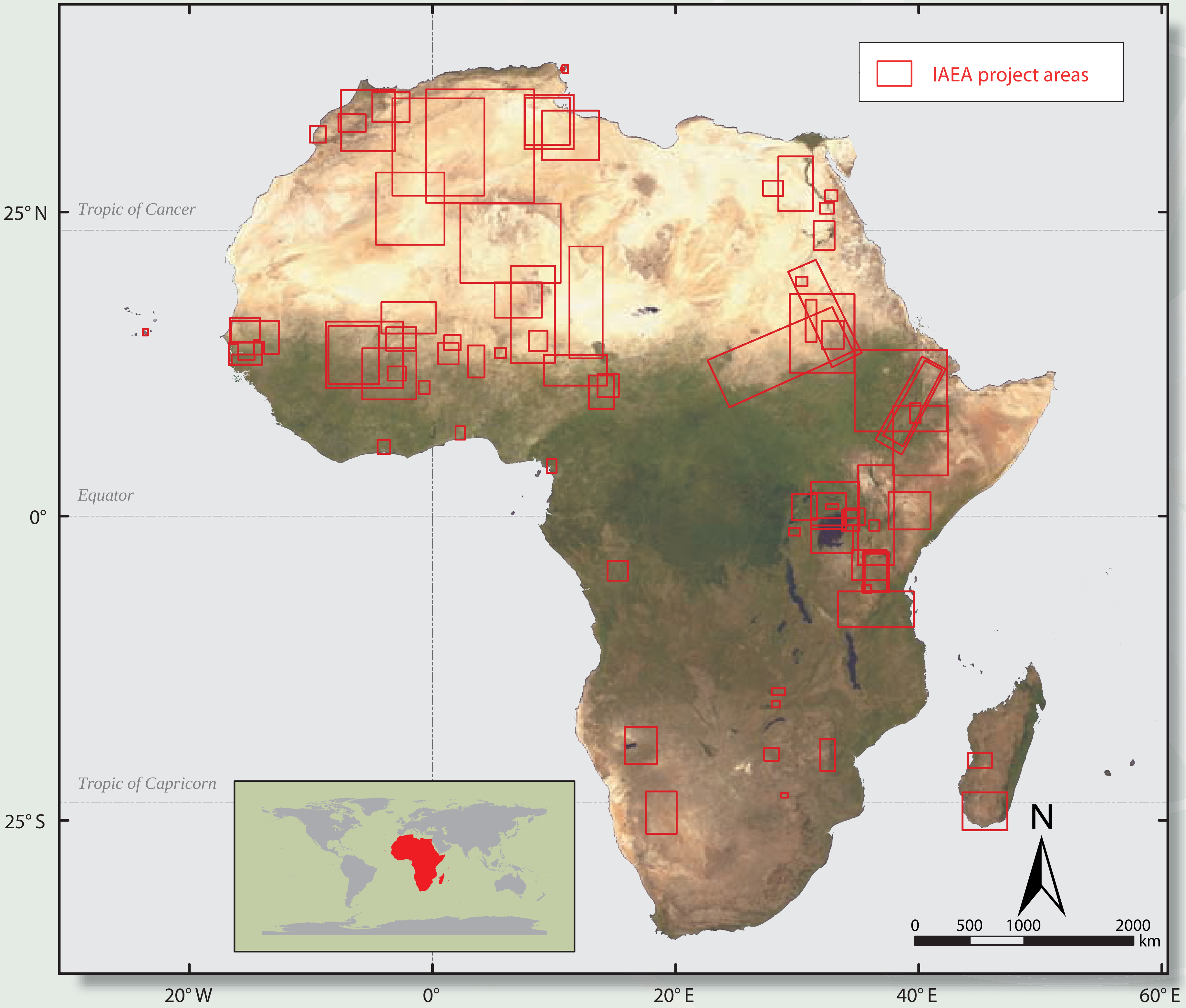
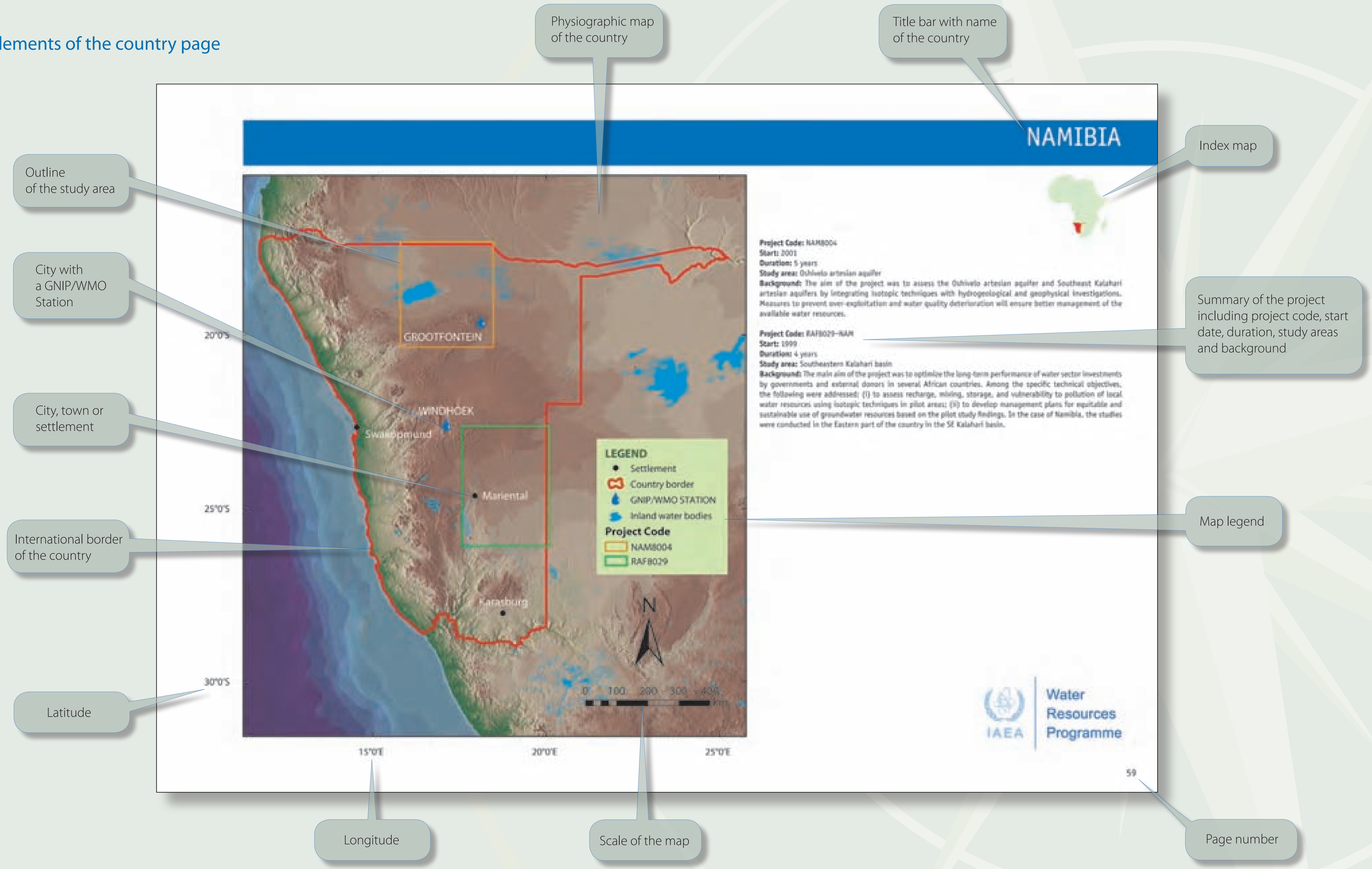


TABLE 1. Summary table showing the list of projects with their codes and study areas

Country	Project	Study Area
Algeria	RAF8007–ALG	North Western Sahara Aquifer System — Northern Algeria
	RAF8022–ALG	North Western Sahara Aquifer System — Hoggar and Tassilis region
	RAF8035–ALG	North Western Sahara Aquifer System — Northern Algeria
Benin	BEN8002	Benin coastal aquifers
Burkina Faso	BKF8002	Western Burkina Faso aquifers
	BKF8003	Southwestern Burkina Faso aquifers
Cameroon	CMR8002	Northern Cameroon aquifers
	CMR8005	Douala sedimentary basin
	RAF8012–CMR	Grand Yaere aquifers
Cape Verde	CVI8002	Santiago island aquifers
Côte d'Ivoire	IVC8002	Abidjan coastal aquifer
Democratic Republic of the Congo	ZAI8013	Mont Amba aquifer — Kinshasa region
Egypt	EGY8016B	Nubian Sandstone Aquifer System — Bahariya depression
	EGY8016F	Nubian Sandstone Aquifer System — Farafra depression
	RAF8010–EGY	Nile River basin aquifers
	RAF8022Q–EGY	Wadi Qena region aquifers
	RAF8022W–EGY	West Isna region aquifers
Ethiopia	ETH8003	Ethiopian Rift Valley
	ETH8005	Lake Beseka area
	ETH8006	Akaki regional aquifer
	ETH8007	Rift Valley aquifers
	RAF8022–ETH	Moyale region aquifers
Ghana	GHA–12954	White Volta River basin
Kenya	KEN 8005	Western Province aquifers
	RAF8029–KEN	Merti aquifer
	RAF8037–KEN	Lake Victoria area
	KEN–7541	Lake Turkana
	KEN–8360	Lake Naivasha area
Libyan Arab Jamahiriya	RAF8035–LIB	North Western Sahara Aquifer System — Djeffara area
Madagascar	MAG8003	Morondava artesian aquifer
	RAF8029–MAG	Southern Madagascar aquifers
Mali	MLI8002	Southern Mali aquifers
	MLI8006	Niger River basin aquifers — Central Mali
	RAF8012–MLI	Niger River basin aquifers — Southern Mali
	RAF8022–MLI	Gondo Plain aquifers
Morocco	MOR8009M	Moulouya Plain
	MOR8009T	Tadla Plain
	MOR8011	Essaouira Plain
	RAF8022–MOR	Central Moroccan aquifers
Namibia	NAM8004	Oshivelo artesian aquifer
	RAF8029–NAM	Southeastern Kalahari basin
Niger	NER8003	Arlit and Bilma regions
	NER8007	Zinder region aquifers
	NER8008	Tillabery region aquifers
	RAF8012–NER	Niger River basin — Dallol Bosso area
	RAF8022–NER	Dallol Maori Valley — Southwestern Niger
Nigeria	NIR8006	Borno State region
	RAF8022–NIR	Rima Group aquifers
Senegal	SEN8003	Casamance basin
	SEN8005	Linguere region
	SEN8006	Dakar suburban aquifers
	RAF8012–SEN	Senegal River basin
South Africa	RAF8029–SAF	The Taaibosch fault zone area
Sudan	SUD8002/SUD8003	Nubian Sandstone Aquifer System — El Obeid region
	SUD8004	Nubian Sandstone Aquifer System — Kordofan Province
	SUD8005	Lower Nile River basin aquifers
	SUD8007	Nubian Sandstone Aquifer System — Dongola area
	RAF8022–SUD	Nubian Sandstone Aquifer System — Northern Sudan
	RAF8036–SUD	Nubian Sandstone Aquifer System — Central Sudan
Tunisia	TUN8015	Cap Bon region aquifers — El Haouaria area
	TUN8018	Cap Bon region aquifers — Takelsa and Groumbolia aquifers
	RAF8007–TUN	North Western Sahara Aquifer System — Southern Tunisia
	RAF8035–TUN	North Western Sahara Aquifer System — Southern Tunisia
Uganda	UGA8002	Northern Uganda shallow aquifers
	UGA8003/UGA8005	Geothermal waters — Kibiro, Buranga and Katwe areas
	RAF8029K–UGA	Kisoro springs
	RAF8029W–UGA	Wobulenzi catchment
	RAF8037–UGA	Lake Victoria area
United Republic of Tanzania	URT8003	Dodoma region aquifers
	URT8004	Humbolo reservoir area
	URT8006	Makatupora basin and Arusha area
	URT8008	Makatupora basin and Arusha area
	URT8010	Ruvu River basin
	RAF8029–URT	Makatupora basin
	RAF8037–URT	Lake Victoria area
Zambia	ZAM8005K	Kabwe aquifer
	ZAM8005L	Lusaka aquifer
Zimbabwe	ZIM8004	Bulawayo area
	RAF8029–ZIM	Save River alluvial aquifers

Elements of the country page



Elements of the project page

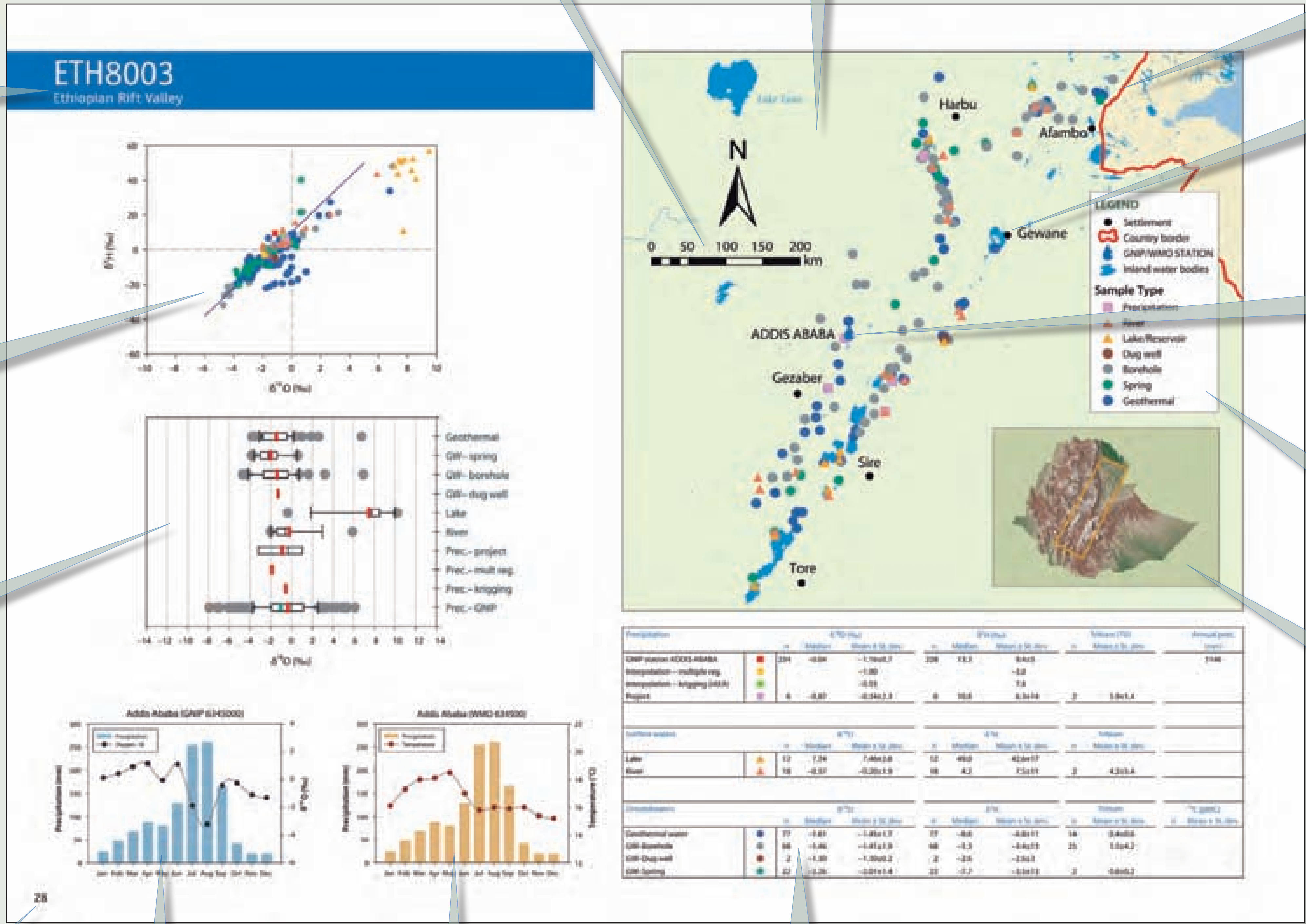
Scale of the map

Study area map showing the location and water types sampled for isotopes

International border of the country

Title bar with the project code and name of study area

City, town or settlement



Scatter plot showing deuterium versus oxygen-18 of samples analysed in the project. Different water types are shown in the legend of the map and in the summary table. The Global Meteoric Water Line [3], $\delta^2H = 8 \times \delta^{18}O + 10$, is included for reference. See the following page for an explanation of units.

City with a GNIP/WMO station

Box-and-whisker plot showing the range of oxygen-18 values for different water types. The central box shows the range of the middle 50% of the data values, between the lower and upper quartiles. The central line shows the value of the median. The red line indicates the mean and the green line shows the long-term amount-weighted mean. The "whiskers" extend out of the extremes (minimum and maximum values) within 1.5 times the inter-quartile range. Outliers are plotted as separate points.

Map legend

Index map

Page number

The oxygen-18 (permil) in precipitation and mean monthly values of precipitation (in mm) from the nearest GNIP station. See the following page for an explanation of units.

The distribution of mean monthly values of precipitation (in mm) and temperature (in °C) is presented from the WMO station closest to the study area [4].

Summary table providing basic statistics of the isotopes in each project. These statistics include the number of isotope measurements, the mean and median of the oxygen-18, deuterium, tritium and carbon-14 values and standard deviations. Long-term weighted annual means for oxygen-18, deuterium, and the amount of precipitation estimated from the nearest GNIP station are shown. For short-term isotope records in the GNIP database, the median is also provided. Estimates of the mean isotope contents of precipitation by interpolation were calculated at the IAEA using multiple regression [5] and kriging [6, 7] methods. Mean values of precipitation samples collected in the project are also listed.
Similar statistics for surface water (e.g. rivers, lakes and reservoirs) and groundwater (e.g. shallow dug wells, deep boreholes, springs and geothermal waters) are presented.

UNITS OF MEASUREMENT

Oxygen-18 and Deuterium

Oxygen-18 and deuterium contents in water samples are expressed as δ values ($\delta^{18}O$, $\delta^{2}H$), which are permil deviations from an internationally accepted standard. The δ unit is defined as:

$$\delta(‰) = \frac{R_{sample} - R_{VSMOV}}{R_{VSMOV}} \times 10^3$$

where, R is the isotope ratio $^2H/^1H$ or $^{18}O/^{16}O$.

In case of water, the internationally accepted standard is called Vienna Standard Mean Ocean Water (VSMOW) [3, 8]. The deuterium and oxygen-18 isotope ratios are determined by mass spectrometric methods. The measurements reported in this Atlas generally have a precision of about ± 0.1‰ for oxygen-18 and ± 1‰ for deuterium at one standard deviation level.

Tritium

Tritium concentration is expressed in tritium units (TU). One TU is defined as one atom of ^3H per 10^{18} atoms of ^1H, which is equivalent to an activity of 0.118 Bq or 3.193 pCi per litre of water. The half-life of tritium is 12.32 years (4500 days) [9]. Due to this relatively short half-life, tritium has been used in hydrogeology as an excellent environmental tracer to identify modern recharge in aquifer systems. Tritium content is measured by counting its radioactive decay, using liquid scintillation spectrometers. Due to very low levels of tritium in natural waters, electrolytic enrichment of tritium is done before counting the radioactive decay. The analytical uncertainty for tritium analysis is usually reported with each measurement. Current analytical methods involving electrolytic enrichment followed by liquid scintillation counting provide uncertainty values in the order of ±0.3 TU for tritium levels lower than 5 TU.

Carbon-14

For hydrogeological applications, radiocarbon or carbon-14 activity is expressed as percentage of modern carbon (pMC). The activity of modern carbon is 95% of the specific activity of the carbon of NBS oxalic acid supplied by the US National Institute of Standards and Technology (NIST). One hundred per cent modern carbon corresponds to a carbon-14 specific activity of 13.56 ± 0.07 disintegrations per minute per gram of carbon. Measurement of carbon-14 activity is generally carried out by decay counting using liquid scintillation spectrometry or, more recently, by measurement of atoms using accelerator mass spectrometry (AMS) methods. Carbon-14 is a key dating tool for groundwaters between 5000 and 40 000 years before present (B.P.).

STABLE ISOTOPES IN PRECIPITATION OVER AFRICA

The analysis of temporal and spatial variations of isotope contents in the different components of the water cycle is required for the characterization of different sources of recharge for aquifers, springs, lakes, rivers, reservoirs, etc.

Ultimately, precipitation is the source of all recharge. Therefore, definition of the isotope signals (^2H, ^{18}O and ^3H) in precipitation is required for proper assessment of location and mechanism of recharge. In other cases, isotopes in precipitation can aid in identifying fossil groundwater (complementary to the use of carbon-14 dating of groundwater) because of the isotopic contrast between modern and past precipitation.

GNIP is one of the main sources of information on isotope signals of precipitation worldwide. This global monitoring programme has been in operation since 1961 through a joint collaboration between the IAEA and the World Meteorological Organization (WMO).

The GNIP database, which is also accessible through WISER (http://www.iaea.org/water), provides basic isotope data for the application of isotopes in hydrological sciences.

The isotope contents of precipitation over Africa have been monitored at more than 70 stations for the last 40 years. The raw isotope data, as well as the summary information (statistical treatment of meteorological and isotope data), are available at: http://www.iaea.org/water.

The locations of GNIP stations in Africa are shown in Fig. 2 and are listed in Table 2. The long term weighted mean $\delta^{18}O$ and $\delta^{2}H$ values of precipitation calculated for the nearest GNIP station for each study area have been included in the summary table for each project.

FIGURE 2. Locations of GNIP stations in Africa

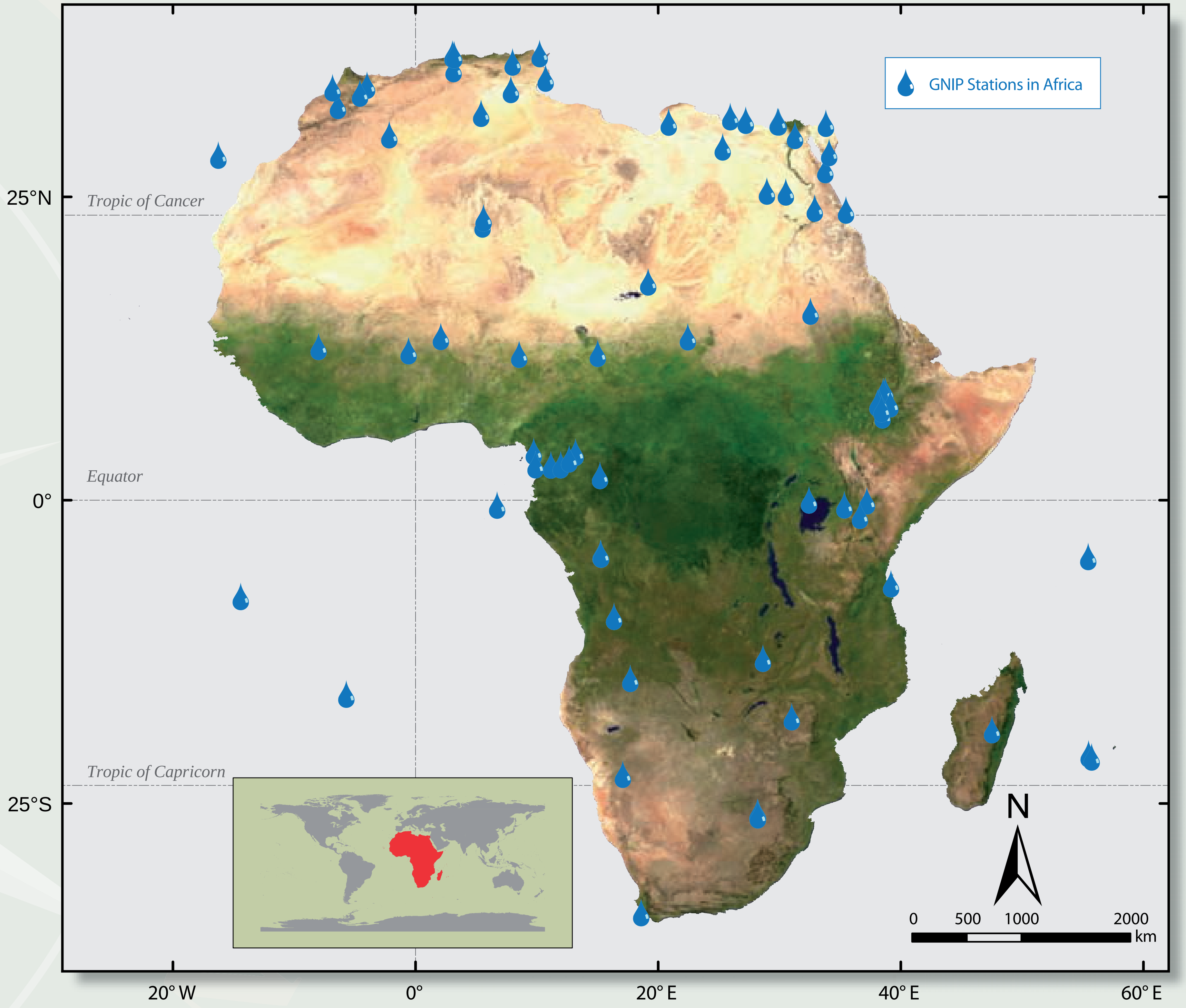


TABLE 2. GNIP stations in Africa

GNIP code	Station Name	Latitude	Longitude
6002000	Santa Cruz de Tenerife, Spain	28º 27′ N	16º 15′ W
6012501	Bab Bou Idir, Morocco	34º 13′ N	04º 00′ W
6013501	Rabat-CNESTEN, Morocco	34º 01′ N	06º 50′ W
6014100	Fes Sais, Morocco	33º 34′ N	04º 35′ W
6019100	Beni Mellal, Morocco	32º 33′ N	06º 24′ W
6036902	Algiers University, Algeria	36º 43′ N	03º 10′ E
6036903	Algiers-CN, Algeria	36º 46′ N	03º 03′ E
6044650	Ain Oussera, Algeria	35º 35′ N	03º 08′ E
6058000	Ouargla, Algeria	31º 55′ N	05º 24′ E
6060200	Beni-Abbes, Algeria	30º 07′ N	02º 10′ W
6067600	Assekrem, Algeria	23º 16′ N	05º 36′ E
6068000	Tamanrasset, Algeria	22º 46′ N	05º 31′ E
6071500	Tunis-Carthage, Tunisia	36º 49′ N	10º 13′ E
6073200	El Kef, Tunisia	36º 08′ N	08º 00′ E
6075000	Sfax, Tunisia	34º 25′ N	10º 24′ E
6076100	Nefta, Tunisia	33º 52′ N	07º 51′ E
6105204	Niamey-Orstom, Niger	13º 31′ N	02º 05′ E
6129100	Bamako, Mali	12º 19′ N	07º 34′ W
6190000	Ascension Island (Atlantic Ocean), United Kingdom	07º 55′ S	14º 25′ W
6190100	St. Helena (Atlantic Ocean), United Kingdom	15º 58′ S	05º 42′ W
6193100	Sao Tome (Atlantic Ocean), Sao Tome	00º 22′ N	06º 43′ E
6196700	Diego Garcia Island (Indian Ocean), United States of America	07º 19′ S	72º 24′ E
6198001	Saint Denis de La Reunion, France	20º 54′ S	55º 29′ E
6230100	Sidi Barrani, Egypt	31º 37′ N	25º 57′ E
6230600	Marsa-Matruh, Egypt	31º 19′ N	27º 13′ E
6231700	Ras Eltine, Egypt	31º 12′ N	29º 51′ E
6231800	Alexandria, Egypt	31º 11′ N	29º 57′ E
6233500	Rafah, Egypt	31º 11′ N	20º 52′ E
6233700	El-Arish, Egypt	31º 04′ N	33º 49′ E
6237100	Cairo, Egypt	30º 04′ N	31º 16′ E
6241400	Aswan, Egypt	24º 05′ N	32º 55′ E
6241701	Siwa, Egypt	29º 08′ N	25º 19′ E
6243200	Dakhla, Egypt	25º 30′ N	28º 58′ E
6243500	Kharga, Egypt	25º 26′ N	30º 31′ E
6245700	Saint Cathrene, Egypt	28º 40′ N	34º 06′ E

GNIP code	Station name	Latitude	Longitude
6246200	Hurgada, Egypt	27º 16′ N	33º 46′ E
6247500	Ras Banas, Egypt	23º 56′ N	35º 29′ E
6272100	Khartoum, Sudan	15º 36′ N	32º 33′ E
6277000	Geneina, Sudan	13º 28′ N	22º 27′ E
6345000	Addis Ababa, Ethiopia	09º 00′ N	38º 43′ E
6345001	Butajira, Ethiopia	08º 04′ N	38º 13′ E
6345003	Addis Ababa (West), Ethiopia	08º 58′ N	38º 34′ E
6345004	Silte, Ethiopia	08º 01′ N	38º 04′ E
6346000	Awasa, Ethiopia	07º 03′ N	38º 29′ E
6346001	Asela, Ethiopia	07º 57′ N	39º 08′ E
6346002	Ziway, Ethiopia	07º 33′ N	38º 25′ E
6369301	Mt.Kenya, Kenya	00º 02′ S	37º 13′ E
6370500	Entebbe, Uganda	00º 03′ N	32º 27′ E
6371401	Kericho, Kenya	00º 22′ S	35º 21′ E
6374101	Muguga, Kenya	01º 13′ S	36º 37′ E
6389400	Dar Es Salaam, United Republic of Tanzania	06º 52′ S	39º 12′ E
6398000	Mahe (Indian Ocean), Seychelles	04º 37′ S	55º 27′ E
6422000	Kinshasa-Binza, Democratic Republic of the Congo	04º 22′ S	15º 15′ E
6470000	N'Djamena, Chad	12º 07′ N	15º 01′ E
6475300	Faya-Largeau, Chad	18º 00′ N	19º 10′ E
6491001	Douala-Hydrac, Cameroon	04º 02′ N	09º 44′ E
6504600	Kano, Nigeria	12º 03′ N	08º 31′ E
6550301	Barogo, Burkina Faso	12º 20′ N	00º 34′ W
6621500	Malange, Angola	09º 33′ S	16º 22′ E
6641000	Menongue, Angola	14º 40′ S	17º 42′ E
6708500	Antananarivo, Madagascar	18º 54′ S	47º 31′ E
6756100	Ndola, Zambia	13º 00′ S	28º 39′ E
6777400	Harare, Zimbabwe	17º 49′ S	31º 01′ E
6811000	Windhoek, Namibia	22º 34′ S	17º 06′ E
6826200	Pretoria, South Africa	25º 43′ S	28º 10′ E
6826201	Lynnwood (Pretoria), South Africa	25º 45′ S	28º 13′ E
6826300	Pretoria (Irene), South Africa	25º 55′ S	28º 13′ E
6881600	Malan (Cape Town), South Africa	33º 58′ S	18º 36′ E
6890600	Gough Island (Atlantic Ocean), South Africa	40º 21′ S	09º 52′ W
6899400	Marion Island (Indian Ocean), South Africa	46º 52′ S	37º 52′ E

REFERENCES

[1] HEARN, P., HARE, T., SCHRUBEN, P., SHERRILL, D., LAMAR, C., TSUSHIMA, P., Global GIS Global Coverage DVD, version 6.4.2 (Developed by U.S. Geological Survey), American Geological Institute, Alexandria, VA (ISBN 0-922152-67-5) (2003).

[2] UNITED NATIONS GEOGRAPHICAL INFORMATION WORKING GROUP, International and Administrative Boundaries, International Boundaries Task Group (2007) available at: http://www.ungiwg.org/inter.htm.

[3] CRAIG, H., Standard for reporting concentration of deuterium and oxygen-18 in natural waters, Science **113** (1961) 1833–34.

[4] WORLD METEOROLOGICAL ORGANIZATION, 1961–1990 Global Climate Normals, Version 1.0, National Climatic Data Center, Asheville (1998).

[5] BOWEN, G.J., REVENAUGH, J., Interpolating the isotope composition of modern meteoric precipitation, Water Resour. Res. **39** doi: 101029/2003WR002086 (2003).

[6] GANDIN, L.S., Objective analysis of meteorological fields: U.S. Dept. of Commerce and National Science Foundation, Washington, DC, (1965). (Original in Russian, obektivnyi analiz meterologicheskikh poleai, 1963.)

[7] HERZFELD, U.C., Inverse theory in the earth sciences — An introductory overview with emphasis on Gandin's method of optimum interpolation, Math. Geol. **28** (1996).

[8] GONFIANTINI, R., Standard for stable isotope measurements in natural compounds, Nature (London) **271** (1978) 534–536.

[9] LUCAS, L.L., UNTERWEGER, M.P., Comprehensible review and critical evaluation of the half-life of tritium. J. Res. National Institute of Standards and Technology **105** (2000) 541–549.

SELECTED FURTHER READING

AGGARWAL, P.K., GAT, J.R., FROEHLICH, K.F.O. (Eds), Isotopes in the Water Cycle — Past, Present and Future of a Developing Science, Springer, Dordrecht (2005).

CLARK, I.D., FRITZ, P., Environmental Isotopes in Hydrogeology, Lewis Publishers, Boca Raton (1997).

COOK, P.G., HERCZEG, A.L. (Eds), Environmental Tracers in Subsurface Hydrology, Kluwer Academic Publishers, Boston (2000).

FRITZ, P., FONTES, J.-Ch. (Eds), Handbook of Environmental Isotope Geochemistry, Vol. 1: The Terrestrial Environment, Elsevier, New York (1980).

FRITZ, P., FONTES, J.-Ch. (Eds), Handbook of Environmental Isotope Geochemistry, Vol. 2: The Terrestrial Environment, Elsevier, New York (1986).

FRITZ, P., FONTES, J.-Ch. (Eds), Handbook of Environmental Isotope Geochemistry, Vol. 3: The Marine Environment, Elsevier, New York (1989).

INTERNATIONAL ATOMIC ENERGY AGENCY, Stable Isotope Hydrology — Deuterium and Oxygen-18 in the Water Cycle, Technical Reports Series No. 210, IAEA, Vienna (1981).

INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on Nuclear Techniques in Hydrology, Technical Reports Series No. 91, IAEA, Vienna (1983).

MAZOR, E., Chemical and Isotopic Groundwater Hydrology — The Applied Approach, Marcel Dekker, New York (1997).

MOOK, W.G., Introduction to Isotope Hydrology — Stable and Radio-active Isotopes of Hydrogen, Oxygen and Carbon, Taylor and Francis, London (2005).

UNESCO-IAEA, Environmental Isotopes in the Hydrological Cycle: Principles and Applications, IHP-V Technical Documents in Hydrology No. 39, Vols I – VI, UNESCO, Paris (2000).