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Rapid evolution of water resources in the Senegal delta

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ABSTRACT

In recent decades major water developments have led to an agricultural transformation of the Senegal delta both in Senegal and Mauritania. This otherwise, semi-arid region of the Sahel band now has an abundant supply of freshwater all year round mostly used for irrigation and urban water supply, including for the capital cities of the two countries. Archives from the Landsat satellites and in-situ hydrographs were used in this paper to retrace and analyse the hydrological changes that have taken place in the region since the middle of the 20th century. The satellite archives indicate that the area covered by irrigation increased by one order of magnitude from 73 km^2 in 1973 to ~770 km^2 in 2010. The observed hydrological changes are complex, multi-faceted and often of great magnitude. If the water cycle was representative of natural conditions in the early 1980s, it is now representative of a heavily modified system controlled and impacted by human activities. The first hydraulic infrastructure was installed in 1947 to enable the Lake of Guiers to become the main water supply for Dakar. Two large dams were built on the Senegal River in the mid-1980s that modified the hydrological regime of the river by 1) preventing seawater intrusion, 2) raising the stage of the river and of Lake of Guiers and 3) moderating floods. Another recent hydrological change in the delta was the opening of river mouth in 2003, which has led to a reduction of the average water level while increasing the semi-diurnal tidal wave between the river mouth and Diama. Each phase of these river regime changes and each step of the irrigation expansion are expressed in localised changes in the physical groundwater system. Increasingly, the retroaction from the shallow aquifer systems is observed as a rise of the saline water table. This poses a threat to the environmental and agricultural value of the region, and the salinization of the soils. Mitigating actions for this threat are currently being envisaged by the authorities.

1. Introduction

The hydrologic cycle is exposed to multiple environmental stressors, such as changes in land cover (e.g. Scanlon et al., 2005, 2007; Favreau et al., 2009), surface water diversion schemes (Leblanc et al., 2012) and climate variability (e.g. Leblanc et al., 2009; Tweed et al., 2009). They all potentially lead to important shifts in the hydrologic cycle by modifying the nature and intensity of the hydrological processes. These impacts on the hydrological cycle vary in magnitude, extent, and timing and feedback mechanisms are also often observed.

Globally, the hydrological impacts from environment changes are particularly visible in semi-arid regions where water resources are limited, natural variability is high and ecosystems resilience is low (e.g. Ragab and Prudhomme, 2002). Many semi-arid regions have also experienced a sharp increase in water demand from high population growth and farming expansion in the 20th century. A severe drought has also affected many the Sahelian countries in the 1970s and 1980s (e.g. Mahé and Paturel, 2009). In the Senegal Basin, the response to this drought and the increase in the precariousness of water resources and agriculture (e.g. Taïbi et al., 2009) led to the construction of a series of dams on the Senegal River initiated by the OMVS (Organisation pour la Mise en Valeur du fleuve Sénégal). The regulation of the river led to many environmental and socio-economic changes. The most important is probably the agricultural transformation of the region with the introduction of irrigation on a broad scale.

This study is based on two main research questions:

i) What changes in the Senegal River and irrigated agriculture were observed?

ii) What were the surface water and groundwater responses to these hydro-agricultural developments?

To respond to these questions, this paper presents an integrated analysis of hydrological changes since the second half of the 20th Century using observations from multi-disciplinary datasets. It concerns only the left bank of the Senegal River, which is situated in Senegal. Though the hydrology of the Basin is relatively well documented under natural

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conditions (e.g. Rochette et al., 1974), recent hydrological changes under the increasing anthropogenic pressures are important and have, to date, received limited attention (Bader and Cauchy, 2013). In this study, surface water and groundwater resources are studied conjunctively. Important interactions between these two major compartments of the water cycle were reported in the region (Saos and Zante, 1985). Accounting for surface water and groundwater interaction is therefore required to grasp the full complexity of the response of the connected hydrosystem to environmental changes. Surface water and groundwater hydrographs provide direct observations of changes in 1) the river hydrological regime, 2) groundwater and surface water interactions and 3) groundwater recharge and storage in irrigated and non-irrigated areas. This information was complemented by a time series of Landsat scenes that allowed us to map the rapid expansion of irrigation across the Senegal delta region and facilitated the interpretation of the hydrograph data.

2. Study area

The Senegal delta, is a vast flat floodplain of meandering channels downstream of Dagana that regroup in a single estuary when reaching the Atlantic Ocean (Fig. 1). The Senegal River is the junction of the Bafing and Bakoye Rivers, whose headwaters are located in the Republic of Guinea, and then traverses 1800 km to the mouth located south of Saint Louis in Senegal. The mean slope of the river is about 0.02‰ over its last 900 km. The river feeds several streams, canals, and lakes in the delta region, including Lake R'Kiz in Mauritania and Lake of Guiers in Senegal, which is the principal source of fresh water supply for Dakar. The Senegal River crosses three climate zones, Guinean, Soudanean and Sahelian (i.e. annual average rainfall varying from ~2000 mm to 200 mm). Within the Senegal delta, annual rainfall is influenced by the northern Sahelian tropical climate, which is characterized by a long dry season (October to June) and a short rainy season (July to September) (Fig. 2a). The average annual temperature is around 27 °C, with a minimum of 23 °C in January and a maximum of 30 °C in September. The relative humidity is high during the rainy season with a monthly average of about 80%. The inter-annual variations of rainfall are presented for Saint-Louis and Podor in Fig. 2b, and highlight the rainfall deficit during the drought that began in 1969 and peaked in the early1980s.

In response to this drought and to support the irrigation development two dams were constructed on the Senegal River by the middle of the 1980s (Diama and Manantali). The introduction of this infrastructure, in particular the Diama dam, induced significant environmental, socio-economic and cultural changes in the Senegal delta by allowing the intensification and expansion of irrigated agriculture. During the initial stages of irrigated agricultural development in the delta, large areas of land were managed by government (SAED: Société nationale d'Aménagements et d'Exploitation des terres du Delta). Subsequently, most of the irrigated land has been handed to groups or individual farmers (PIV: Individual Perimeters).

The Senegal delta is part of the Senegalese-Mauritanian sedimentary basin dated Mesozoic-Cenozoic. The oldest formation is the Maastrichtian, which is mainly comprised of sand and sandstone (Sall, 2006). This is overlain by the discontinuous Eocene marine clay, marl and limestone, and the continuous layer of sandy clay detrital sediments that form the Continental Terminal formation, which outcrops at Dagana (Rochette et al., 1974). During the Quaternary, sea level transgression and regression cycles were accompanied by fluvial erosion and alluvial deposits (Le Brusq, 1980; Van Lavieren and Van Wetten, 1988; Loyer, 1989). During the marine transgression, the Inchirian I (sandy clay sediments with low permeability) and Inchirian II

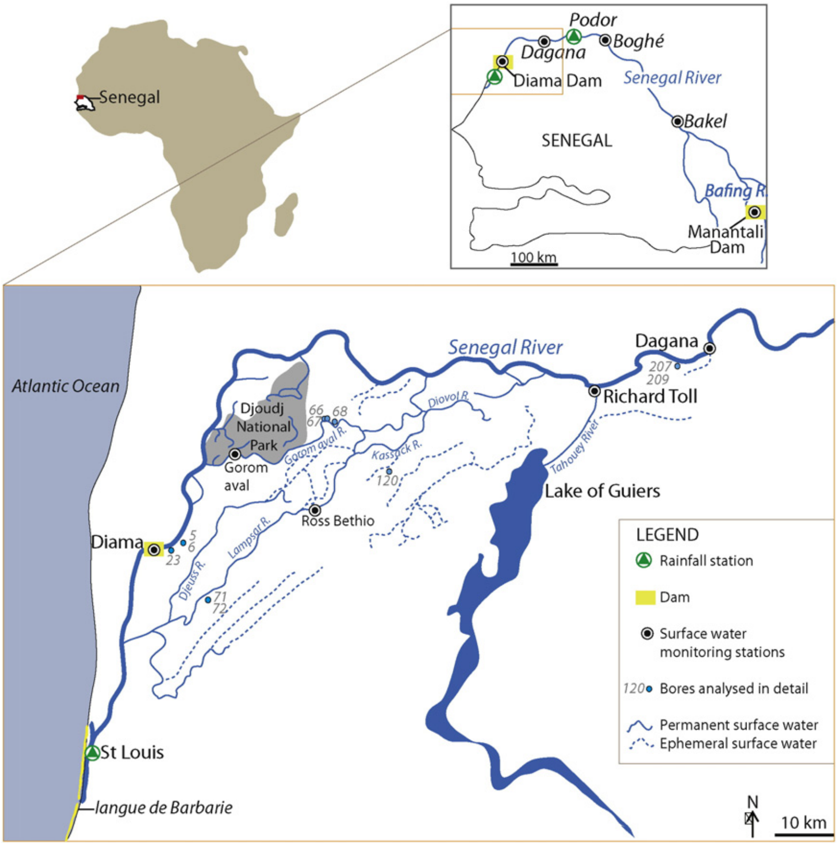


Fig. 1. Location of Senegal in northwestern Africa, Senegal River, other permanent and ephemeral surface waters, the Diama and Manantali dams, surface water and rainfall monitoring stations, and the locations of groundwater bores analysed in detail in this study. Only the Senegal part of the delta is presented in this figure.

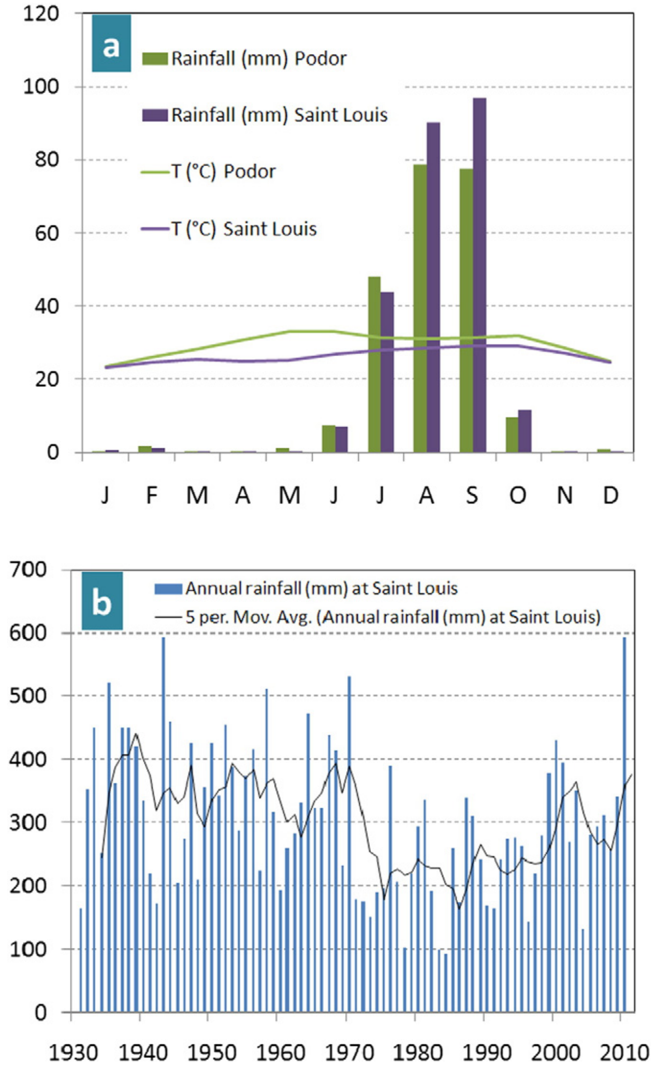


Fig. 2. Historical climate. (a) Mean monthly temperature and mean monthly rainfall at Saint Louis and Podor. (b) Variability in annual rainfall from 1931 to 2010 at Saint Louis (blue bars: mean annual rainfall; black line: 5 year moving average).
Source: Data from Agence Nationale de la Météorologie du Sénégal

(sandstone and clay layers) formations were deposited. The aridity that accompanied the following marine regression resulted in the accumulation of aeolian sediments and the formation of sand dunes (Da Boit, 1993). An ensuing marine transgression resulted in the deposit of the Nouakchottian formation (clay and sand deposits; Audibert, 1970). In this study we consider groundwater in the shallower aquifers; the Quaternary upper aquifer (bore depth < 18 m) and the Quaternary lower aquifer (bore depth > 20 m). The Nouakchottian aquifer overlies the Inchirian aquifer and the two systems are hydraulically connected, although in some areas they are separated by a discontinuous layer of silt and clay (SAED/DPDR, 1998).

The delta region is characterized by an abundance of wetlands and floodplains, which are often considered as a hotspot for biodiversity in the Sahel region, especially for water and migratory birds. Arguably the most significant wetland is the Djoudj national park. Protected since 1971, this 17,000 ha water body is listed under as a Ramsar wetland and was added to the UNESCO World Heritage sites in 1981. Other protected areas in the region include the 'Langue de Barbarie' national park and the Guembeul reserve in Senegal, the Diawaling national park and the Chat TBoul reserve in Mauritania. In 2005, the high biodiversity value of this region was recognised and listed as a UNESCO transboundary MAB biosphere reserve.

Land use in the delta is mostly occupied by agricultural activities. Traditionally, irrigation agriculture in the Senegal delta was practiced only during the rainy season and just after the annual flooding of the delta (that peaks in Saint Louis in October and November). Supported by the implementation of the surface water infrastructure, more recent farming in the delta now involves irrigation throughout the year using water from the Senegal River. From June to December, rice crops dominate the land; from October to April, vegetable produce such as tomatoes and onions are grown; and during the dry season (February to June) rice and groundnut crops are present. A large irrigation area located north of Lake of Guiers is farmed for sugar cane by the Senegalese Sugar Company (CSS). This increasing intensification of irrigation throughout the year and the expansion of areas cultivated since the 1970s have inevitably impacted groundwater hydraulic heads throughout the region. The magnitude and extent of these impacts is important information for the management of water resources in the Senegal River delta.

3. Data and methods

3.1. Remote sensing

A time series of Landsat archives was used to map the evolution of irrigation in the Senegalese side of Senegal delta from 1973 to 2010. This time series, which is made of four time steps spanning across these 37 years, calls upon 3 types of Landsat sensors: Multispectral Scanner System (MSS) for 1973 and 1981, Thematic Mapper (TM) for 1984 and 2010, Enhanced Thematic Mapper Plus (ETM+) for 2000 (Table 1). The Landsat scenes were selected in April or May, where irrigation sharply contrasts with dry land. They were downloaded from the USGS Glovis website. They are cloud free in our region and come with radiometric and geometric corrections applied to them (level 1T processing).

The scenes digital numbers were converted to reflectance values using GRASS toar (top-of-atmosphere radiance or reflectance) algorithm (http://grass.osgeo.org). For each scene, a vegetation index (NDVI) and a moisture index (NDWI) were computed to assist in the detection of irrigated areas (Gao, 1996). In the end, a visual interpretation proved the most robust means of detection as irrigated schemes are often characterized by their context, a homogenous texture, a geometrical shape, sharp edges with pronounced contours (Lillesand et al., 2004). It was possible to distinguish three categories of irrigated land: irrigated scheme with crop, irrigated scheme inundated, irrigated scheme left dry and uncultivated. In mapping irrigated areas in this study area a large part of the irrigated land was uncultivated at the time of mapping; this often indicates a farm whose owners have fallen behind at the start of the irrigation campaign due to lack of funds. Results from the Landsat imagery in Senegal were compared with agricultural data obtained independently by the SAED through field surveys (OMVS, 2011).

3.2. Surface water and groundwater data and analysis

3.2.1. Surface water

Since the beginning of the 20th century, >130 gauging stations were monitored at one time or another on the Senegal River Basin. For ten of them, installed on the main course of the river (e.g. Kayes, Bakel, Dagana), the water level has been continuously observed since 1903 or 1904, except during low water periods before 1950. Between 1936 and 2010, >3200 discharge measurements were carried out on 63 gauging stations in the basin. Most of the 51 gauging stations still operated in recent years are managed by national water services of the concerned countries (Guinea, Mali, Mauritania, Senegal).

Table 1
Details of the Landsat data analysed. Data were downloaded from the USGS Global Visualisation Viewer (http://glovis.usgs.gov). The Level 1T (L1T) data are provided with systematic radiometric and geometric processing while employing a Digital Elevation Model (DEM) for topographic accuracy.

Landsat satellite	Sensor	Acquisition date	Path	Row	Cloud cover (%)	Processing level	Scene ID
1	MSS	16/04/1973	220	49	0	L1T	M1220049_04919730416
3	MSS	28/04/1981	220	49	0	L1T	M3220049_04919810428
5	TM	10/05/1984	205	49	10	L1T	L5205049_04919840510
7	ETM +	28/04/2000	205	94	20	L1T	L72205049_04920000428
5	TM	16/04/2010	205	49	0	L1T	L5205049_04920100416

OMVS, which regroups these four countries, maintains a hydrometric database containing all the observations available for the basin. These data, recently homogenized (Bader and Cauchy, 2013), are used here to describe the flow regime of the river with the following gauging stations: Bakel, which controls most of the flow of the river in the valley is a flawlessly rated old gauging station, showing the natural fluctuations of discharge and its changes under the influence of the Manantali dam; Dagana is also an old gauging station, which is used to describe the evolution of the river level in the upstream part of our area study, as a result of natural fluctuations and under the impact of Manantali and Diama dams; Diama is a flawlessly rated gauging station, whose upstream and downstream levels are used to describe the evolution of flow through the anti-salt Diama dam and the river levels in the downstream part of our study area.

3.2.2. Groundwater

Time series of groundwater hydraulic heads were analysed for changes in local seasonal fluctuations, inter-annual trends and vertical hydraulic gradients. Hydraulic heads were monitored on the network of bores installed by the USAID by the research programme EQUESEN (Environnement et qualité des eaux du fleuve Sénégal) between 1987 and 1990, and by the SAED since 1997/1998. Analysis of this time series data therefore has a major data gap between 1990 and 1997 (transition from EQUESEN to SAED). There are also smaller gaps in the data within the time series. For example, many piezometers do not have data between July 2004 and June 2005. For this dataset, the highest temporal resolution for hydraulic head monitoring is monthly; however consecutive monthly intervals of data are inconsistently present. During the monitoring periods 1987–1992 and 1997–2011, the median number of hydraulic head measurements is $3.5\cdot a^{-1}$ and $6.1\cdot a^{-1}$ per bore respectively.

Bores screened in both the upper and lower Quarternary aquifers were analysed in this study. 200 bores were analysed for linear trends in hydraulic heads between the years 1985 and 1991, the depths of these bores ranges from 2 to 49 m (average depth 11.4 m). 40 bores were analysed for longer time series trends in hydraulic heads between the years 1985 and 2013. Of these bores, 18 are screened in the upper Quaternary aquifer (depth 5.4–16.7 m), and 22 are screened in the lower Quaternary aquifer (depth 5.6–49.2 m).

11 of these bores were then analysed in more detail to highlight the inter-annual and seasonal trends in hydraulic heads with impacts from the changes in river regime and irrigation expansion. The locations of these 11 bores are presented in Fig. 1 (bores 5, 6, 23, 66, 67, 68, 71, 72, 120, 207 and 209), and includes 4 sites where the bores are nested and analysed for changes in vertical hydraulic gradient changes (5 and 6, 66 and 67, 71 and 72, and 207 and 209). From July 2012 to July 2013, 6 of these bores were installed with Solinst loggers which recorded daily measurements of hydraulic head, and were therefore used for a higher temporal resolution analysis of seasonal changes in hydraulic head. The field characteristics within proximity to each of these 11 bores analysed in detail are presented in Table 2. Interannual tendencies were computed as linear trends (least squares approach) in $m\cdot a^{-1}$ with starting and finishing dates that are from the same hydrological season (i.e. rainfall season or irrigation season). A positive vertical hydraulic gradient indicates a potential upward flow direction (from lower aquifer toward upper aquifer).

To analyse influences of river changes on groundwater, the bores 5, 6 and 23 are used as they are located near Diama, have a long time series of hydrograph data (1987 to 2012/2013) and this data only reflects impacts of changes in the river regime on the groundwater system. Unlike the bores located close to Dagana, these bores at Diama are not influenced by irrigation waters as they are located outside of irrigated areas and have higher hydraulic head values compared with surrounding bores. The impacts of irrigation on the physical groundwater system in the Lower Senegal delta are analysed in detail at three sites to illustrate some of the variations observed in groundwater in the delta due to irrigation practices. The first site is where there has been irrigation impacts since the beginning of groundwater monitoring data in 1987 (nested bores 71 and 72), the second site is located in an area where waste irrigation water is disposed (bore 120), and the third site is where temporal variations in both local river regime and irrigation practices have influenced the groundwater hydraulic heads (nested bores 66 and 67, and bore 68).

Table 2
Distance to rivers, geology, and presence of irrigation fields and irrigation channels near (<300 m) bores that are analysed in detail in this study.

Bore ID	5	6	23	66	67	68	71	72	120	207	209
Distance (m) to closest river	800 SR[1]	800 SR	132 SR	382 GR[2]	381 GR	242 GR	1000 LR[3]	1000 LR	8500 KS[4]	169 SR	900 SR
Surficial geology	Sand dune	Sand dune	Sand dune	Clay sand	Clay sand	Clay sand	Sand dune	Sand dune	Clay	Sand clay	Sand clay
Bore located <300 m from irrigated field:											
In Apr.-00	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No
In Apr.-10	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No
Bore located <300 m from irrigation channel:											
In Apr.-00	No	No	No	Yes	Yes	Yes	No	No	No	No	No
In Apr.-10	No	No	No	Yes	Yes	Yes	No	No	No	No	No

1: SR = Senegal River; 2: GR = Gorom Aval River; 3: LR = Lampsar River; 4: KS = Kassak River.

4. Results

4.1. Changes in the Senegal River

The flow of the Senegal River, which declined naturally with lower rainfall conditions in the 1970s and 1980s (Figs. 3, 4a and 5), is largely supplied by the monsoon rains from May to October on the upper basin, in the Fouta Djallon mountains. Downstream from Bakel (located about 800 km from the mouth), the river receives only negligible inflows and the annual flood propagates slowly (<20 km per day for the largest floods) on a vast floodplain. The annual flood peak is even more smoothed when it reaches, around October, the city of Dagana, located <200 km from the mouth (Bader and Cauchy, 2013).

Until October 1983, the hydrological regime of the Senegal River evolved naturally. The stage of the river downstream of Dagana was very low each year from Janurary to June. Marine waters regularly invaded this estuarian portion of the river, progressing up to ~200 km upstream (i.e. Dagana) during this period, before being pushed into the ocean by the arrival of the annual flood (Rochette et al., 1974). In exceptionally dry years like 1983, seawater was observed 300 km upstream of the ocean. The influence of the oceanic tides was felt up to the city of Boghé (~400 km from the river mouth) (Rochette et al., 1974).

From November 1983, at the beginning of each low flow period a temporary dam was re-built across the river at Rheune, about 50 km upstream of Diama (Saos and Zante, 1985). This period marks the first important anthropogenic change in the hydrological regime of the river. Before being destroyed by the annual flood, the Rheune dam prevented the inflow of saline water and maintained a reserve of freshwater (Cogels et al., 1994). The water levels behind the dam first rose while inflows from upstream were still sufficient then dropped more than a meter below sea level during the low flow recession (Fig. 4a).

Operational since 1986, the Diama dam definitively replaced the temporary Rheune dike, with the same objective of preventing the intrusion of saline water in the estuary. This structure is subject to a security constraint, which imposes an upper limit of the dissipated power within the flow through the dam. The respect of this constraint requires a partial or total opening of the dam gates during the passage of the annual flood of the river (Bader, 2004).

Operational since 1987 on the Bafing River in the upper basin, the Manantali dam is a large reservoir that regulates the discharge of the Senegal River. The support of low flow was moderate until January 1992; from 1987 to 1991, the water level upstream of Diama was maintained permanently above the sea level but allowed to drop during low-flow conditions (Bader et al., 2003). The support of low-flow by the Manantali dam was amplified in two stages; firstly in 1992 with a release often >100 $m^3 s^{-1}$ to meet the needs of irrigated agriculture in the Senegal River Valley and delta, and secondly in 2003 at the start of hydropower production, with release often >150 $m^3 s^{-1}$ in low-flow conditions (Fig. 5). Embankments were built along the river upstream of Diama to allow these permanent water inflows to raise the minimum water level; during low-flow conditions, the average water level upstream of Diama changed from 150 cm IGN in 1992 to 220 cm in 2002 (Figs. 4b and 5).

Due to the security constraint mentioned above, the maximum water level allowed upstream of Diama decreases when the river discharge increases. This water level, which must also be high to facilitate withdrawals for irrigated agriculture, must therefore be reduced annually during the passage of the flood. So, maintaining a high level in the river upstream of Diama is a management objective that is paradoxically more difficult to achieve during the flood than during the low-flow period. The water level at Dagana, which is under the opposite influences of the increased discharge from upstream and decreased level at Diama, increases almost every year during the flood (Fig. 5). It decreased only during the 2004 flood, due to the very low discharge which let the downstream influences prevail. Between Diama and Dagana, the water level evolution during the flood is intermediate (Bader, 1992).

The Manantali and Diama dams have therefore strongly modified the hydrological regime of the river in its estuarine portion, allowing the development of irrigated agriculture across the Senegal delta due to the sustained high water levels and freshwater all year round. Under natural conditions, Lake of Guiers was subject to important seasonal fluctuations in surface area and salinity. Before the implementation of the anti-salt Rheune dike and then the Diama dam, gates were installed in 1947 on the Tahouey River at Richard Toll allowing Lake of Guiers to become a vast reserve of fresh water used as a major water supply for Dakar (Cogels et al., 1994). Prior to February 1992, the Tahouey gates were only opened when: 1) the water in the Senegal River at Richard Toll was not brackish (this was always true since November 1983) and 2) the river level was higher than the lake's. Water levels in Lake of Guiers decreased seasonally as a result of evaporation but always remained higher than the river during low-flow conditions. Since March 1992, the lake level evolved to become almost similar to that of river levels at Richard Toll, probably due to permanent or semi-permanent opening of the gates in the Tahouey.

Another recent hydrological change in the delta was the opening of the Langue de Barbarie in October 2003. This emerged sand bar, 200 to 400 m wide, separates the river from the ocean between St. Louis and the mouth >30 km away. It was voluntarily breached in October 2003 seven kilometres south of the city, to avoid a high risk of flooding by the river water. The operation was a success, lowering the level of the Senegal River at St. Louis by about 80 cm in 4 days. Thereafter the breach naturally extended several hundred metres wide in a few weeks (Deroin et al., 2012). As a result of this action, new hydraulic conditions have prevailed until today and have altered the hydrological regime of the river between the mouth and Diama (Bader and Cauchy, 2013): i) the river water levels are greatly reduced (65 cm downstream of

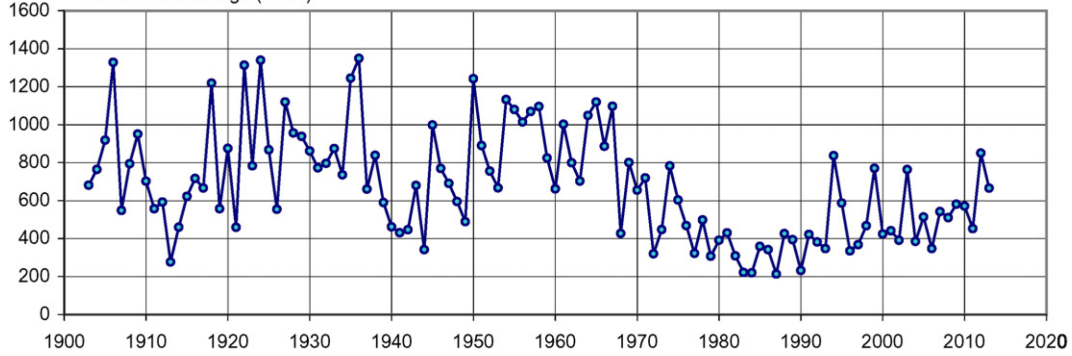


Fig. 3. Yearly (May to April) observed discharge of the Senegal River at Bakel since 1903.

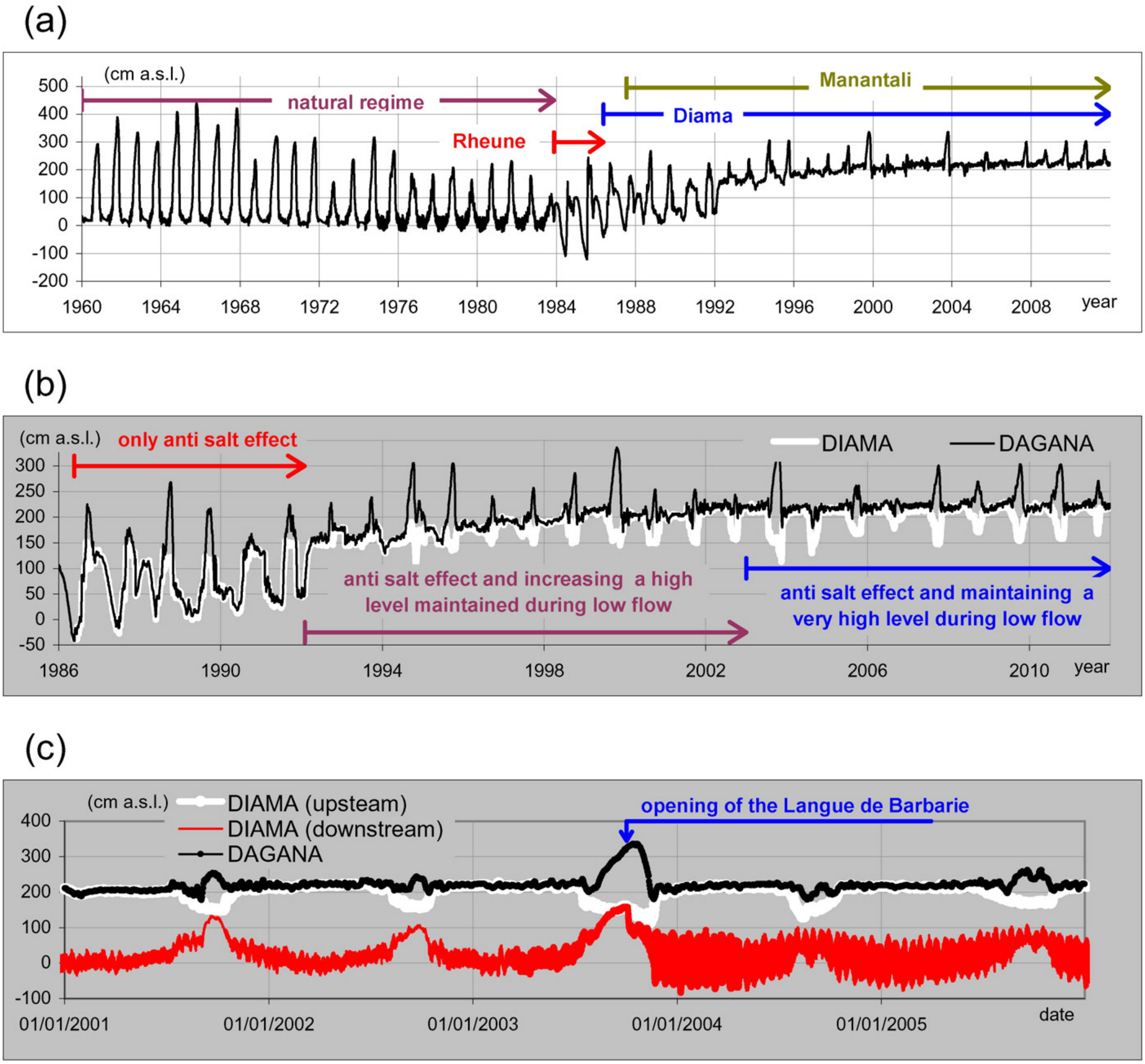


Fig. 4. Some key hydrographs illustrating the observed changes in the hydrological regime of the Senegal River. (a) Level of the Senegal River at Dagana from 1960 to 2011 in natural conditions till 1983 and under the influence of the different dams thereafter. (b) Level of the Senegal River at Dagana and Diama (upstream) from 1986 to 2011 with successive management modes of the Diama dam. (c) Water level of the Senegal River at Dagana and Diama (upstream and downstream), from 2001 to 2005, showing the effect of the opening of the mouth of the river 'langue de Barbarie' downstream of Diama.

Diama and 105 cm in St. Louis for a discharge of 2000 $m^3 s^{-1}$, and ii) the semi-diurnal tidal wave is greatly increased in the estuary and is now permanently perceptible, even for high river discharges (Fig. 4c).

4.2. Irrigation mapping

The time series of irrigation maps derived from the Landsat archives shows an important expansion of irrigation between 1973 and 2010 (Fig. 6). The remote sensing approach allowed for the detection of irrigated fields in culture or not at time of imagery. Fields that were not in culture, still maintained sharp boundaries with geometric forms and a homogenous internal texture, which allowed for their detection by visual interpretation.

The Landsat time series shows a linear trend giving an average expansion rate of ~19 $km^2 \cdot a^{-1}$ since 1973 (Fig. 7). In 1973, irrigated fields are scattered north of a line between Lake of Guiers and Lake Djoudj and only represent a surface area of ~73 km^2. In 1984, while continuing to expand in the northern part, irrigated fields also appeared in the south, mostly along the main road that links Richard Toll to Saint Louis (N2); total area of irrigated crops in 1984 was 139 km^2. In 2000, the expansion continues (total irrigated area of ~550 km^2) and is mostly localised north of the N2 road. In 2010, the total irrigated area reached ~770 km^2, mostly through a densification of irrigation north of the N2; interestingly one also note the apparition of numerous new irrigated fields, though limited in their size, along the Lake of Guiers.

A first estimation of the uncertainty of our irrigation maps is given by a comparison in Senegal with agricultural data collected independently by the SAED. In Senegal, the SAED independently evaluated the total area occupied by irrigated fields by compiling planning data and conducting field surveys (OMVS, 2011). Our total irrigated area in Senegal

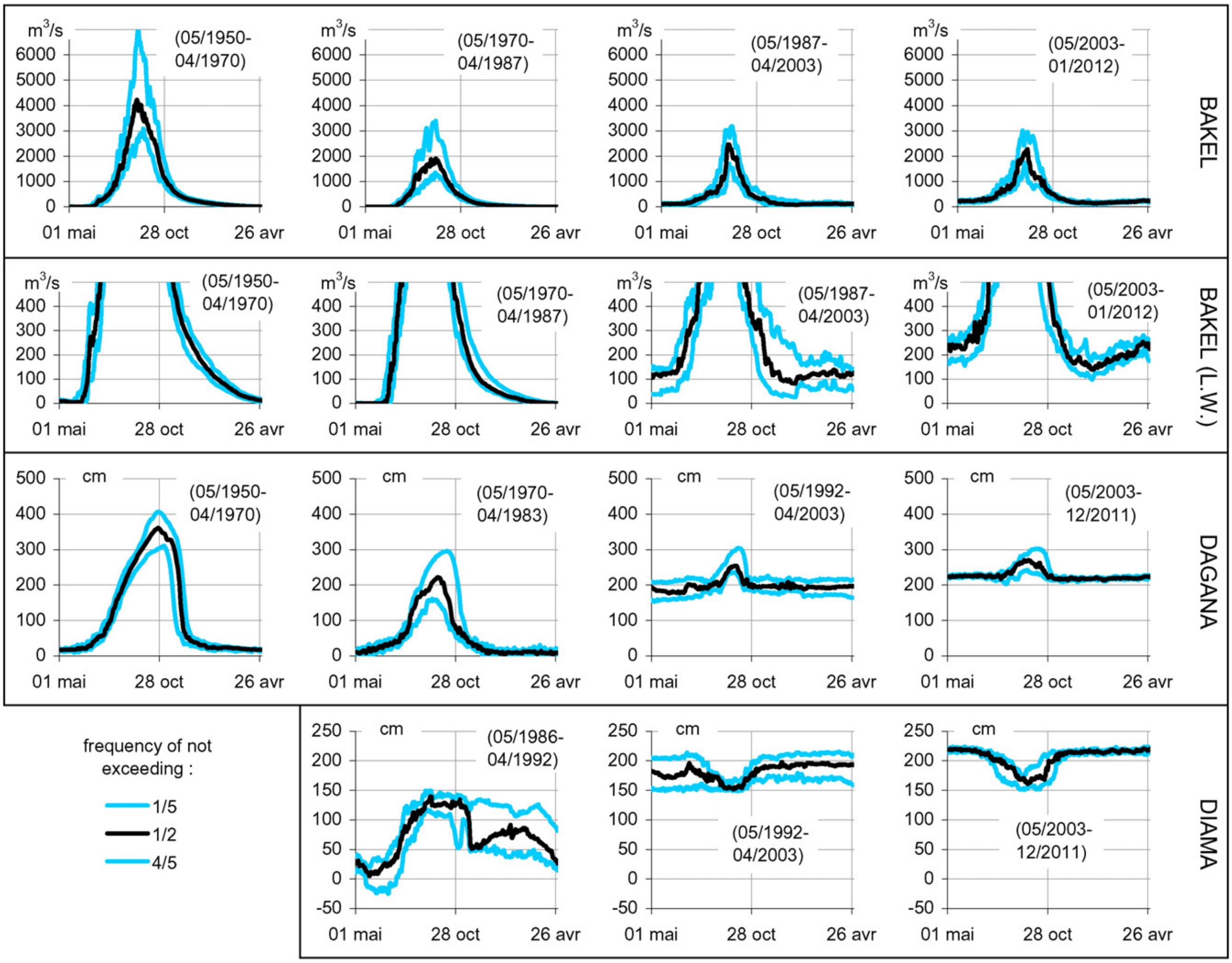


Fig. 5. Median and five-year values of the Senegal River discharge at Bakel and of the river level at Dagana and Diama during the year, for successive periods since 1950.

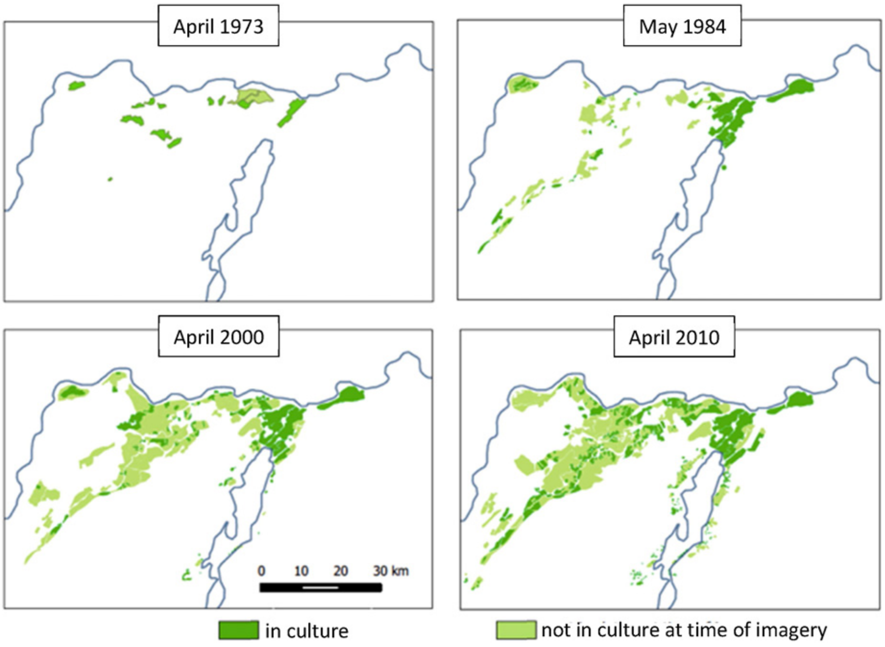


Fig. 6. Time series of maps showing the expansion of irrigated agriculture in the Senegal delta derived from Landsat data.

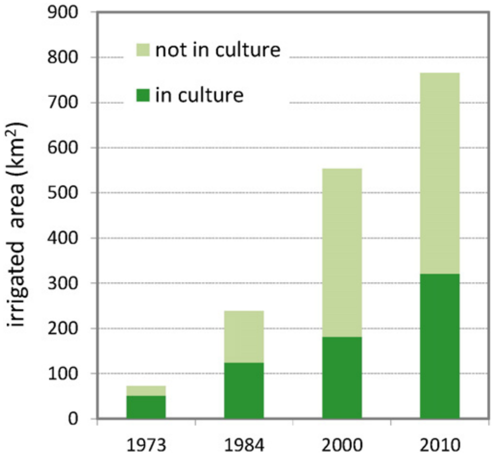


Fig. 7. Increases in the areas irrigated of the Senegal River delta from 1973 to 2010. Graph showing the expansion of irrigated agriculture in the Senegal delta derived from Landsat data.

is in good agreement though in average 28% higher than the SAED irrigated area (min +19% in 1984 and max +38% in 2000). The fact that our total irrigated area in Senegal is consistently higher than the SAED estimates since 1984 could be explained by the detection of additional privately operated irrigation fields (not always fully included in the SAED estimates), and abandoned irrigated crops. These new irrigation maps are also required for the analysis of changes in groundwater recharge and storage which follows; irrigation being a major driver of groundwater change, the distance between a piezometer and the nearest irrigated field and or irrigation channel are keys parameters in our analysis.

4.3. Changes in groundwater

The time series of groundwater hydraulic heads analysed in this study starts in 1985 and could therefore potentially be too recent to highlight impacts from the drought, which peaked in 1983 and 1984, on the physical groundwater system. In the lower Senegal delta not all groundwater bores monitored show declines in hydraulic heads. From the 200 bores analysed during the period 1985 to 1991, only 39% had declining linear trends in hydraulic heads, 57% showed positive linear trends in hydraulic heads, and 8% had insignificant inter-annual variation during this time period (Fig. 8). The positive and negative trends are observed in bores at all depths, and the greatest range in linear trend values are observed in the shallower bores (−0.50 to 0.44 $m \cdot a^{-1}$ for bores <10 m depth; Fig. 8). Therefore, regional trends due to the regional impact of drought are not evident in the hydraulic head data. Instead, the spatial variability of the inter-annual trends in hydraulic heads during 1985–1991 highlights a groundwater system responding to multiple and localised influences. The greater proportion of groundwater bores showing a positive linear trends in hydraulic heads may reflect the increase in average rainfall during this period (Fig. 2b), and/or as discussed below localised river regime and irrigation impacts.

As described previously, the lower Senegal delta continued to be subject to changes in the river regime and irrigation expansion after 1991, however there is a large gap for hydraulic head data across the region between 1992 and 1997. A comparison of the average hydraulic heads between 1985 and 1991 and 1999–2003 shows that hydraulic heads across the study area predominantly increased. 80% of the bores with monitoring data show an increase in hydraulic head (Fig. 9). Between the upper and lower Quaternary aquifers, the ranges in the magnitude of change in hydraulic head between 1985 and 1991 and 1999–2003 are similar. From the 20 monitoring points in the upper Quaternary aquifer the median groundwater hydraulic head change between the periods 1985–1991 to 1999–2003 is an increase by 0.47 m. The median change in groundwater hydraulic heads between 1987 and 1991 and 1999–2003 for 20 bores screen in the lower Quaternary aquifer is an increase of 0.50 m. There are no obvious spatial trends in the magnitude of change, i.e. with distance from the Senegal River or irrigated area. The rates and magnitude of changes in hydraulic heads across the delta are controlled by both the spatially heterogeneous hydraulic properties of the aquifers, and localised variations in changes in the river regime and irrigation practices that are also temporally variable on seasonal and inter-annual timeframes. 11 bores within the study area are presented in detail below to highlight some of the localised impacts of river regime changes and irrigation influencing groundwater hydraulic heads within the study area.

4.3.1. Impact of river changes on groundwater

The Senegal River and groundwater hydrograph data are analysed in detail at sites near Dagana and Diama (Fig. 10a). Increases in groundwater hydraulic heads from 1987 to 1991 for most bores observed at both

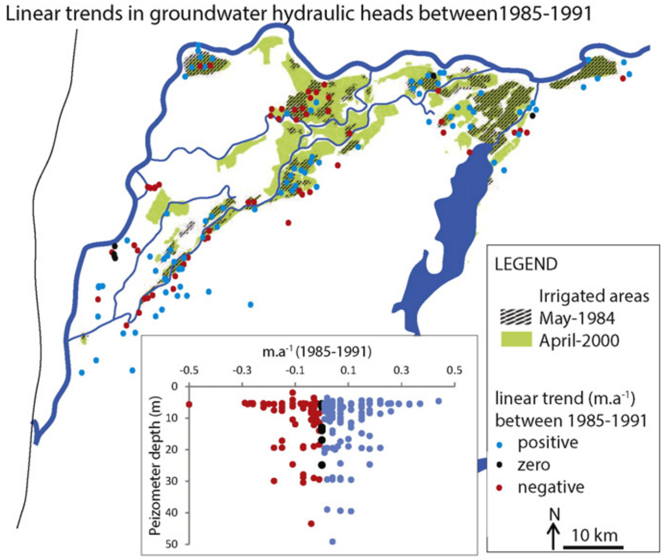


Fig. 8. Inter-annual trends in hydraulic heads between 1985 and 1991 relative to areas irrigated in 1984 and 2000. Also shown in the insert are the depth for bores with positive, zero and negative changes in the linear trends of hydraulic heads between 1985 and 1991.

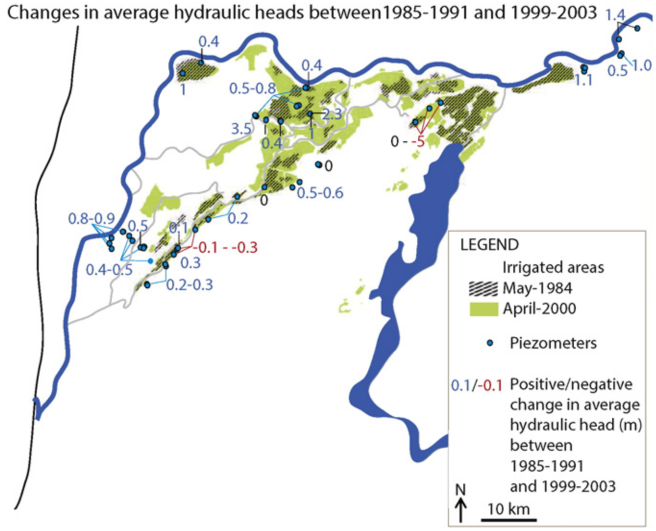


Fig. 9. Irrigated regions (up to 2010) and changes in groundwater hydraulic heads (m) between the time periods 1985–1991 to 1999–2003 (positive values indicate an increase in the average hydraulic head values, and negative values indicate a decrease in the average hydraulic head values between 1985 and 1991 and 1999–2003).

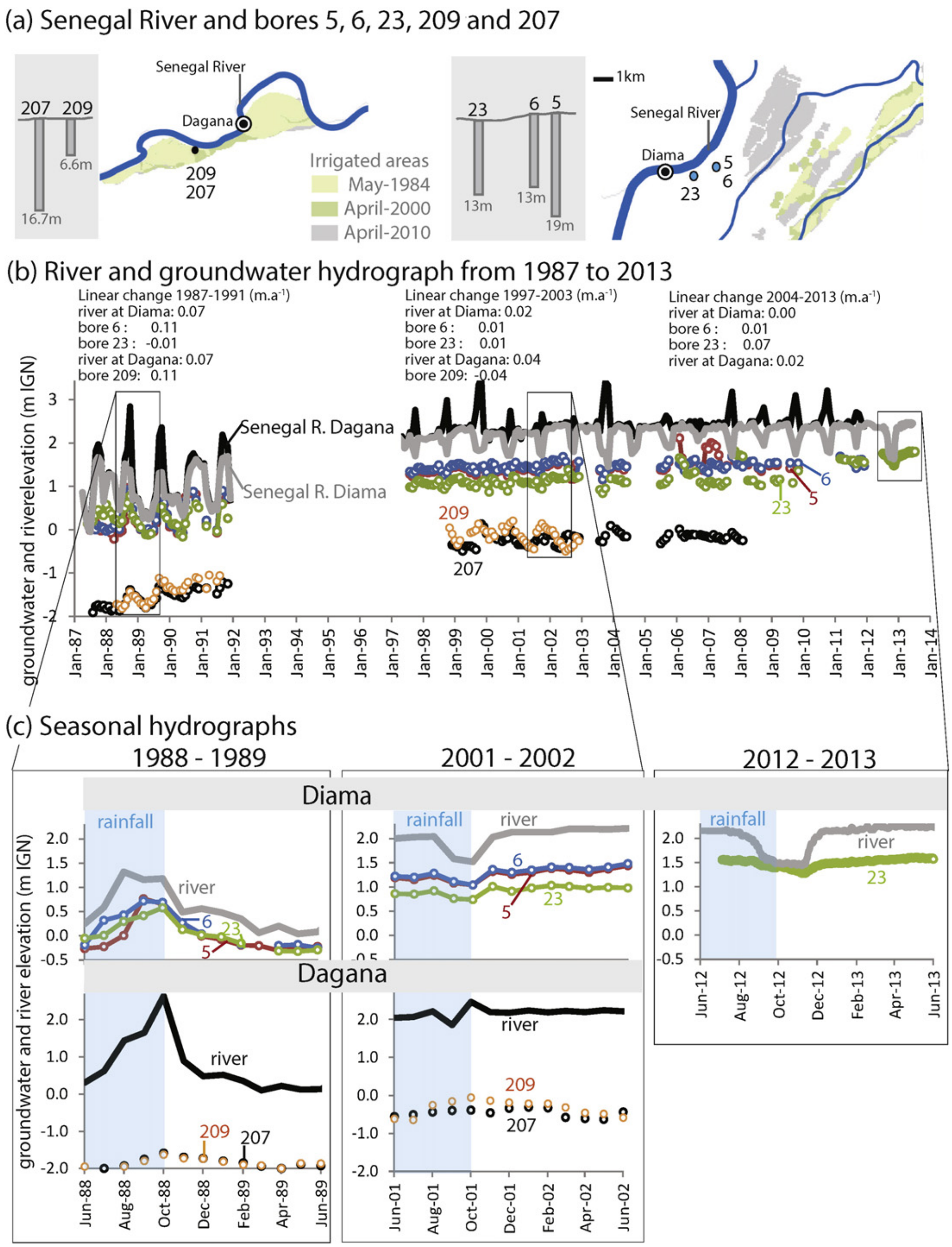


Fig. 10. (a) Locations of bores relative to rivers and irrigated areas. (b) Hydrographs of the Senegal River at Diama and Dagana presented with hydrographs of bores 5, 6 and 23 near Diama, and bores 209 and 207 near Dagana. (c) Seasonal hydrographs for groundwater bores and river at Diama and Dagana.

the Diama and Dagana sites are analogous with the rise in the river stage (Fig. 10b). The nested bores 5 and 6, 0.80 km from the river at Diama, show increases in groundwater hydraulic heads during 1987 to 1991 of 0.08–0.11 $m \cdot a^{-1}$. Hydraulic heads at bore 23 are slower to respond to river level rises, and the linear trend indicates a slight decline in hydraulic heads during this period (-0.01 $m \cdot a^{-1}$). Upstream, bores 207 and 209, 0.17 and 0.90 km respectively from the Senegal River near Dagana, show an increase in groundwater hydraulic heads during 1987–1991 at rates of 0.11–0.15 $m \cdot a^{-1}$.

During the period 1997 to 2003, the river levels continued to rise, although at a lower rate at both Diama and Dagana (linear changes are 0.02 and 0.04 $m \cdot a^{-1}$ respectively). This change corresponds to groundwater that also rises at lower rates. At Diama bores 6 and 23 both rise at rates of 0.01 $m \cdot a^{-1}$. After 1997, in addition to lower rates of inter-annual change, the seasonal river fluctuations for both the river and groundwater change. During the period 1987–1991, the seasonal fluctuations of the Senegal River and groundwater at the both Diama and Dagana correspond to seasonal rainfall (Fig. 10c). The ensuing changes in river regimes between Diama and Dagana, resulting in inverse seasonal fluctuations, are also observed in the groundwater data after 1997. The examples presented for 2001–2002 and 2012–2013 (Fig. 10c) show that, in comparison to 1988–1989 data, both river and groundwater levels at Diama decreases during the rainfall season. Whereas at Dagana, the shallow groundwater continues to peak during the rainfall season for all time periods, and corresponds to the river fluctuations at this site. Since 2004, inter-annual trends in river levels at Dagana and Diama remain relatively stable (linear changes of 0.02 and 0.00 $m \cdot a^{-1}$ respectively). Whereas the recent groundwater hydrograph data at bore 23, located 0.13 km from the Senegal River near Diama, indicates a continued increase in hydraulic heads at a linear rate of 0.07 $m \cdot a^{-1}$ (Fig. 10c).

4.3.2. Impact of irrigation on groundwater

The long-term inter-annual impacts of irrigation on groundwater are observed in increases in hydraulic heads for nested bores 71 and 72 (Fig. 11a), which resulted in an increase in average values of 0.4–0.5 m between 1987 and 1991 and 1997–2001. Between 2001 and 2008, groundwater data from bores 71 and 72 decreased, which may indicate affects from drainage (Fig. 11b). The long term trends in hydraulic head values from bores 71 and 72 are similar, resulting in little inter-annual variation in the vertical hydraulic gradient at this nested site (Fig. 11b). In the more recent data (2012 − 2013) the vertical hydraulic gradient has changed from downward to upward, however the gradient remains low (≤0.01). The impacts of irrigation on groundwater are also observed in the seasonal peaks of the groundwater hydrographs. Natural rainfall recharge groundwater peaks are expected during or soon after the rainy season, and where irrigation recharge is significant groundwater peaks are also observed during the dry season. Groundwater bores 71 and 72 have 56% of groundwater peaks occurring during the rainfall season (July to November) and 44% of peaks during the dry season (Fig. 11c).

At the site next to the Gorom Aval River (Fig. 12a), the shallow bores 67 and 68 show large inter-annual variations in hydraulic head values. Between 1987 and 1992 there are declines in the groundwater hydraulic heads at bores 67 and 68 by 0.27 and 0.08 $m \cdot a^{-1}$ respectively, whereas the deeper bore 66 remains relatively stable with an increase of 0.06 $m \cdot a^{-1}$ (Fig. 12b). The decline in groundwater hydraulic heads during 1987 and 1992 may be due to a decline in irrigated areas at close proximity and changes in the Gorom Aval River regime. The seasonal variations in hydraulic heads for each of these bores from 1989 to 1990 are in phase with seasonal rainfall (Fig. 12d). Between 1991 and 2000 the groundwater hydraulic head values increase may be due to changes in the Gorom Aval River regime. The greatest magnitudes of change are observed in the shallow bores 67 and 68 compared with the deeper bore (66); change in average hydraulic head values of 3.6

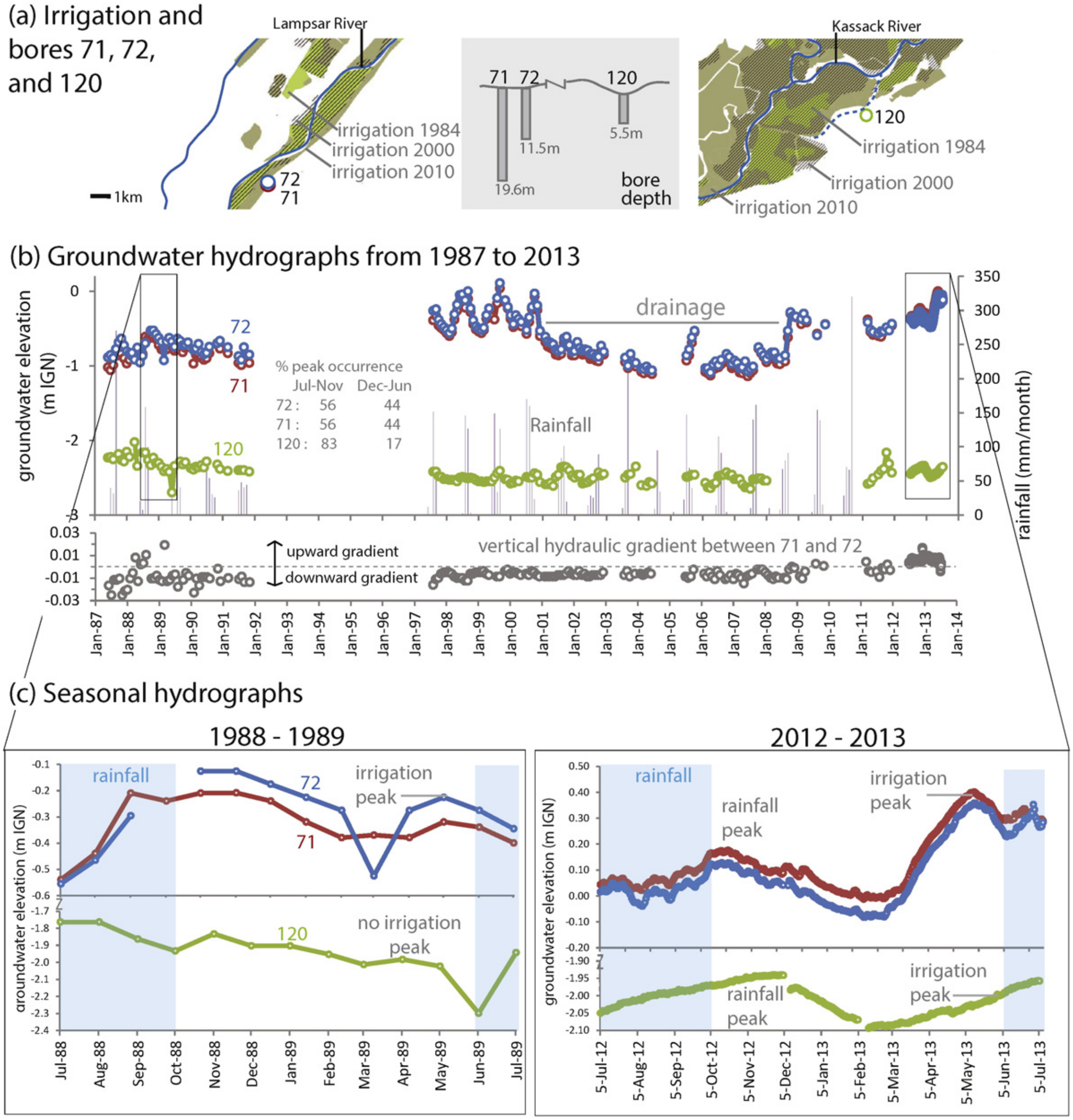


Fig. 11. (a) Locations of bores relative to rivers and irrigated areas. (b) Long term and seasonal hydrographs of bores located close to irrigation areas. (b) Hydrographs of the bores 72, 71 and 120, and vertical hydraulic gradients between 71 and 72. (c) Seasonal hydrographs for groundwater.

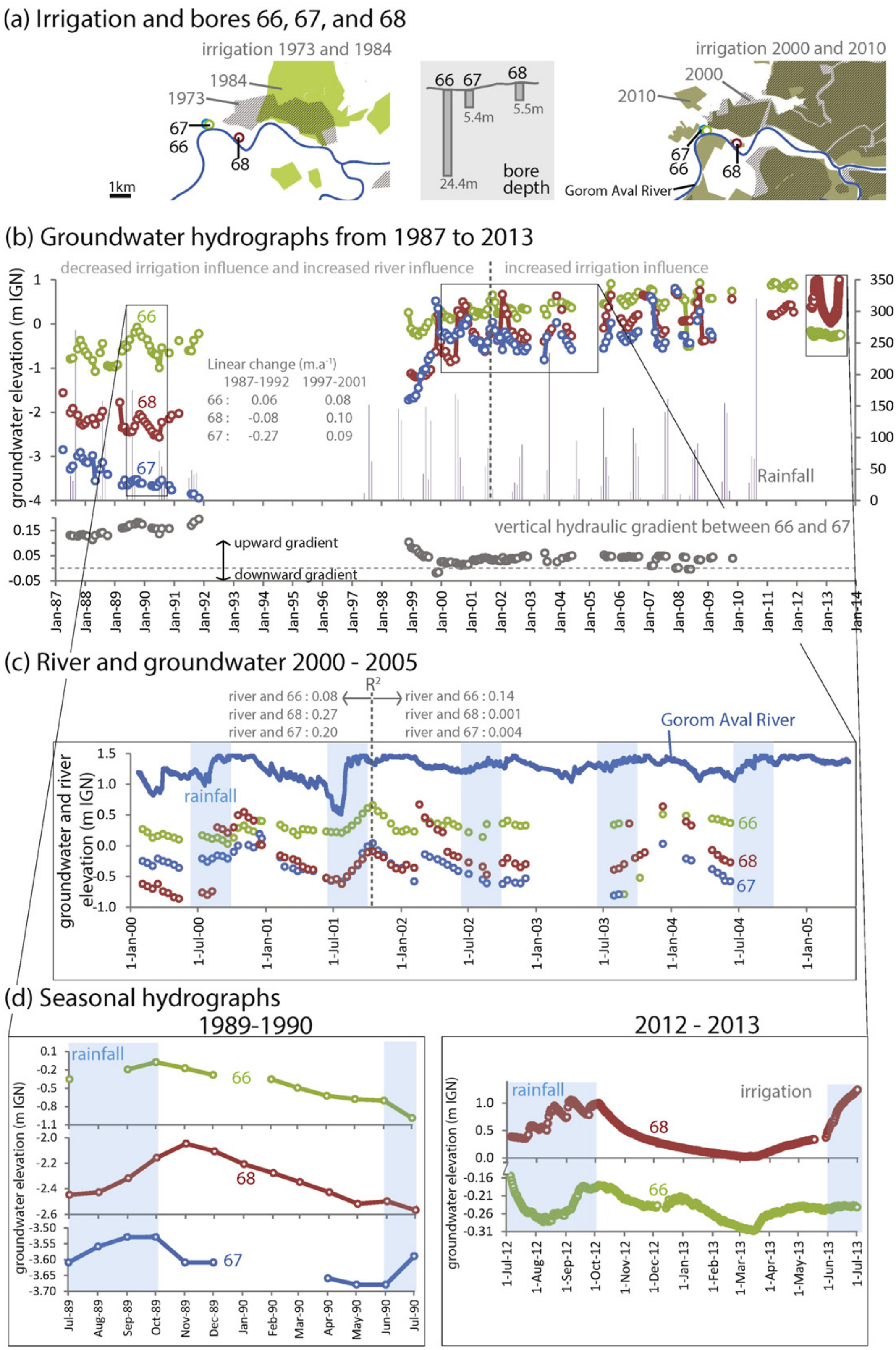


Fig. 12. (a) Locations of bores relative to the river and irrigated areas (b) Hydrographs of the bores 66, 68 and 67, and vertical hydraulic gradients between 66 and 67. (c) Seasonal hydrographs for groundwater.

and 1.8 m for bores 67 and 68 respectively. In comparison, after 2001, the shallow groundwater changes at bores 67 and 68 poorly correlate with Gorom Aval River level changes (Fig. 12c), and more seasonal peaks are observed outside of rainfall seasons. These inter-annual variations observed in the shallower and deeper groundwater at this site resulted in changes in the vertical hydraulic gradient. The relatively sharp rise in hydraulic heads in the shallow bores between 1991 and 2000 causes a decline from a high upward vertical hydraulic gradient during 1987–1991 (0.11–0.20) to lower values during 1998–2009 (0.10 to −0.02); resulting in gradient reversals during four monitoring time periods (Fig. 12b). By 2012, the hydraulic head data indicates that there are dry season increases in hydraulic head values in both the shallow bore (68) and deeper bore (66) (Fig. 12d).

5. Discussion

5.1. Hydrological responses to the hydro-agricultural development

Droughts, changes in river regimes and irrigation expansions are all phenomena that can significantly alter the physical and chemical groundwater system. In many semi-arid systems, the impacts from modified surface water and land cover/use have been more severe compared with competing impacts of climate variability (e.g. Leblanc et al., 2008). In comparison, other studies have highlighted the dominance of severe drought impacts on physical (e.g. Leblanc et al., 2012) and chemical (e.g. Tweed et al., 2011) hydrosystem changes. In this study, the drought between 1970 and 1984 precedes the period of groundwater monitoring data available (from 1985). In addition, the average rainfall from 1985 to 1991 increases relative to the three precedent years (1982–1984) and also corresponds to a period of significant change in the river regime and irrigation expansion. Therefore, under these conditions we are unable to distinguish the regional impacts of drought on groundwater system. The bores that do show negative trends between 1985 and 1991 may indicate a delayed impact from the drought, but may also reflect localised impacts from irrigation drainage or decreases in the smaller river regimes during 1985–1991 (e.g. Gorom Aval and Lampsar Rivers). An additional localised influence on declines in hydraulic heads away from irrigated areas (sand dune regions) may also include groundwater pumping for subsidence agriculture. In contrast, the bores that show positive trends between 1985 and 1991 indicate areas where groundwater hydraulic heads were responding to either (a) the increases in annual rainfall levels after the peak of the drought in 1984 (Fig. 2), (b) increases in the Senegal River recharge to the groundwater system with increases in river levels (Fig. 4), or (c) increased recharge from irrigation waters due to the expansion of irrigation areas throughout the region (Fig. 8).

Understanding the impacts of environmental change in such a region system requires a comprehensive history of the multiple stressors, which are heterogeneously distributed in time and space. The response of the groundwater system to stressors in this study area was observed at both the seasonal and inter-annual scale. At the Dagana and Diama sites the river water recharges the groundwater system and the series of changes in the Senegal River delta result in changes in the surrounding shallow groundwater system. Firstly, from 1987 to 1991 the inter-annual river levels increased and a corresponding increase in groundwater hydraulic heads is observed. Secondly, during 1997–2003 a low rate of river level rise also results in groundwater that rises at lower rates. During this period the seasonal fluctuations at Dagana and Diama were inversely controlled resulting in inverse seasonal fluctuations of groundwater between these two sites (Fig. 10c). These seasonal variations at both locations highlight the strong hydraulic connection between the river and shallow groundwater.

In irrigated areas, groundwater hydraulic heads are impacted by (a) infiltration of irrigation excess water in the paddock, (b) leakage/seepage along the network of irrigation channels (which includes the natural drainage network in the study area), and (c) drainage of irrigation water away from the site. The spatial and temporal variability of irrigation influences on groundwater are significant and difficult to represent at the regional scale, and results highlight a rapid evolution of groundwater changes to localised pressures. For example, highly localised effects of irrigation are observed at bore 120 where, in comparison with bores 71 and 72, shows relatively stable inter-annual groundwater hydraulic head values (linear change 1997–2008 is $-0.003\ \mathrm{m \cdot a^{-1}}$; Fig. 11b). Bore 120 is located close to a surface depression where waste water from irrigation is deposited. The relatively high quantity of surficial clay results in evaporation of this waste water. However, the presence of an irrigation peak in the recent hydraulic head data of 2012–2013 (Fig. 11c) suggests that either infiltration of irrigation water from up gradient areas, or irrigation waste water has begun to impact hydraulic heads at bore 120. In addition, in some areas the impacts of irrigation expansion are beginning to over-ride impacts from local river regime changes. At the location of bores 66–68 the increases in groundwater hydraulic head values due to changes in the Gorom Aval River regime (1992–2000) are followed by a greater influence from irrigation Fig. 12c).

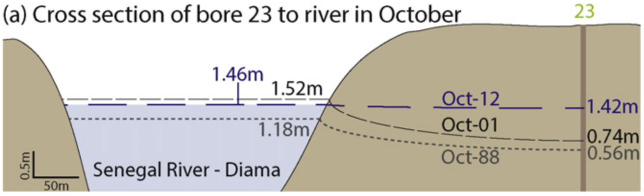
The hydrogeological response to changes in such a heavily modified system can remain in a transient state ranging from the event-scale to thousands of years (e.g. Rousseau-Gueutin et al., 2013), depending on intrinsic factors such as the hydraulic connectivity between the different water reservoirs and the magnitude of the forcing. Recent groundwater data highlights a continued change in hydraulic head after the river levels remain stable. The increase in groundwater hydraulic heads relative to the stable river levels at bore 23 is likely to reflect the ongoing transient state of groundwater in response to the historical river changes, where the groundwater is yet to reach its new steady state. This time lag in the physical groundwater system compared with surface water changes the hydraulic gradients. Seasonally, when river levels are low (e.g. October-2012), the relative increase in hydraulic heads at bore 23 results in hydraulic head values that are closer to river levels than previously recorded; resulting in historically low hydraulic gradients between the river and groundwater (Fig. 13a). In comparison, the seasonally high river levels (e.g. April-2013) increase hydraulic gradients between the river and groundwater (Fig. 13b).

The onset of environmental change impacts on the chemical system, which is controlled by en mass flow rates, is often delayed compared with the more immediate pressure changes exerted on the physical system (e.g. Glover and Johnson, 1974). In this study, only physical groundwater changes have been analysed. Future work in the Senegal delta requires a determination the implications of these environmental changes for water resources quality, as discussed below this is particularly important in terms of managing salinization with the appearance of degraded soil along irrigated perimeters.

5.2. Socio-economic drivers and implications

The objective of the hydro-agricultural change in River Senegal Delta was to promote socio-economic development in the region through the planned management of available water resources. The dams' main roles were to stop the loss of fresh water to the sea and the intrusion of sea water within the delta, as well as providing significant reservoirs for irrigation. For example the Diama dam is in the top 15% (based on

(a) Cross section of bore 23 to river in October



(b) Cross section of bore 23 to river in April

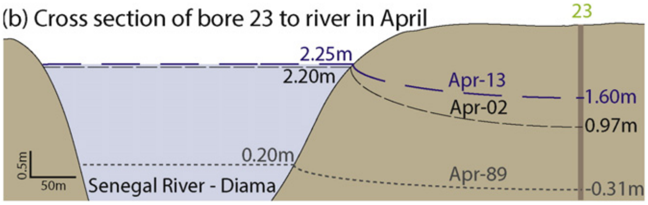


Fig. 13. A schematic showing the relative changes in groundwater and Senegal River water elevations during (a) October 1988, 2001 and 2012, and (b) April 1989, 2002 and 2013.

reservoir capacity) of the dams used for irrigation in Africa (594 total in 2007; AQUASTAT Programme, 2007). At an elevation of 2.5 m IGN, the volume of the reservoir is 585 million m^3.

Since the installation of the dams in the Senegal Delta, there have been significant socio-economic benefits. The Diama dam participates in securing drinking water supply for many rural and urban communities as well for large cities (e.g. St. Louis and Dakar). It also contributes to the domestic and pastoral water requirements of rural populations. Significant socio-economic benefits have also been driven by the agricultural expansion (detailed in this study) and intensification. This agricultural development was aimed to reinforce food security in the region, but also to improve economic prospects by the selling of a large part of the food produced in the Delta. For example, the commercialisation of vegetables and rice produced is now an important component of the agricultural market. The availability of irrigation water all year round has increased production by allowing three crop rotations per year (Fig. 14a).

The dams have substantially improved the local economy with the development of rice over large irrigated areas developed by the government (SAED). In addition, the dam water supports agro-industrial practices; such as the irrigation of sugarcane for the Senegalese Sugar Company (~13,500 ha with yields of up to 146 T/ha), and the irrigation of tomatoes for the Society of Food canning of Senegal. These companies contribute to the local socio-economic development via employment. The surface area of irrigated crops managed by the SAED has remained stable since early this century, whereas a growth is observed in the crops managed by such agro-industries and individual farmers since 2007 (Fig. 14b).

There have however been negative socio-economic effects due to the hydrological changes since the construction of the Diama dam. These are associated with impacts on ecosystems, agricultural practices, salinization, and human health risks. Before the construction of dams and dikes, the delta was alternately flooded by marine salt water and fresh river flood waters. This alternation favoured the development of mangroves in the estuarine area, and conditions were also favourable for fish reproduction and bird nesting (Mietton et al., 1998). After the installation of the dam, the changes in salinity, disappearance of floods and prolonged flooding upstream of the dam, have significantly depleted the flora of the alluvial plain to an extent that some species have disappeared. The mangrove areas were greatly reduced, and the areas occupied by *Sporobolus robustus*, a plant exploited by local artisans, were also decreased (Duvail, 2001). The disappearance of the brackish estuarine also significantly limited the anadromous migration of euryhaline species, and removed a highly productive area and spawning ground (Diouf et al., 1993). There was a significant drop in the number of species and the fishery potential.

Some agricultural activities have also suffered that were, before the dam, sustained by the annual flooding of the Senegal River. Flood recession agriculture was practiced in the lowlands of the alluvial plain, and was complemented by rain-fed agriculture on sandy clay levees. Changes in the types of agricultural practices have had secondary negative environmental effects. For example, the expansion of rice crops and therefore clear felling the land has resulted in high wind erosion rates. In addition, irrigation has induced secondary salinity impacts. As presented in this study the irrigation expansion has led to increasingly shallow water tables in some areas. The salinity concentrations of shallow groundwater are naturally high; with electrical conductivity values oscillating between 2 and 68 mS/cm (Ngom, 2013), due to the sea water intrusion during the Inchiriennes and Nouakchottiennes transgressions (Mietton et al., 1998). There are areas where the groundwater salinity has declined due to infiltration of the Senegal River water or irrigation canal water; however the groundwater remains brackish. The rising of shallow water tables have exacerbated the salinity issue through increased effects of evapotranspiration on soil water and groundwater salinity levels (e.g. Diaw et al., 2016), and the inevitable development of salt crusts are already observed in some of the agricultural plots (Diaw et al., 2011; Ndiaye et al., 2008). In the future, issues associated with salinization are one of the main obstacles for the continued development of irrigated agriculture in the Senegal River delta.

Many water-related diseases are endemic in the delta; including malaria, diarrhoea and especially intestinal schistosomiasis. In the case of the latter, a survey by the IUCN (World Conservation Union) found a prevalence rate of 60% at Richard-Toll in 1990. Changing ecologic conditions following the impoundment of the dams has allowed the installation of intestinal schistosomiasis by providing the conditions conducive to its development (Mietton et al., 1998). Future increases in irrigated agriculture throughout the delta will compound such human health risk problems by providing conditions that promote the presence of pathogenic viruses and bacteria (e.g. Dobigny et al., 2015).

Fifteen years after the commissioning of these dams in the Senegal Delta, the conclusions were made that the negative effects of such major developments in terms of health (Handschumacher et al., 1992) and social impacts were underestimated, and initial agricultural objectives were far from being achieved. Such results can only be improved via a cooperative effort at the government policy, resource management and farming levels. It is theoretically possible to achieve both the dams' production objectives and provide the needs for water users and ecosystems downstream. For example, artificial flooding can restore or support ecological processes and natural resources. In the Senegal River Delta, the restoration of part of the floodplain and the creation of an artificial estuary helped mitigate some of the negative impacts of the dam (Hamerlynck and Duvail, 2003; Duvail and Hamerlynck, 2006). A programme was also initiated between Senegal and Mauritania for the revegetation of wetlands of global importance (Lake Djoudj and Diawling). Future socio-economic challenges in this study area are evidently closely linked to an improved management of water and land resources; to both minimize negative environmental impacts and to allow more users to benefit from the socio-economic development in the Delta.

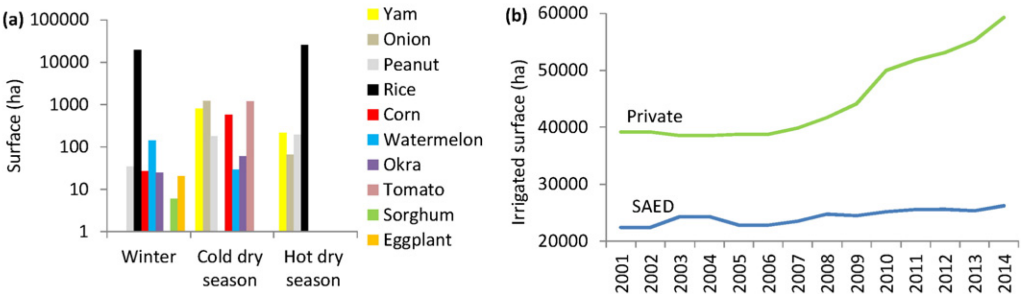


Fig. 14. (a) Seasonal changes in irrigated crops for the years 2011–2012, and (b) Inter-annual changes in surface area of irrigated crops managed by the government (SAED) and private owners (agro-industries and individual farmers).
(Source: Data from SAED, accessed 2016)

6. Conclusion

An integrated analysis of hydrological changes in the lower Senegal delta Basin since the second half of the 20th Century shows significant impacts from the multiple environmental stresses affecting the system. Relatively low rainfall conditions during the 1970s and 1980s drought, was soon followed by the construction of dams along the Senegal River since 1983, and Landsat imagery between 1973 and 2010 identified a rapid irrigation expansion across the Senegal delta. These multiple stressors simultaneously impacting the hydrological system are expressed in seasonal and inter-annual scale shifts in the (i) river hydrological regime, (ii) groundwater elevations in the alluvial aquifer, and (iii) interactions between these resources. This study has found that the compounding environmental change impacts on the hydrological processes are spatially heterogeneous, and highlight a hydrological system in various stages of transient response to river regime modifications and irrigation expansions.

Acknowledgements

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