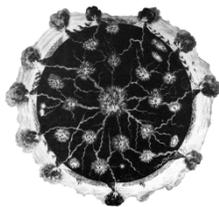


**THE ORSTOM-IRD CONTRIBUTION TO THE HYDROLOGY OF
LOW-LATITUDE REGIONS (1943–2024): OPERATIONAL ISSUES,
PROCESS STUDIES, REGIONAL HYDROCLIMATOLOGY AND
LONG-TERM MONITORING**

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ABSTRACT



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ORSTOM-IRD, a French research institution, has contributed during 80 years to the observation of various components of the hydrological cycle in diverse low-latitude regions. Initially devoted to the monitoring of large river systems in Africa, ORSTOM-IRD hydrologists started to instrument small catchments during the 1950s to address technical needs for developing infrastructures, with the aim of better understanding the processes controlling the local water cycle in various environments. Since the early 1990s ORSTOM-IRD hydrologists have been actively involved in so-called ‘Regional Hydroclimatology Projects’ (RHPs), which are large international programs intended to decipher the interactions between land surfaces and the atmosphere in tropical environments. Long-term observing programs arose from the RHPs and they now constitute a key tool for monitoring the evolution of the hydrological cycle in regions where safe access to water is still not guaranteed and threatened by the impacts of global change.

Keywords: Low-latitude, hydro-meteorological processes, hydrological engineering, monitoring and databases, capacity building
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1. INTRODUCTION

Low-latitude-inter-tropical regions receive half of the total amount of solar energy on Earth, and thus host the greatest volume of continental water cycle exchanges in the world with major consequences for the global climate. Scientific water resource studies in former colonial territories located in these regions began in the last decades of the 19th century, especially in the British Empire. In Africa, systematic observations of the main rivers (Nile, Senegal, Niger, Congo) started in the late 19th century and early 20th century. They were the work of the colonial powers which were interested mainly in the fluvial transportation routes and in the agricultural potential.

In the French colonies, a generalist scientific institution, initially called *Office de la Recherche Scientifique Coloniale* (Figure 1), dedicated to the colonies, was initiated in 1943 and was fully organized in 1946 after the victory of the Allies in World War II (Gleizes 1985; Bonneuil 1991). The term ‘colonies’ was changed to ‘overseas territories’ in 1949. The mission of the ‘Office’ later evolved into assisting the young independent countries and more recently to contribute to an international agenda of sustainable development, in low-latitude regions. The name of the Office changed several times; the most used and best known are ORSTOM (*Office de la Recherche Scientifique et Technique Outre-Mer* from 1953 to 1998) and IRD (*Institut de Recherche pour le Développement*) since 1999.

A ‘River Hydrology Center’ was created in 1946 (Figure 1). It expanded its scope and quickly grew to become one of the most important sections within ORSTOM, training

hydrologists specialised in tropical environments, not only in France, but also in the countries and territories where it operated: North, West and Central Africa, Madagascar, French Overseas Departments and Territories, and South America. An early agreement with the overseas department of 'Électricité de France' allowed competence and resources to be shared, with the aim of coping with the engineering problems of flood control, infrastructure design and water supply (Dubreuil 2003).

MINISTÈRE DE LA FRANCE D'OUTRE-MER

OFFICE DE LA RECHERCHE SCIENTIFIQUE COLONIALE

Centres de formation de Chercheurs Coloniaux

Établissement public doté de la personnalité civile et de l'autonomie financière, chargé d'assurer la formation des spécialistes des disciplines scientifiques nécessaires aux laboratoires et services de recherches des territoires d'outre-mer, l'Office de la Recherche Scientifique Coloniale a ouvert à cet effet un certain nombre de Centres de formation où sont admis les jeunes gens qui, à leur sortie des grandes Ecoles ou des Facultés, se destinent à cette carrière.

Les enseignements donnés dans ces Centres sont surtout orientés vers la pratique, leur but est de mettre entre les mains des candidats le métier de Chercheur spécialisé. Ils comportent l'enseignement des diverses techniques que les jeunes gens auront à appliquer et tendent à développer les qualités qui doivent caractériser le Chercheur.

ANNÉE SCOLAIRE 1949-1950

Les Centres de formation ouverts sont les suivants :

CENTRE DE GÉNÉTIQUE VÉGÉTALE	ET	CENTRE DE PHYTOPHYSIOLOGIE
CENTRE DE GÉNÉTIQUE ANIMALE		CENTRE DE PÉDOLOGIE
CENTRE D'ENTOMOLOGIE AGRICOLE		CENTRE DE PHYSIQUE DU GLOBE
CENTRE D'ENTOMOLOGIE MÉDICALE		CENTRE D'OcéANOGRAPHIE BIOLOGIQUE
VÉTÉRINAIRE		CENTRE D'OcéANOGRAPHIE PHYSIQUE
CENTRE DE PATHOLOGIE VÉGÉTALE		CENTRE D'HYDROLOGIE FLUVIALE

Figure 1. Poster for the training of 'Colonial Scientists' during the academic year 1949-1950, including a 'Center of River Hydrology'

From the late 1950s to the mid-1980s, most actions were geared towards solving technical and operational problems, often with national and international agencies, but also services provided to third parties. The mid-1980s was a turning point in many respects for both, 'Hydrology as a geoscience' and ORSTOM as a research institution (Chevallier and Pouyaud 1995). As stated by Eagleson:

Hydrologists are now being forced to consider the atmosphere and the land surface as an interactive coupled system, a perspective which draws us closer to the geophysicist's viewpoint of global scale process. (Eagleson 1986, p. 6S).

In 1985 ORSTOM became a public research institution whose main mandate was to carry out academic research in environmental, health and socio-economic sciences, focusing on tropical regions. A 'Continental Water Department' was created in 1987. When ORSTOM became IRD in 1999, 'joint research units' (*unités mixtes de recherche*) were setup with universities (Grenoble,

Montpellier, Toulouse and Paris), national research institutions such as CNRS (*Centre National de la Recherche Scientifique*), INRAE (*Institut National de la Recherche pour l'Agriculture et l'Environnement*), CNES (*Centre National d'Etudes Spatiales*) or Meteo-France, and few other establishments, in order to promote interdisciplinary research involving hydrologists, climate modellers and micrometeorologists, soil scientists and agronomists, environmental chemists, plant physiologists and remote sensing specialists. In parallel, helping to reinforce local research capacities in the countries where ORSTOM was active, interdisciplinary research remained as a central mission of the institution.

At the beginning of the 21st century, the French Academy of Sciences wrote:

Research aimed at developing countries, which used to be primarily a matter of solidarity, development aid, and scientific and technological transfer, has now become an integral part of most research into global commons. (Académie des Sciences 2006, p. xxviii).

This being said, it remains that safe access to water, food security, global health and poverty reduction are still key challenges in many tropical countries, as emphasized by the publication of the *Sustainable Development Goals (SDGs)* by the United Nations Organization general assembly in 2015, requiring the commitment of a wide scientific community, to which the hydrologists at ORSTOM-IRD bring an original, unique and long-standing experience.

The purpose of this paper is to document how ORSTOM-IRD hydrology evolved during nearly 80 years from a colonial service to a scientific contributor to the most recent developments in the discipline, keeping its focus on the low-latitude environments and global human and environmental development stakes including observations and field programs, and not forgetting to mention some key scientific results that branched out from these field activities. Of course, this does not render full justice to all the hydrological activities carried out at ORSTOM-IRD during eight decades, but we felt that observation being the first step of any natural science, it provides a good thread for contributing to the history of hydrology, especially for inter-tropical regions.

After providing a general historical overview of the development of hydrological activities within ORSTOM-IRD in section 2, the following sections examine the two broad categories of research activities in more detail: those mostly concerned with process studies in section 3, while section 4 deals with hydroclimatic regional programs, acknowledging that there is often some overlap between the two. Then, section 5 is devoted to presenting the technical activities that always accompany observation activities and are key for downstream research.

The references given in the text are only representative; they were selected from a huge corpus of scientific production amounting to several thousands of hydrological papers and books published by ORSTOM-IRD researchers. Such a selection does not pretend to be exhaustive but it is intended to help readers in their bibliographical quests, depending on their main areas of interest.

2. DOCUMENTING HYDROLOGICAL REGIMES AND PROCESSES IN LOW-LATITUDES

ORSTOM involvement in hydrological observations in tropical Africa is rooted in the colonial history of France, exploration by European explorers having been seen by some historians as the mother of colonization (Bonneuil 1991). The *terra incognita* attraction of tropical Africa, along with its resources and relatively low population density (as compared to Europe) fuelled this dual impulse for exploration and colonization. As a consequence, and until the early 1900s, most scientific information collected in the tropical regions came from explorers, whether civilians (naturalists, geographers), soldiers, or missionaries, acting on an individual basis, even though they might get some institutional support from scientific societies, the army, or churches. This

type of exploration was not propitious for a consistent and long-term monitoring of meteorological or hydrological conditions, nor was monitoring by local populations.

After the First World War, the development of these regions became a major issue for the colonial powers in Africa. Development had a different meaning than nowadays, but at that time it clearly referred to maximizing the extractive capacities of natural resources, with little consideration for the benefits that local populations may get out of this process (Hours 2020). Meteorological services were created with the mission of providing much-needed knowledge to support agricultural activities. In West and Central Africa, this led to the development of networks that had as many as several hundred meteorological stations in 1945. At the same time, hydrological monitoring lagged behind, with only 40 water-level gauging stations set up in the Niger and the Senegal basins and about the same number in the Congo basin (Olivry and Sircoulon 1998). Water-level readings were carried out mostly on a weekly basis, with little gauging performed to calibrate these stations. Thus, very little was known about the hydrological regime of these major rivers and almost nothing on small catchments. While the political contexts were different in South America and Southeast Asia, the need for a better knowledge of the water resources and water-related hazards was recognized, leading to the progressive emergence of a ‘tropical hydrology’ vision.

After World War Two, the building of infrastructure was boosted by the acceleration of mining, agricultural and forestry exploitation, urban development, and road construction. Many road bridges and small agricultural dams collapsed, illustrating the devastating consequences of building infrastructure without appropriate hydrological knowledge substantiated by adequate measurements (Dubreuil 2003). The ‘*Bureau Central Hydrologique*’ of ORSTOM was thus created at the very right time for it to take over the development of both a systematic long-term monitoring program of large rivers, and a more specific program of shorter-term measurements over a large array of catchments. In 1955, ORSTOM was given the responsibility for implementing and organizing a series of hydrological studies over small catchments (area smaller than 1,000 km²), called ‘*Bassins Versants Représentatifs et Expérimentaux*’ (BVRE)—see section 3 below for details.

At the time of the independence of the African colonies in the early 1960s, ORSTOM had become the major, if not the sole, hydrological operator in the former French colonies in Africa. National hydrological services were created in every new independent state, taking over the operational networks. ORSTOM continued to afford strong support to these new National Hydrological services, mainly under the umbrella of the CIEH (*Comité Interafricain d’Etudes Hydrauliques*), which coordinated similar operations in 14 francophone states in sub-Saharan Africa. ORSTOM was active in training engineers and technicians, helping in collecting data and assembling them in yearly data books as well as publishing so-called *monographies* for all the large basins of West and Central Africa (see section 4, below). ORSTOM also developed instrumental capacities in digitizing data since the beginning of records at gauging stations and organizing them in databases (see section 5, below).

After independence, the operational role of ORSTOM started to diminish until it ended mainly during the 1980s, but some actions lasted until the end of the 1990s, for instance in Mali where a team of ORSTOM hydrologists carried out the management of the main Niger River network gauging stations until around 2000 (Marieu *et al.*, 1998). Also, the BVRE program continued for some time but it increasingly turned to acquiring a better understanding of hydro-meteorological processes in different tropical environments (arid, semi-arid, humid savannah, forest, urban and even in high mountainous areas) as detailed in the following section (see also Dubreuil 1985, for a review of the scientific heritage of these field operations in these post-independence years), and it ended with the publication of a reference book (Nouvelot 1993).

The independence of the former African colonized territories also provided an incentive for ORSTOM scientists to turn their eyes towards the hydrology of other tropical regions, at first

mostly South America and then Southeast Asia. The first ORSTOM hydrological study in South America was undertaken by Dubreuil (1966) on the Jaguaribe river basin in the Nordeste region of Brazil. In the Mediterranean regions, the first study was on the Maghreb (Tunisia and Morocco).

After a decade during which its scientific activities became increasingly important in regard to its operational objectives, ORSTOM, becoming IRD in 1999, was requested to develop only scientific actions, in partnership with developing countries, and involving more and more academic partners from the global scientific community.

A new generation of African hydrologists got involved in the FRIEND–Water program (*Flow Regimes from International Experimental and Network Data*) of UNESCO IHP (*Intergovernmental Hydrological Programme*), whose component for West and Central Africa started in 1995 under the aegis of ORSTOM/IRD (Servat *et al.*, 1998). It is worth noting that the involvement of ORSTOM–IRD scientists in FRIEND–Water stems from a long-established and deep involvement in IAHS (*International Association of Hydrological Sciences*) activities, dating back to Jean Rodier who dedicated his life to measuring and understanding tropical hydrology and published a well-known book in an IAHS collection ‘*World Catalogue of Maximum Observed Floods*’ (Rodier and Roche 1984). After decades of participation of ORSTOM-IRD hydrologists in IAHS activities, and the increasing participation of African colleagues and of their research on tropical hydrology (Amoussou *et al.* 2021), the IAHS bureau appointed the regional committee for Africa in 2018, the first ever IAHS regional committee.

This inspired South-American hydrologists to also focus on specific topics and led to the creation of the Latin America IAHS regional committee in 2023. These events were accompanied by enhanced international recognition of the specificities of tropical hydrology in IAHS, as well as of its importance in the comprehension of the global terrestrial water cycle. The ORSTOM-IRD hydrologists undoubtedly played a significant role in the construction and training of the regional scientific community of hydrologists in West, North and Central Africa, and helped to accelerate the sharing of knowledge.

The importance of the tropical water cycle in Earth’s climate was also at the heart of some large international programs, set up under the *World Climate Research Program* (WCRP) to better understand the interactions between the atmosphere, water and land surfaces, which shape the climate of tropical regions in conjunction with their energy budget. Several IRD teams contributed to these programs, both in Africa and South America, as discussed later in section 4. In the early 2000s, the creation in France of *Services Nationaux d’Observation* (SNO, <https://www.insu.cnrs.fr/fr/les-services-nationaux-dobservation>) adopted the philosophy of *Regional Hydroclimatology Projects* (RHP), even though they were not solely dedicated to hydroclimatology.

During the same period (1990s and early 2000s) research-oriented long-term observatories were deployed either as a contribution to these international programs (*e.g.*, AMMA–CATCH, HYBAM, Glacioclim; see section 4 for details) or as a prolongation—in a different scientific context—of the various process-study field programs initiated by ORSTOM over the 1960–1990 period (see section 3 below). Later on, at the end of the 2000s, the concept of the critical zone progressively emerged and the above-mentioned observatories became part of the French OZCAR network (*Observatoires de la Zone Critique: Application et Recherche*) of critical zone observatories, which is itself included in a larger European setup, eLTER–RI (<https://elter-ri.eu/>).

Throughout the 80 years of field measurement campaigns listed in this paper, there have been continuous technological improvements, whether in the domain of *in situ* instrumentation, access to remote sensing data, or computing capacities. There is not enough space in a single paper to review all these additional tools that have allowed the most to be made out of field observations in terms of knowledge advances. Let us just mention that ORSTOM–IRD hydrologists contributed to designing new instruments, such as the portable rainfall simulator

(Figure 2), designed for characterizing the soil surfaces and their hydraulic properties and widely tested on a large range of surfaces in tropical environments (Casenave and Valentin 1992).

They also were early adopters of using Landsat imagery for land-use mapping and the identification of land-cover patterns; pioneering the design of 'Digital Terrains Models', facilitating the identification and location of water paths (Quinn *et al.* 1991); promoting geochemical proxies as a mean for better understanding the water transfer mechanisms at the soil-vegetation-atmosphere interface (Bariac *et al.* 1995); and taking advantage of the breakthrough in computing capacities for using high resolution physical models as early as in the beginning of the 1980s for producing 3D simulations considering the coupling between surface, soil and underground water (see *e.g.*, Girard *et al.* 1981).



Figure 2. Pyramidal structure of a rainfall simulator in a typical Sahelian environment during the dry season at Mare d'Oursi, Burkina Faso. The blue tarpaulins protect the simulated rain from the strong winds. – March 1981. Photo: P. Chevallier ©IRD

3. DESCRIBING, UNDERSTANDING AND MODELING HYDROLOGICAL PROCESSES

As mentioned in section 2, ORSTOM launched in 1955 an ambitious program of so-called '*Bassins Versants Représentatifs et Expérimentaux*' (BVRE). Over about 30 years, more than 120 BVREs were instrumented for periods lasting between 3 and 5 years in West and Central Africa (Nouvelot 1993) with the main objective of assessing the dependency of peak flows on different types of land cover, climatic conditions and size of the catchments (Rodier and Auvray 1965). The catchments were classified into 5 categories following their degree of permeability. In addition, slope criteria were used, by combining transverse and longitudinal slopes. This led to a collection of charts aimed at extrapolating the results to ungauged catchments for assessing the decadal flood. The 'Rodier–Auvray method' has been widely used for designing infrastructure until the late 1990s. Within this BVRE program the 10-year monitoring (1962–1972) of the Waraniene–Korhogo catchment in the open savannah of Northern Ivory Coast is especially worth mentioning, since it allowed the evaluation of the impact of land cover change on flow regime (Camus *et al.* 1976), with an emphasis on the characterization of the runoff/infiltration processes

in line with the pioneering work of Horton (1933). It then became clear that an in-depth knowledge of the soil properties, the topography, and the vegetation cover is a key to understanding the hydrological functioning of these tropical catchments (Dubreuil 1986).

During the late 1970s and the beginning of the 1980s, new catchments were selected for more systematically exploring these interactions between soil, vegetation and hydrology in i) the arid zones of the African Sahel (*e.g.*, Chevallier *et al.* 1985) and the Brazilian Nordeste (*e.g.*, Cadier 1993), (ii) the wet savannah of Ivory Coast (Hyperbav 1990), and (iii) the tropical forest of French Guiana (Fritsch 1992). The challenge of identifying the water paths that control the runoff production became a central issue, especially targeting the concept of soil slope organization advocated by Kirkby (1988). Other studies targeted the effects of agricultural practices on surface and subsurface runoff and on soil erosion. Studies by Perez *et al.* (1998), Castro *et al.* (1999), Nasri *et al.* (2004), and Al Ali *et al.* (2008) are examples of increased knowledge learned in a large variety of environments (West Africa, South America, and Maghreb).

The BVRE story found an extension in the context of regional field programs such as HAPEX-Sahel and AMMA (Lebel *et al.* 2010—see also below in section 4), which led to a better understanding of the Sahelian and Sudanian water cycle variability and improved rainfall-runoff parameterization at the local scale.

At the scale of large river basins, regional programs like West and Central Africa FRIEND-Water UNESCO IHP program, including many IRD hydrologists, also contributed to improving knowledge. Activities included a regional database open to all FRIEND program members, and a large number of hydrologists from West and Central Africa participated in this program. ORSTOM-IRD scientists strongly supported the creation of the African FRIEND-Water groups from the very beginning (Mahé *et al.* 2021). This networking approach of the FRIEND program was further extended in the Mediterranean area (Servat *et al.* 2003).

This context led to identify what would be known later as the ‘Sahelian Paradox’ (Mahe *et al.* 2005). Although it had long been observed that runoff coefficients had significantly increased for small catchments during the 1970s and 1980s drought in West Africa (*e.g.*, Pouyaud 1987), in correlation with the reduction of the vegetation cover, it was initially hypothesized that some other processes were taking over to account for this change in hydrological behavior, when upscaling. A first hitch to this scale-related vision occurred when it was documented that the Sahelian ‘Continental Terminal’ water table (CT3) started to increase at the beginning of the 1980s—*i.e.*, during a severe drought period (Leduc *et al.* 2001; Favreau *et al.* 2009)—all over the left bank of the Sahelian part of the Niger river in the territory of the Republic of Niger. Since this aquifer is essentially recharged from ponds in an endoreic hydrological landscape, this was a clear indication that runoff increase was a regional phenomenon, bringing more surface water in pools and ponds, from which it infiltrates to the aquifer. This reasoning holds for the semi-arid Sahelian environment, but not so much for more humid environments where a continuous drainage network does exist, and where, in fact, both the river flows and the aquifer levels were severely diminished, with river flow decrease largely exceeding the rainfall decrease. In a context of dramatically reduced annual rainfall, hydrologists had thus to face a contradictory behavior of increased runoff at the outlet of small Sahelian catchments and very high decrease of river flows in more humid tropical river basins (*e.g.*, Descroix *et al.* 2009).

This led to distinguishing between two subregional domains characterized by different surface conditions and different linkages between the surface and the groundwater (Mahé *et al.* 2013): (1) the Sahelian area, roughly north of the 750 mm annual rainfall amount towards northern arid lands, where river discharge essentially comes from surface runoff, and where the long lasting rainfall reduction leads to a reduction of vegetation and biomass, and thus to a reduction of the soil water holding capacity and an increase of direct runoff; and (2) the humid tropical West and Central Africa where the rainfall reduction leads to a durable decrease of the groundwater table,

which in turn brings less groundwater to the river discharge. Since the 2000s, such observations were used to alert national and international institutions about the need to revisit all the hydrological norms used for designing infrastructure even in humid Africa (*e.g.*, Paturel *et al.* 2003).

However, a further puzzling question arose when it was observed that the CT3 water table level continued to increase during the 2000s and 2010s despite the slight but significant annual rainfall recovery and accompanying greening of the vegetation, to the point of becoming a significant contributing factor for the repeated and unprecedented inundations in many large Sahelian towns (Sighomnou *et al.* 2012). It has thus to be assumed that the Sahelian paradox is in fact a mixed response to rainfall regime modifications—and more specifically the hydroclimatic intensification well analysed by Panthou *et al.* (2014)—and land surface and subsurface degradation. The drought had a major impact on deep-rooted trees reducing the effective water holding capacity of the soils and favouring surface crusting (Patirel *et al.* 2017). Since it takes time for this vegetation cover type to recover, the effect on surface runoff properties lasted well after the core of the drought.

In order to explore how a change in the precipitation regime can combine with these vegetation-related factors, the data of the Northern Mali AMMA–CATCH site (Mougin *et al.* 2009) were used to explore the possible existence of hydrological tipping points, that may involve a long-lasting new hydrological era in the Sahel. Using a dynamical model, Wendling *et al.* (2019) showed that the Sahelian hydrosystem effectively presents two alternative states and that during the drought it tipped from a high-vegetation/low-runoff regime to the alternative low-vegetation/high-runoff one where it has remained trapped until now.

Sediment transport has in parallel been a subject of interest since the 1970s (*e.g.*, Claude and Chartier 1977). A large research/development program was setup in the mountainous central-northern Tunisia, with the objective of preserving or improving the water storage capacity of dams built at the outlets of small catchments (Albergel *et al.* 2004). Sediment transport at basin scale has also been a topic of research in sub-Saharan Africa, most notably within the Senegal, Niger and Congo River basins (Picouet *et al.* 2001; Laraque *et al.* 2009).

Eventually, a large-scale experiment was carried out in Cameroon in the early 2000s during which daily sediment transport was studied for 3 years over 6 large catchments stretching over a large range of bioclimates from the Sahelian north area to the equatorial forest in the South, and crossing Central mountains and plateaus (Lienou *et al.* 2005). This study helped to better describe how sediment transport was linked to major hydroclimatic changes occurring in Central Africa, where small changes in seasonal rainfall distribution during boreal Spring leads to a major reduction of the Spring flood in large rivers of southern Cameroon, Gabon and Congo (Lienou *et al.* 2008), thus emphasizing that even the very humid equatorial Africa experiences hydroclimatic changes linked to global change (Bogning *et al.* 2020). Later on, the reconstruction of past sediment load to the sea demonstrated that most of the sand was trapped inside large impoundments, and was no longer reaching the coasts, accelerating the beach erosion and increasing the vulnerability of coastal areas to submersion (Kotti *et al.* 2018; Hzami *et al.* 2021; Hadour *et al.* 2021). During the last decade, Maghreb countries developed several programs to study sediment transports in relation to reservoir silting, showing for instance in Morocco that most of the sediment trapped in reservoirs comes from the reservoir's banks rather than from the rivers flowing into the impoundments (Hallouz *et al.* 2018, Ezzaouini *et al.* 2020), thus helping to design additional programs for soil conservation.

In addition to this large and intensive research program focused on better understanding what happens to water once it is on the ground, one must not forget that the processes driving the exchanges of water between land surfaces and the atmosphere also received some attention. Pioneering evaporation observations were carried out in the region of Lake Chad (Riou 1967) and later on in Central Africa (Riou 1972), using a Bowen ratio approach to consistently link energy

and water budgets (see also Pouyaud 1979). Regarding precipitation, rainfall measurements were made systematically on BVREs, but it was only in the late 1980s that specific campaigns were organised to study the multiscale spatial structure of rain fields using a combination of ground based, radar and satellite measurements (Lebel 1997).

At the beginning of the 1990s, ORSTOM hydrologists started to investigate hydrological processes in a quite different climatic environment, *i.e.*, in the high-altitude mountains of the Andes (Ribstein *et al.* 1995) and, later, in the Himalaya. These studies focused on the hydrological balance of low-latitude glaciated basins and the components of the glacial mass balance. Particularly interesting results have been achieved regarding the phase and distribution of precipitation as a function of altitude (*e.g.*, Savean *et al.* 2015), the detail of the water budget components (*e.g.*, Caballero *et al.* 2004; Mimeau *et al.* 2019), and the role of sublimation and turbulent fluxes (*e.g.*, Wagnon *et al.* 2009; Litt *et al.* 2015; Autin *et al.*, 2022).

Alongside this brief overview of watershed studies carried out by ORSTOM researchers, we must also mention their involvement in urban hydrology. For both physical and socioeconomic reasons, the large cities of developing countries have been facing huge water-sanitation and flood-control challenges for decades. The first measurements in African cities date back to the 1950s and 1960s, and were carried out on the Makelekele basin in Brazzaville (Congo) (Herbaud 1966a) and on the Gounti–Yena basins in Niamey (Niger) (Herbaud 1966b). In the late 1970s and early 1980s, new experimental basins were installed in several African capitals (Ouagadougou, Burkina Faso; Niamey, Niger; Lomé, Togo (Figure 3); Cotonou, Benin; Abidjan–Yopougon district, Ivory Coast), at the request of the CIEH.

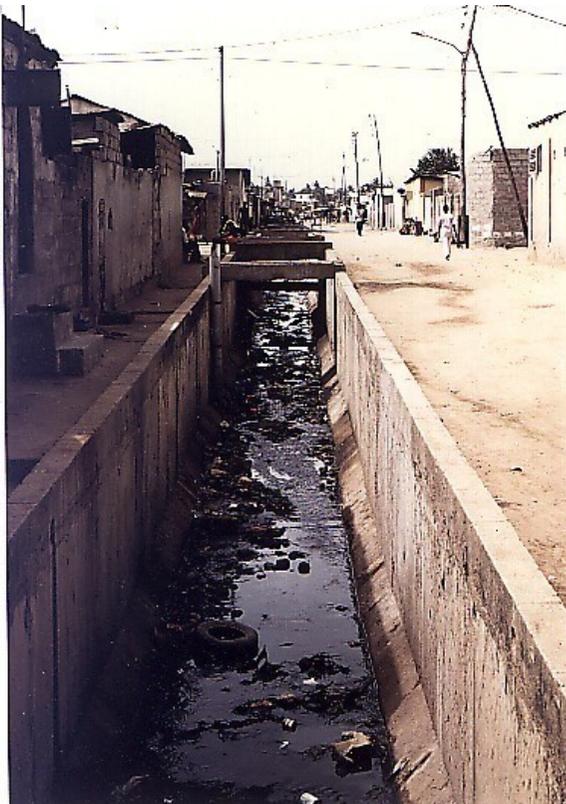


Figure 3. View of a street-side open collector in Lomé, Togo—photo taken in the 1980s. This type of collector is still widely used in African cities. Photo: C. Bouvier ©IRD

This effort was triggered by the accelerating growth of these big cities, generating increasingly frequent flooding and damage. These new campaigns took place in a context of emergence of urban hydrology in France and elsewhere in the early 1970s, due to a growing awareness of the specific water-related stakes in urban environments (Desbordes 1974; Chocat 1978). A total of 16 experimental basins were consequently installed by ORSTOM in West Africa between 1977 and 1987. In addition to these basins, rainfall simulation experiments were carried out in four of these cities in 1985–1986 to characterize the hydrodynamic behavior of urban soils, keeping in mind that a great proportion of urban areas of African towns were unpaved. These measurements led to the development of formulas and models for calculating design flows in African cities (Bouvier and Desbordes 1990; Bassel 1995; Miller *et al.* 2022; Chahinian *et al.* 2023).

Another approach has been to set up GIS-based spatial models that can finely simulate runoff over the entire city, and detect overflows from drainage structures (Bouvier *et al.* 2017; Diémé *et al.* 2022). In the framework of World Bank-funded projects, such GIS-based models associated with dense networks of rain gauges equipped with remote data transmission allowed the implementation of real-time forecasting demonstrators in Ouagadougou, Burkina Faso and Bamako, Mali.

IRD is currently pursuing this work in Dakar, Senegal (as a component of the *Changement Climatique et Cycle de l'Eau* project) and Abidjan, Ivory Coast (*Evidence* project), emphasizing co-construction with, and training of, African hydrologists. A strong scientific and technical community is more than ever needed at a time when African cities are growing at an unprecedented rate.

4. THE REGIONAL PERSPECTIVE

The global water cycle has long raised puzzling questions to scientists, most notably the Greeks, who wondered how water was reinjected into the atmosphere after having precipitated on Earth. However, over the following centuries, hydrology was essentially developed as an engineering science privileging local scale studies with the aim of providing tools for a reliable and safe access to water resources and protecting societies against droughts and floods. ORSTOM hydrology did not escape that trend, but there was also a will for documenting the regional hydroclimatology of the large West and Central African rivers, by assembling and synthesizing the observations available on the key parameters of their hydrological balance in a series of *monographies* (Table 1).

At that time, measuring the flow at the outlet of large tropical rivers, such as the Amazon (see *e.g.*: Jacon *et al.* 1987) or the Congo (Pouyaud 1972; Molinier 1979), was a real challenge pertaining to exploration (Figure 4). ORSTOM hydrologists were the first to use ‘Acoustic Doppler Current Profiler’ measurements in South America when regularly gauging the Amazon embouchure downstream of Obidos (Kosuth *et al.* 2009). Progressively new ground-based technological developments and satellite monitoring allowed for more accurate routine monitoring of large river flows and sediment transport (see *e.g.*, Mangiarotti *et al.* 2013; Emery *et al.* 2022).

However innovative they might have been in terms of spatial scale, these regional studies were still embedded in a practical problem-solving approach, targeting flood control, water supply and public health. The WHO onchocerciasis program is an emblematic example of such large river scale programs, targeting a central public health issue in humid tropical West Africa (Hougard *et al.* 2001) (Figure 5).

At the beginning of the 1990s, in line with the pioneering work of Eagleson (1978), scientific understanding became by contrast a central organizing principle advocated by the *Global Energy and Water Exchanges* (GEWEX) component of WCRP. GEWEX promoted RHP as an essential tool for understanding and predicting hydroclimates, requiring to bring together

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various disciplines on water-related issues. Low-latitude regions were clearly hot spots for such projects since they are key energy suppliers of the terrestrial climate while displaying a strong coupling between the land-surface energy balance and the water balance (Koster *et al.* 2004).

Table 1: Inventory of the “Monographies Hydrologiques” published by ORSTOM-IRD Editions (in case of several successive editions for the same basin or region, only the last one is quoted)

Basin or region	Publication date	Authors
Niger, the inland delta	1960	Auvray, C.
Niari	1965	Hiez, G., Billon, B., Touchebeuf, P., Chaperon, P.
Logone	1966	Billon, B., Bouchardeau, A., Roche, M., Rodier, J., Callède, J., Jarre, P., Pieyns, S., Riou, C.
Bandama	1972	Camus, H.
Delta of Oueme	1972	Colombani, J., Sircoulon, J., Moniod, F., Rodier, J.
Chari	1974	Billon, B., Guiscafne, J., Herbaud, G., Oberlin, G.
Sanaga	1975	Dubreuil, P. Guiscafne, J., Nouvelot, J.C., Olivry, J.C.
Martinique	1976	Guiscafne, J., Klein, J.C., Moniod, F.
Volta	1977	Moniod, F., Pouyaud, B., Séchet, P.
Gabon	1978	Carré, P.
Medjerdah	1981	Rodier, J.A., Colombani, J., Claude, J., Kallel, R.
Guadeloupe	1985	Chaperon, P., L'Hote, Y., Vuillaume, G.
Cameroon	1986	Olivry, J.C.
Niger (2 volumes)	1986	Brunet-Moret, Y., Chaperon, P., Lamagat, J.P., Molinier, M.
Oueds Zéroud et Merguellil *	1986	Bouzaiane S., Lafforgue, A.
Cape Verde	1987	Olivry, J.C.
Gambia	1987	Lamagat, J.P., Albergel, J., Bouchez, J.M., Descroix, L.
Likouala Mossaka	1987	Thiébaux, J.P.
Benin	1993	Le Barbé, G., Alé, G., Millet, B., Texier, H., Borel, Y., Gualde, R.
Madagascar	1993	Chaperon, P., Danloux, J., Ferry, L.
Lake Chad	1996	Olivry, J.C., Chouret, A., Vuillaume, G., Lemoalle, J., Bricquet, J.P.
Oubangui	2010	Callède, J., Boulvert, Y., Thiébaux, J.P.
Senegal	2014	Bader, J.C. (éd.)

* Coedition with the Tunisian Ministry of Agriculture.

The first GEWEX tropical experiment, Hapex-Sahel, was established in the West-African Sahel, in 1991 under the joint initiative of Meteo-France, NASA and ORSTOM (Goutorbe *et al.* 1994). Hapex-Sahel was a study of land surface-atmosphere interactions at the mesoscale in a dry tropical environment, built upon a regional rainfall monitoring program set up in Niger by ORSTOM (Lebel *et al.* 1992). A comprehensive set of hydrometeorological instrumentation was deployed, including flux stations, soil moisture measurements, pool gauging, radiometers and instrumented aircraft overpasses. Hapex-Sahel paved the way for the first-ever tropical RHP, operating from 2001 to 2010 over the whole West African region, including its oceanic and



Figure 4. Aerial view of Congo River at Maluku–Tréchet upstream from the pool Malebo where the discharge measurements were made in the 1970s. September 1985. Photo: P. Chevallier ©IRD



Figure 5. World Health Organisation Onchocerciasis Program. Monitoring by helicopter of an infested river in the Parc National d'Arly, South-East Burkina Faso, August 1978. Photo: P. Chevallier ©IRD

atmospheric boundaries: the *African Monsoon Multidisciplinary Analyses* (AMMA) project (Redelsperger *et al.*, 2006). One interesting outcome of this West African RHP was to provide the scientific basis and financial means for promoting a long-term regional hydroclimatic observing system *Analyse Multidisciplinaire de la Mousson Africaine - Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique* (AMMA-CATCH), (<https://amma-catch.osug.fr/>) sampling the west African eco-climatic gradient (Lebel *et al.* 2009; Galle *et al.* 2018) (Figure 6).



Figure 6. Banizoumbou, Niger. Turbulent flux measurement in a Sahelian environment, as part of the AMMA field campaigns and long-term AMMA-CATCH observatory. May 2006. Photo: T. Lebel ©IRD

The Niger data set alone now represents 35 years of high-resolution rainfall data (30 km spacing and 5-minute time resolution), without any other equivalent in sub-Saharan Africa. These data are heavily used for documenting the multi-scale evolution of the Sahelian rainfall regime in a context of climate warming, evidencing a strong intensification (Chagnaud *et al.* 2022). AMMA-CATCH also provides the longest, ongoing, flux monitoring in Africa (AMMA-CATCH 2005). Combining this unique data set with other hydrological measurements carried out on the observatory, allowed to address a series of important scientific questions such as the role of various climatic and land cover factors in controlling the hillslope hydrology (Richard *et al.* 2013) and the mesoscale water cycle (Peugeot *et al.* 2011) in a 14,000 km² catchment (Upper Ouémé – Northern Benin).

In this region of Sudanian climate, runoff is marginally Hortonian and closely controlled by unsaturated zone processes and especially sub-surface flow which provides the main contribution to river flow (Giertz and Diekkkruger 2003). The modelling study carried out by Herzog *et al.* (2021) with a critical zone model (Parflow–CLM at 1×1 km² resolution) making use of the large array of AMMA–CATCH hydrometeorological data has allowed the exploration of the role of the upper part of the weathering layer (clay content and vegetation) and of the hydraulic properties of the aquifer in controlling the river flow. It additionally confirmed that tree cover plays a key role in the seasonal water table depletion, through deep root water uptake in this region.

Another emblematic hydrological object of sub-Saharan Africa is Lake Chad, located in the Central Sahel. ORSTOM hydrologists have been working on the lake and its tributaries since the 1950s (Figure 7). After being ranked as the world's sixth largest inland water body with an open water area of 25,000 km² in the 1960s, it shrank dramatically at the beginning of the 1970s and reduced to less than 2,000 km² during the 1980s. However, over the last twenty years, the Lake Chad area increased by 24% (Mahamat Nour *et al.* 2021). This recovery is a good example of the effects of the hydroclimatic intensification mentioned above, resulting in repeated heavy floods: in 2022, 19 out of 23 provinces in Chad located in the southern part of the basin were flooded, with almost 1.5 million people affected and 350,000 hectares of land devastated. Due to its location at the confluence of the Chari and Logone Rivers, the capital city, N'Djamena, is an extremely exposed city (see *e.g.*, Gbetkom *et al.* 2022). In 2022, more than 250,000 people were affected by flooding and needed to be supported by the humanitarian system. On 19 October 2023, Chad declared a state of emergency.



Figure 7. Aerial view of the Chari River Delta into the Lake Chad. February 1978. Photo: M. Roche. ©IRD

In South-America the first studies date back to the 1960s on Rio São Francisco (Dubreuil, 1960) and during years they worked mainly in the Nordeste, with a first study on the Rio Jaguaribe (Dubreuil, 1962). The ORSTOM hydrologists started with their Brazilian colleagues to investigate the Amazon basin only in the beginning of the 1980s (Callede *et al.* 1985). Many other

studies investigated the upper Amazon basin in other countries (Bolivia, Peru, Equator), and only much later on Orinoco.

From all these experiences, and after a first international program PIRAT (Olivry 1989), started the idea to create the international Amazon basin network. The *Hidrologia da Bacia Amazônica* (HIBAM) international program launched in 1993 (Molinier *et al.* 1993), was very instrumental in providing the hydrological monitoring of *Large-Scale-Biosphere-Atmosphere Experiment in Amazonia* (LBA) (Avisar and Nobre 2002), a huge international effort that, among other major results, substantiated the intuition that the deforestation of the Amazon basin affects very significantly its hydroclimatology as well as that of other locations on Earth (Avisar *et al.* 2002).

A long-term monitoring program of the Amazonian basin *Hydrologie du Bassin Amazonien* (HYBAM, following HIBAM), (<https://hybam.obs-mip.fr/>) was subsequently launched in 2003 by IRD and its South American partners (*e.g.*, Cochonneau *et al.* 2006), to document the long-term variability and trends of the largest world hydrological system, with a particular emphasis on sediment transport (Moquet *et al.* 2016; Vauchel *et al.* 2017). In 2008 HYBAM was labeled part of the French network of observatories (Guyot 2008). Operational since 2003 and focused on monitoring rivers and water resources in the Amazon (Figure 8), HYBAM carried out long-term hydrological, sedimentary and geochemical measurements to understand the origin and evolution of waters and transported materials (sediments, organic matter, nutrients, etc.) in Amazonian rivers from the Andes Cordillera to the Atlantic Ocean. This network includes additional rivers that also drain into the tropical Atlantic Ocean: the Orinoco, Maroni and Oyapock Rivers in South America, and the Congo River in Africa. Since then, HYBAM has sourced a significant volume of information on tropical rivers and institutional articulations with countries of the Amazon basin (agencies and universities), plus actions in the Orinoco and even Congo by complementing the environmental monitoring carried out in countries by national bodies.



Figure 8. “Encontro das Aguas”: confluence of the Rio Negro (black water) and the Rio Solimões (muddy water), close to Manaus (Brazil), February 1993. Photo: P. Chevallier. ©IRD

Inheriting from the regional impetus provided by HYBAM and based on various climatic studies linking surface and atmospheric processes between the Amazon basin and the Andean Cordillera (*e.g.*, Segura *et al.* 2020), a new RHP—ANDEX (<https://www.gewex.org/>

project/andex/home/andex-rationale/—was launched in 2020 by the international community. It aims to understand, model and predict the dynamics of the water and energy cycles over the Andes Cordillera, at a wide range of temporal and spatial scales, and their linkages with the surrounding oceans, land surface and major river basins (<https://www.gewex.org/project/andex/science/white-book/>). This integrative vision of basic hydroclimatic processes and climate variability is crucial to face the urgent challenges brought about by anthropogenic climate change as well as land use change and deforestation along the Andes.

Among other recent regional initiatives by IRD researchers with their local partners, the Glacioclim (<https://glacioclim.osug.fr/>) and Cryobsclim observing systems are especially worth mentioning. With the emergence of the global warming issue, the future of the cryosphere in the mountain ranges of the low latitudes was identified in the first IPCC reports as a major scientific and societal challenge, since it plays a critical role in shaping hydrological regimes and water resources of some of the largest worldwide basins. While the glacier and snow cover extent are reduced in the Tropics *stricto sensu* (Central Andes, East Africa, Papua), it is a major landscape component in Hindu–Kush Himalaya and Central Asia, which have a lot to do with the monsoon climatic regimes that are typical of the tropical regions. The difficulty in carrying out scientific observations in these remote areas, where harsh climatic conditions prevail, explains why they are poorly documented.

Even though remote sensing is more and more instrumental for monitoring the retreat of glaciers worldwide, *in situ* measurements are still crucial for establishing reliable mass balances and for validating models. This is why heavily instrumented glaciers are used as both regional hydroclimate indicators and as the basis for process studies in this very specific environment. To that end, the Great Ice (*Glaciers et Ressources en Eau dans les Andes Tropicales – Indicateurs Climatiques et Environnementaux*) component of Glacioclim (Sicart *et al.* 2015) has been monitoring two tropical glaciers and their associated catchments: one, since 1991, in the external tropics (Zongo glacier in Bolivia) and the other, since 1997, in the internal tropics (Antizana glacier in Ecuador). This observatory has already provided a large array of scientific results, ranging from process studies (*e.g.*, Autin *et al.* 2022; see also section 3 above) to the impact of Andean glacier shrinkage on the water resources (*e.g.*, Soruco *et al.* 2015).

More recently Cryobsclim has undertaken to monitor two glaciers in the Himalayas (HMA), the Chhota Shigri (Azam *et al.* 2016) and the Mera glaciers, respectively in India and Nepal. Associating the Cryobsclim ground monitoring with remote sensing measurements, Brun *et al.* (2017) were able to provide an assessment of the mass balance of the Himalayan–Karakoram glaciers highlighting contrasting behaviors between the western and the eastern parts of the HMA. This is crucial information for the calibration of the models used for projecting glacier response to climatic change, as these models do not capture the pattern, magnitude and intra-regional variability of glacier changes at present.

5. DATA ACQUISITION, PROCESSING, ANALYSIS AND MANAGEMENT.

In most low-latitude regions harsh climatic conditions make *in situ* measurements challenging, especially when regular maintenance of instruments is necessary. The BVRE campaigns thus required a permanent presence of technicians and researchers on site during the rainy seasons, in order to minimise periods of missing measurements. Paper recording gauges—either for rainfall or streamflow—were the norm in the 1950s until the 1970s, but early in the 1980s, recording raingauges began to be equipped with digital *read-only memories (ROM)*, a technique that ORSTOM contributed to develop in partnership with Elsyde[®], a private company. This technique was used at full scale for the EPSAT–Niger (*Études des Précipitations par Satellite*) campaigns that started in 1989, with more than a hundred recording raingauges installed over an area of 16,000 km² in the vicinity of Niamey (Niger).

This allowed data fed into a database in quasi-real time, that provided the founding component of what would become the AMMA-CATCH database, itself being used as the prototype of the SNO databases. This technique of ROM data storage progressively equipped stations of the operational services in West and Central Africa, allowing for the first time in this part of the world to feed directly digital databases, and avoid the cumbersome task of digitizing paper records. At the end of the 1990s, the ROM systems started to be replaced by easier to handle systems; these devices allowed a preliminary control of the data and a possible correction step, and next a transfer to the data bases.

During the same period, new techniques of data transmission were developed based on sensors and transmitters used by the community of oceanographers and atmospheric physicists. For instance, in the WHO Onchocercosis project (see previous section) the stations were equipped with sensors sending by satellite the basic information (date and time, water level) stored in a data base. The collected informations allowed a quasi-real time planification of the aerial treatments of the rivers, which were conditioned on their levels (Servat and Lapetite 1990). All these pioneering automated transmission techniques have now been replaced by more robust and higher flow-rate systems.

Downstream of this progressive automation of data acquisition and transmission, ORSTOM developed data processing softwares, such as Pluviom for rainfall data and Hydrom for streamflow data (see *e.g.*, Raous *et al.* 1990), which were widely distributed to and used by operational services and research labs. Since then, numerous hydrometeorological softwares have been developed here and there in various countries, but IRD has been building on the previous ORSTOM expertise to develop a new analysis software dedicated to the analysis of extreme rainfall based on a multi-scale approach in time and space (Panthou *et al.* 2014). This is the cornerstone of an on-going action for revising the hydrological norms in West Africa, a component of the ‘*Cycle de l’Eau et Changement Climatique*’ project (<http://www.projet-cecc.org/>).

ORSTOM hydrologists have also contributed to developing hydrological database. As early as 1967 (Roche 1968), they proposed a definition and codification of gauging stations, applying the standardisation strategies recommended by AFNOR (French normalisation system) in connection with ISO standards. In the HAPEX-Sahel experiment (Goutorbe *et al.* 1994), ORSTOM data scientists partnered with NASA and Meteo-France colleagues to create one of the first ever integrated database using a java interface, assembling meteorological, hydrological and ecological data.

Since the end of the 1990s the IRD’s joint units (in the French public research organisation, a joint unit is shared by several institutions including universities) have inherited this historical ORSTOM database. It has been partly completed by data from various sources: African National Services, FRIEND-Water program of UNESCO (with databases created in each of the eight regional groups), and data coming from research programs. A new database, SIEREM (*Système d’Informations Environnementales sur les Ressources en Eau et leur Modélisation*), was thus created, enlarged to all African countries with 13,722 hydrological or rainfall stations, dating back to 1837 for the first observations, to the present (Boyer *et al.* 2006). Only metadata are accessible, as SIEREM relays all data requests to National Services. But SIEREM proposes free ‘processed’ data as monthly rainfall grids (1940–1999, for all Africa) (see also the African Database of Hydrometric Indices (ADHI), Tramblay *et al.* 2021), a number of maps (rainfall, river basins, etc.), GIS data linked with about 400 African river basins (basin contours, hydrographic network, FAO-derived Soil Water Holding Capacity, vegetation cover, geology), pictures of many hydrological stations, numerical version of many technical documents dating back to the creation of the stations and ‘*monographies hydrologiques*’ for about 20 rivers.

One major issue for the near future relates to saving and compiling infra-daily measurements. Indeed, apart from the SNO’s data that are stored in quasi-real time in the Theia

information system (see below), only 25% of the BVRE data are stored in the SIEREM database (Table 2) and most of the infra-daily data produced by operational services are either not even digitized or are not accessible through any information system. Making these fine time step data available to the research and operational community is a real challenge, given the diversity of data and actors involved. The UNESCO–IRD project aiming at re-assessing hydrological norms in sub-Saharan Africa or the IAHS Africa committee might provide potential arenas for promoting actions in that direction (Amani and Paturel 2017).

Table 2: BVRE records available in the SIEREM data base (2018).

Country	Locations (urban catchments in italics)	Available records	
		River gauges	Rain gauges
Benin	Boukombe, Dodou, Lhoto, Tero, Djougou, Tiapalou <i>Cotonou</i>		2
Burkina Faso	Bambassou, Gagara, Lac de Bam, Leraba, Manga, Mare d'Oursi, Massili <i>Ouagadougou, Wentenga</i>	11	26
Cameroon	Méfou, Nooun, Ottotomo, Sanguere <i>Yaoundé</i>	19	14
Cape Verde	São Nicolau		1*
Congo	Comba	3	4
Ivory Coast	Booro Borotou (Hyperbav), Korhogo, Taï, Sakassou, Yopougon, Abidjan, <i>Adiopodoumé, Bagatogo, Dioman, Mahandouni, Morondo, Odienné</i>	14	50
Gabon	Nzémé		2
Ghana	Kulaw, Morago, Nabogo	3	
Mali	<i>Bamako</i>	4	14
Mauritania	Dionaba, Ghorfa, Seloumbo	10	
Niger	Badeguicheri, Goulbi de Gabi, Kountkouzout, Teloua Agadez, Vallée Keita <i>Niamey</i>	5	4
Central African Republic	Ngola, Sarki	9	12
Senegal	Djiguinoum, Thyse Kaymor <i>Dakar, Podor, Tambacounda, Ziguinchor</i>	9	18
Chad	Bade, Bam Bam <i>Ba Illi, Deli, Ndjamena, Bol Dune</i>	10	10
Togo	Koza, La Daye <i>Lomé</i>	2	7

* manual observation

NB. Only the records stored in the SIEREM data base are listed. Other BVRE data exist in the archives, but are still not integrated in SIEREM or not digitized. More details are given in the SIEREM web site.

Today IRD is keen to join the international challenge of open science and data sharing, and several data have already been shared publicly *e.g.*, (i) the AMMA–CATCH data set in 2005 (<https://doi.org/10.17178/AMMA-CATCH.a>), (ii) the Paprika–Preshine data set in the Everest region (<https://doi.org/10.23708/000521>), (iii) the ‘ADHI: African Database of Hydrometric Indices’ deposited in the ‘DataSuds’ storage center, which is one of the elements of the open science system that IRD promotes (<https://dataverse.ird.fr/dataset.xhtml?persistentId=doi:10.23708/LXGXQ9>).

Based on the data collected, the ORSTOM–IRD hydrologists have endeavoured to provide summaries on a global scale: *e.g.*, for the annual precipitation in the interval 1940–1999 over

Africa (Mahé *et al.* 2012; Dieulin *et al.* 2019). In the 1990s they contributed for Africa to the project ‘*Water Resource Assessment*’ of the World Meteorological Organisation (<https://community.wmo.int/en/activity-areas/hydrology-and-water-resources/water-resources-assessment>). Later they coordinated for the Mediterranean basin and the Caribbean the ‘*World Hydrological Observing System*’ project of WMO aimed at regionally rationalising the hydrological observation networks.

The SNO’s (see sections 3 and 4) also generated important databases collecting the meteorological and hydrological field observations as spatialized remote data acquired through the successive generation of satellite imagery. These data are publicly available through the Theia platform (<https://www.theia-land.fr/>), which federates scientific expertise on a national scale around five major themes: cryosphere, continental waters, land cover, agro-systems and biodiversity, imagery and radiometry.

Finally, two actions driven by ORSTOM-IRD should be mentioned in this section because, beyond the historical background, it reflects the spirit of co-construction that has always inhabited the ORSTOM-IRD institution and its researchers.

First, the RIO network (‘*Réseau informatique de l’ORSTOM*’), which between 1989 and 1995 introduced the first Internet services, particularly e-mail, in a dozen countries in sub-Saharan Africa: Senegal, Mali, Niger, Burkina Faso, Côte d’Ivoire, Congo, Togo, Madagascar, Cameroon, Congo, and Guinea. In 1995, when the Internet emerged from its academic confines, the RIO project involved more than 100 institutions in 15 African countries. The project will subsequently eclipse the national structures, but will have shown, in particular, that it is possible for the least developed countries to acquire advanced know-how while this is still being appropriated in the technological metropolises (http://www.rio.net/Rio_Innovation&CooperationV2.html).

Second, the ‘*Horizon Plein Textes*’ database, an online bibliographic database created by ORSTOM-IRD (<https://horizon.documentation.ird.fr/exl-php/accueil>), covers all disciplines of the institute, not only hydrology. The database records and provides access to the publications of the Institute’s scientists and co-publications with scientific partners in the South, as well as to the holdings of its documentation centres around the world. With more than 110,000 documents, 80,000 of which are freely accessible online, it allows the dissemination of the scientific heritage of the IRD (the oldest documents date from the 1940s), but also of the science in progress with about 3,000 new publications registered each year. This resource contains a wealth of information and data that has not always been digitized, including many hydrological field reports. It is a historical scientific heritage probably unique to the world. At the end of 2017, the Institute’s documentary collection was awarded the ‘collections of excellence’ label within the framework of the CollEx-Persée1 national programme, for a renewable period of five years (2018-2022). The Horizon database is dedicated to supporting an open access policy (https://en.wikipedia.org/wiki/Horizon_Pleins_textes).

6. DISCUSSION AND CONCLUSIONS

This paper presents a brief review of how ORSTOM-IRD hydrologists have been involved over the past 80 years in observing and monitoring various components of the hydrological cycle in low-latitudes regions, witnessing major evolutions of Hydrology as a science and of the socio-environmental challenges faced by populations of these regions. From problem-solving approaches to an understanding-driven science, from local studies to a global change agenda (Eagleson 1991), from short-term and focused measurements to long term monitoring systems, hydrological observations were carried out for various purposes in different regions and at different scales. ORSTOM-IRD hydrologists have trained hundreds of African hydrologists, technicians, engineers and academics, of national services, high schools and universities, being often very innovative in instrumentation and in the use of new technologies, like computing hydrological models, satellite transmission of data, and more recently, use of radar altimetry for

ungauged basins, and they set up national hydrological networks in more than 30 countries or territories.

Due to this large and time-evolving array of motivations, it would be difficult to pretend that a clearly enunciated strategy presided over this vast ensemble of field deployments. Many technical and scientific issues, responding to solicitations from governments and agencies, fed the curiosity of groups of researchers, seizing the opportunity for participating in large international programs and sharing their field and technical knowledge with the international community. Notwithstanding this heterogeneity of motivations and operational setups, the result is an impressive, even though far from comprehensive, ensemble of results and achievements that help document the fascinating and diverse facets of Tropical/Mediterranean hydrology, especially in West and Central Africa, tropical South America, the Maghreb and Southeast Asia, from arid subtropical lands to equatorial forests.

Historically, ORSTOM-IRD activities have been largely dominant in Africa, especially in West Africa, less so in Central and North Africa. It is also in Africa that the Institute's staff has worked most extensively, and this is reflected in the article.

Current extensions of these traditional regions of interest include the Mekong River in Southeast Asia, through partnerships with international agencies where ORSTOM-IRD hydrologists shared their long experience in setting-up and managing large river networks, and low-latitude mountainous regions, such as the Himalayas and the Andes, where they were among the pioneers in exploring the high tropical mountains hydrology. The legacy of this investment is both scientific and operational, and it is worth remembering that it all results from continuous and fruitful collaborations between ORSTOM-IRD's scientists and partners in many different countries, supported during many decades by the French government funding.

An important point should be made here. ORSTOM/IRD is, and always has been, a French government institution depending of its foreign policy. The choice of projects, partners, and locations for intervention is therefore largely dependent on France's geopolitical strategy or on the state of France's relations with the regions concerned. For example, it is now (2020 and later) extremely difficult, if not impossible, to conduct field research in countries such as Mali, Niger, or Burkina Faso. France's partnership with Southeast Asian countries has only resumed in the last few decades, after a long period of tension. The case of so-called emerging countries, particularly India, South Africa, Mexico, and Brazil, where ORSTOM/IRD has sometimes been active for a long time, is significantly different. The research teams in these countries are highly skilled. Researchers there now work together in close partnership, sharing resources and fieldwork sites to improve knowledge of the physical and human environments of low latitudes with a view to global sustainable development.

The desire to share actions with all stakeholders, from the first 'overseas' observations to the advanced research underway or planned, is obvious at every stage of that 'story'. Shy and self-interested in colonial times, the training and participative approach has changed completely over the nearly 80 years of work by ORSTOM-IRD hydrologists. Scientists, technicians, local actors, professors, students, trainees, administrators, observers, villagers, and others were involved in the scientific works devoted to observing, mapping, monitoring, analyzing, understanding, or modelling the hydrological processes in a large range of situations in the low-latitude regions and in the developing countries. In terms of staff and work, it was actually on the local scales that ORSTOM-IRD *stricto sensu* staff intervened, including for operational studies. Work on the major basins (Congo, Amazon) started late, generally with less numerical involvement of ORSTOM-IRD staff and with broad participation of local partners.

These local, national, and international contexts raised many scientific questions regarding the specific water processes at the same level as in the global Earth, and the recent development of the different open data warehouses, for hydrology and climatology help increase the research

activities throughout the Tropics and improve the quality of the studies of the critical zone especially in Africa.

For almost 20 years, ORSTOM–IRD has also been promoting exchanges between partners from different regions of the world, for example between West Africa and North Africa, and even South America. Key scientists from the South are also invited to participate in the laboratory assessment procedures in France. Some scientific common events are mentioned in the paper, but there are dozens of ways to share knowledge, projects, and future visions. Among the most recent events organised within the FRIEND–Water network with the active support of IRD researchers and funding, one can cite several training sessions in Africa and South America on using satellite data to assess water heights at ungauged points on rivers, or to assess water turbidity (Mahe *et al.*, 2023), and also a series of large continental events, conferences, workshops and training sessions about large river hydrology in Africa, started in 2015 (Amoussou *et al.*, 2021). IRD strongly supported these events which increased exchanges between the communities of hydrologists from different regions of Africa.

While this paper has focused on quantitative hydrology, there are other aspects of the research carried out by ORSTOM–IRD scientists that would have deserved to be described. Erosion and sediment transport have been briefly addressed in section 3, but they are only one facet of a larger problem, that is water and environmental quality, also dealing with emergent contaminants, plastics and more recently water re-use. Over the past twenty years an active core of IRD scientists has invested in this field, whether in Africa with its Mediterranean coast (*e.g.*, Hzami *et al.* 2021), in Amazonia (*e.g.*: Moreira-Turcq *et al.* 2013), in the Andes (*e.g.*, Elbaz-Poulichet *et al.* 1999) or Southeast Asia (*e.g.*, Boithias *et al.* 2021), often leading to collaborations with UNESCO IHP, and more recently with the *French Agency for Development* (AFD). Undoubtedly, this is a burning issue, since water quality is being degraded in many countries by anthropogenic activities; in regions where water is scarce due to climatic conditions, this degraded quality is an additional factor of stress for the local populations and calls for setting up ambitious research programs that are multidisciplinary by nature.

Such multidisciplinary programs emerged at the end of the 1970s at local scales (see *e.g.*, Chevallier *et al.* 1985) and they are too numerous to be listed here, but it was definitely an early characteristic of ORSTOM–IRD to be in a position to promote and achieve such initiatives. With the emergence of global change related issues, multidisciplinary international programs were launched at regional scale, some of them being located in tropical regions such as AMMA (Redesperger *et al.* 2006) in which ORSTOM–IRD scientists were very active. Systemic and transdisciplinary approaches will certainly remain central in the future to address the multiple challenges associated to global change. Water is at the heart of many of these challenges, whether as a vector of pollution, a key component of the regional climate dynamics or an essential component of life on Earth.

However, many questions related to hydrological processes remain unanswered and need further investigation, especially for low-latitude regions. Global warming is already affecting societies through an increase in frequency and intensity of heat waves, droughts, and extreme rainfall, as well as coastal erosion and submersion due to sea level rising. Furthermore, human activities often worsen the climate change impacts on water resources, quality, and the environment. Observation and modelling uncertainties, scale effects (space and time), energy balance and evapotranspiration assessment, snow and ice melting and sublimation in mountainous environment, groundwater flows, solid matter and contaminant transfer, land-use planning and water resource management policies and rules, are among the key issues that require great attention in the coming years and decades. Especially relevant in that context is the fact that the IAHS Africa committee has started a wide consultation to identify and prioritize the major challenges faced by Africa in matters of hydrology and climate, building on various prospective documents such as the 23 Unsolved Problems in Hydrology (Blöschl *et al.* 2019).

Even though much remains to be achieved in matter of tropical hydrology, the ORSTOM–IRD contribution over the past decades has been significant in at least three main respects: First, the quantity of data collected is particularly impressive, especially in Africa; many of them have been quality assured and stored following reliable and reproducible methods, so that they are today largely used or referred to by many users in and out of the continent. Second, ORSTOM–IRD hydrologists have consistently and actively been involved in training activities in either academic or operational institutions, which contributed to the emergence of a high-level academic community as well as to improving the technical expertise of meteorological and hydrological national and regional services. Third, the knowledge produced covers a large array of topics, and has proved very useful for operational applications in diverse domains such as water mobilisation, including dams, assessment and prediction of large floods as well as health and socioeconomic issues.

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However, given their skills, interests, and personal work, the five co-authors can only present what is likely a biased view of the scientific history of an institution that was part of a turbulent period. The text would undoubtedly have been written differently by others. Obviously, the same story told by the southern partners who were closely involved would be fascinating, presenting a totally different perspective.

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Our thoughts are especially with those who have passed away.

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