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Contribution of the Catchment Area to the Hydrology of a Saharan Wetland, the Imlili Sebkha (Dakhla Region, Morocco) – Use of GIS and Satellite Data

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ABSTRACT

This study concerns a Saharan wetland of southern Morocco, the Imlili Sebkha, located south of the Dakhla city. Considered among the rare permanent saharan sebkhas, it is recharged by episodic surface water supplies from an endorheic hydrographic network and by the unconfined aquifer, which emerges permanently through tens of shallow natural cavities. Using satellite data (DEM and rainfall), supplemented by field observations, an analysis of surface water supplies is carried out in this article. Due to the low slopes and the almost generalized silting of the catchment area, most of the rainwater is evaporated or recovered by the phreatic aquifer. Only a small proportion would arrive to the wetland, which would come from the surroundings of the sebkha. Nevertheless, these low inputs can flood a large part of the wetland, including the groundwater cavities, especially during the biggest autumn storms.

Keywords: GIS, hydrology, satellite data, Saharan Sebkha, Morocco.

INTRODUCTION

The Imlili wetland is located in southern Morocco, about 60 km as the crow flies south of the coastal town of Dakhla, between northern latitudes 23.202439° and 23.293465° and western longitudes -15.891996° and -15.946094°. It corresponds to the outlet of an endoreic hydrographic network, composed of four wadis, one of which is about 280 km long, and several cha'bas. Because of its vast, almost flat bottom, made up of salt-enriched sand, it is described as a sebkha, but its genesis is linked to the recent (Holocene) installation of a large sandy dam on the lower course of the above-mentioned hydrographic network. This genesis earned it the character of a natural dam guelta, more particularly a permanent dune guelta, of which the Imlili wetland is the only known representative (Dakki et al. 2020). The presence in this wetland of a cichlid fish, the Guinea tilapia *Coptodon guineensis*, a sign of water permanence, has drawn the attention of many researchers to this environment (Qninba et al. 2009; Agnèse et al. 2018; Himmi et al. 2020).

The present work, which is in line with these studies, aims to elucidate a fundamental aspect of the hydrological functioning of this wetland, which lies in the analysis of the water inputs of its hydrographic network. These inputs originate from pluvial and phreatic sources and their balance is supposed to be strongly influenced by the low pluviometry, the rock fissuring and the soil silting. This analysis is based mainly on the compilation of satellite data, supplemented by field surveys, carried out on 27-28 November 2012, which covered both the wetland and its surroundings.

GEOGRAPHICAL CONTEXT OF THE WETLAND AND IT'S CATCHMENT AREA

Physiographic context

The Imlili wetland is located at about 36–45 m above ocean level. It occupies a vast elongated depression, running NNE-SSW, about 10 km long and 2.6 km wide, covering a surface area of 17.3 km² (Fig. 1). The depression's shores (or Bank) are mostly low cliffs, whose slope is locally softened by aeolian dune deposits. To the south of the depression, these deposits form a large field of dunes regularly fed by sand from northern winds; this field has formed a natural dam, which occupies an ancient valley (Dakki et al. 2020). At the level of the Imlili wetland, this valley has been filled in by sandy-silt deposits, whose almost flat surface gives it the appearance of a sebkha, but this bottom still has a slight inclination from north to south.

The current configuration of the wetland gives its hydrographic network an endoreic character; it is practically derived from the Cretaceous and Cenozoic reliefs to the east and north-east of the sebkha. At its northern end, the wetland receives two large tributaries, Wad Al Hawli and Wad Al Faj; at its southern limit, it also receives another tributary, Wad La'rad, which is no less important than the two previous ones. Other cha'bas come to enrich this network on the reliefs that dominate the sebkha to the east.

The sebkha's bottom is dotted with more than 160 shallow, saline groundwater discharges of various shapes, located in its north-western area (Himmi et al. 2020). Although subject to filling, these discharges never dry up together, allowing this wetland to be described as permanent, a character that is exclusive to it as a sebkha (Dakki et al. 2020). On its north-western shore (or bank) and in its southern part, this sebkha displays wet flow channels, intermittently filled with water, sometimes bordered by emerging hydrophytes.

Geological context

The Dakhla-Lagwira coastal area lies at the southern end of the Tarfaya-Laâyoune-Dakhla sedimentary basin, formed since the Cretaceous period. Within this basin, the Imlili sebkha lies in a long depression-oriented SSW-NNE, separated

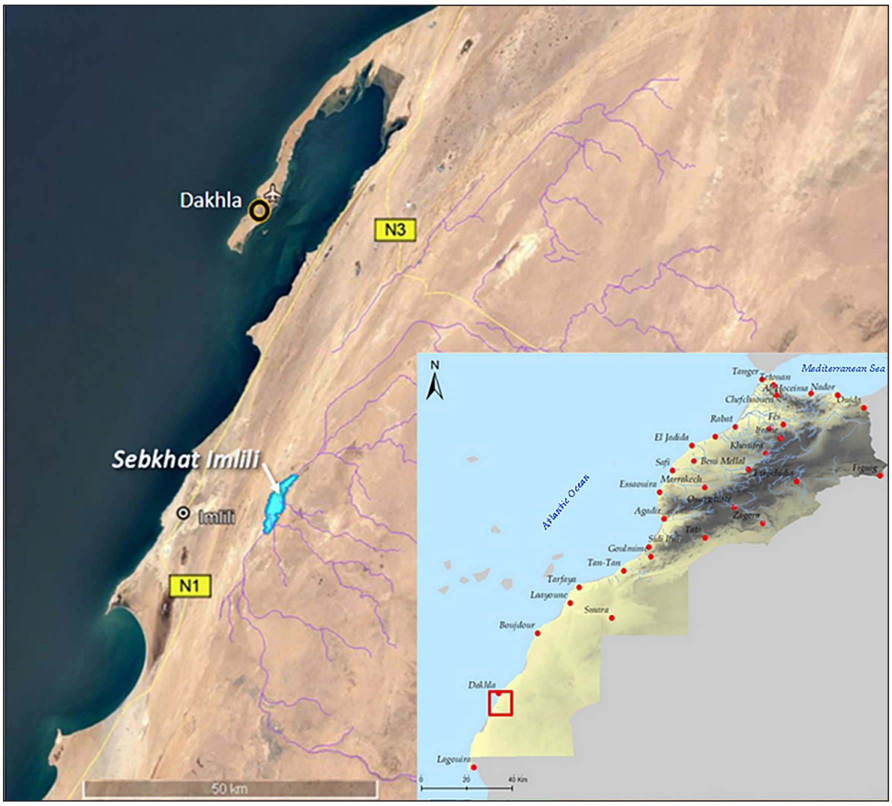


Fig. 1. Location of the Imlili wetland

from the Atlantic coast by a plateau some 15 km wide. This wetland is surrounded by outcrops of Neogene age (Rjimati et al. 2011): conglomerates, lumachelles, quartzites, calcareous, marly or quartzite sandstones; these terrains are often covered by aeolian sandbanks, sometimes in the form of massive fields that fill in depressions and wadi beds or are backed by embankments. To the north of the sebkha, the relief takes on a ruiniform appearance, in elongated ridges or in the form of flat-topped hillocks (garas), strongly shaped by wind activity. At present, this activity works against the undulating effect of the wadis, by attenuating the slope of the banks and levelling their beds with predominantly sandy deposits, which often gives them the appearance of wide dead valleys. The presence of conglomerate and/or sandy alluvial terraces in most of the valleys and depressions and the large extension of these valleys attest to a well rainfed Holocene past, but the ancient flow channels are often erased by wind erosion.

The Neogene formations are permeable and ensure a good circulation of water infiltrated into the subsoil, to constitute an important reserve of groundwater (Hilali et al. 2020). These formations are underlain by layers of Cretaceous-Paleogene age, dominated by marl, clay or sandy-clay (formations that are generally not very permeable to impermeable, sometimes quartzite, with intrusions of evaporites. The layout of the Meso-Cenozoic lands reflects the brittle tectonics that mark the Tarfaya-Laâyoune-Dakhla basin; in this respect, we will emphasise a long NNE-SSW fault, which runs along the depression whose extension towards the South passes through the wetland (Rjimati et al. 2011).

Climatic context

The catchment area of the Imlili wetland covers an arid zone, where the contribution of the oceanic air to the humidification and cooling of the atmosphere, although still felt at the level of the vegetation cover, is relatively attenuated. On the coast (Dakhla station), the average annual rainfall for the period 1935–2005 was 29 mm (Sebbar et al. 2013); prior to 1965, it was around 37.6 mm (Quezel, 1965); but during the last four decades, which have been marked by droughts, rainfall has been much lower, with annual averages of almost zero in some years (Hilali et al. 2020), with the wettest years barely exceeding 100 mm. Rainfall often comes in short showers; it is mainly autumnal (corresponding to the occasional upwelling of the Gulf of Guinea lows, the Anti-Alizes), with a few winter thunderstorms (corresponding to the remnants of the North Atlantic lows), and is practically negligible during the rest of the year.

Temperatures are generally between 10 and 35°C on the coast, but they can exceed 40°C on the reliefs far from the coast, especially with SE winds, which increase evaporation. In this region, as in the entire Saharan coastline, wind activity is very frequent, with a predominance of northerly winds, often strong (8–40 m/s); they act against the rise in temperature, but they are above all recognised as the main agent of erosion and sand transport, a function well illustrated by the predominance of dune deposits.

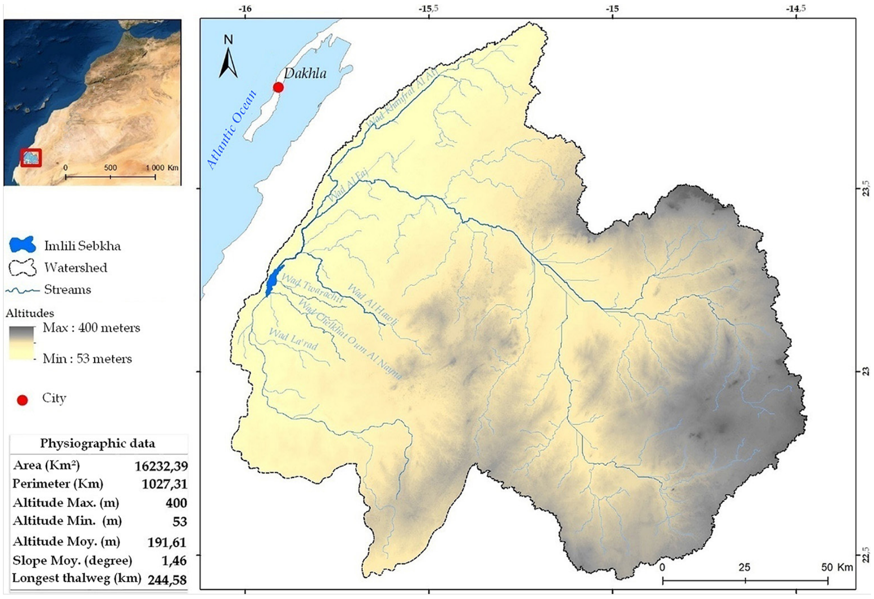
MATERIAL AND METHODS

This note aims above all at estimating the water inputs of rainfall origin, via a simulation of the extreme flows at wetland level and of the average annual inputs of surface water. Thanks to daily rainfall data provided by satellites, these inputs are estimated for weeks of the year.

Preparation of the orohydrographic data and geoprocessing

The flow estimations required a preliminary delimitation of the Imlili catchment area, which was carried out thanks to the Digital Terrain Model (DTM) of 30 m resolution (GDEM Aster V2 model); which also allowed the wetland delimitation and the reconstitution of its hydrographic network (Fig. 2). These elements were obtained using the “Hydrology” geoprocessing tools in ArcGIS Pro.

It is important to note that in order to simulate the entire river system that converges on the wetland, several “low points” were selected around its perimeter and their basins were generated. By adopting this approach, it was possible to include in the sebkha basin a large river system, Wad Al Faj, which flows into the sebkha at its northern end, probably after joining Wad Al Hawli. The lower course of this tributary follows a wide depression with a slightly undulating bottom, interrupted by small ridges and hamadas running in a N–S direction. This vast depression, which is the extension of the Imlili sebkha to the north, does



Physiographic data	
Area (Km²)	16232,39
Perimeter (Km)	1027,31
Altitude Max. (m)	400
Altitude Min. (m)	53
Altitude Moy. (m)	191,61
Slope Moy. (degree)	1,46
Longest thalweg (km)	244,58

Fig. 2. Orohydrography of the Imlili wetland watershed

not have clear flow channels, like many dead valleys in the Boujdour-Dakhla region. The course of this tributary, established with the help of the DTM, has been clarified with the help of Google Earth; it shows that the flow can be intercepted by sandy obstacles of 2-4 metres in height, which would only be broken by exceptional floods. This delimitation of the catchment area, close to the topographic reality of the site, maximises the estimation of inputs to the wetland, which would be superficial (following heavy rainfall), but also underground, as the flow of surface water is often intercepted by dune deposits which favour its infiltration into the subsoil.

Due to the low resolution of the DTM, the modelling was completed using the 1:100,000 topographic map, which allowed the delineation of the low gradient sub-basins, located to the south and north of the wetland. Most of the watercourses have the appearance of dead valleys with poorly individualised edges covered with sand, which sometimes piles up in the form of banks that can obstruct the flow, or even create graras (shallow depressions with fine sediments, where rainwater enables the development of shrub and herbaceous vegetation, sometimes dense) or small sebkhas.

Estimated volumes of water received by the wetland

The average annual surface water inputs that the catchment provides to the wetland are assessed in terms of the catchment water balance. This has been estimated by taking the lowest point of the wetland, which is near its southern end, as the reference point (outlet). The calculation is based on the following Equation 1:

$$P + S = R + E + I \tag{1}$$

where: P – precipitation in mm, S – accumulation from the previous rainy period in mm, R – height of runoff in mm, E – evaporation in mm; I – infiltration in mm.

The volume of water reaching the wetland during a rainfall event is proportional to the catchment area and the average runoff height (R), the latter being dependent on the runoff coefficient (RC). This volume is calculated as follows (2):

$$V = A \times R = A \times RC \times P \tag{2}$$

where: V – volume of water runoff in m^3, A – catchment area in m^2, R – average height of runoff in mm, P – precipitation in mm, RC – runoff coefficient in %.

Precipitation is obtained as simulated data using satellite techniques (Chirps V2 images in 5 × 5 km² pixels), with a daily frequency for a period of 35 years (1981 to 2015). They were extracted within the catchment boundary polygon.

The runoff coefficient (RC) is calculated based on the infiltration rate in the soil, the slope of the land and the land use. In Morocco, this coefficient has been estimated experimentally for the different prevailing soil types

Table 1. Recommended values for the runoff coefficient based on soil type, slope and land occupation rate

Nature of the soil	Sandy			Clay		
Slope	Flat	Undulating	Steep	Flat	Undulating	Steep
Land use (%)	2	2–7	> 7	2	2–7	> 7
Runoff coefficient	0.10	0.15	0.20	0.17	0.22	0.35

(Table 1). In the Imlili catchment area, the land use type that can be generalised to the whole catchment area corresponds to "steppe vegetation" (Fig. 3). This generalisation is illustrated by a map established using a supervised classification of LandSat 8 images from the OLI (Operational Land Imager) sensor using a remote sensing softeware, which images were acquired for the wettest period of the year, as defined by the rainfall analysis.

The runoff coefficient is 10% in the lower parts, west of the catchment area (about 60% of its surface area), and 15% further east, in the higher part (Fig. 4). Only on a few ridges, of insignificant surface, this coefficient reaches values of 20%. The permeability of the Quaternary soils, added to the predominance of sandy soils in the catchment area, works against the prolonged accumulation of surface water reserves, especially as the rainfall regime is characterised by short showers separated by long dry periods. This makes it possible to assume that the parameter S (accumulation of the previous rainy period) has a near-zero value. Similarly, at the time of the rains, the atmosphere is humid, and evaporation is assumed to be negligible ($E \approx 0$).

Simulation of extreme flows

The known calculation methods use empirical formulas that consider two characteristics of the catchment area, the size, expressed here by the surface area, and the topographic gradient, expressed by the average slope of the longest river. These parameters are established in ArcGIS Pro, using the degital elevation model Aster GDEM V2 and the 1:100,000 topographic map.

The approach used in this study combines the Hazan-Lazarevic formula (Hazan et al. 1969) and the Fuller 1 formula (Fuller, 1914) for transposing flows. These authors would have used data from about fifteen hydrological stations located in different basins, supposed to cover the Moroccan territory. The Hazan-Lazareviç formula calculates the millennial flow generated downstream of a catchment as a function of its surface area and two parameters ($k1$ and $k2$) that are specific to it:

$$Q_{t(1000)} = k1 \cdot S \cdot k2 \tag{3}$$

where: $Q_{t(1000)}$ – peak flow (in m³/s), recurrence period 1000 years, S – watershed area (in km²). The values of the parameters $k1$ and $k2$ depend on the geographical location of the basin, which determines its average annual rainfall. For the Saharan coastal area, $k1 = 9.38$ and $k2 = 0.74$.

The conversion of millennial flood flows to recurrence flows of a shorter period (T) is calculated as follows Fuller formula (4):

$$Q_t(T) = \frac{Q_{(1000)} \times (1 + a \times \log(T))}{1 + a \times \log(1000)} \tag{4}$$

where: $Q_t(T)$ – peak recurrence flow rate T (in m³/s), a – regional coefficient that varies with the location of the concerned basin (for the Saharan area, the Water Department recommends).

RESULT AND DISCUSSION

Hydrological summary – surface water input to the wetland

Given the scarcity of rainfall in the Saharan zone, the estimation of water inflow to the wetland was carried out during the wettest periods of the year; in order to look for opportunities of rainfall concentration in time, the unit interval of calculation was reduced to one week. The graph below (Fig. 5) illustrates the variations of the average weekly rainfall, calculated on a daily data set obtained for the period 1981–2015.

Rainfall is very discontinuous (in the form of showers) and the wettest period covers weeks 36–39, corresponding almost to the month of September, with significant showers at the end of August and during the winter, with peak rainfall occurring in the first and last weeks of September, with 3.97 mm and 3.15

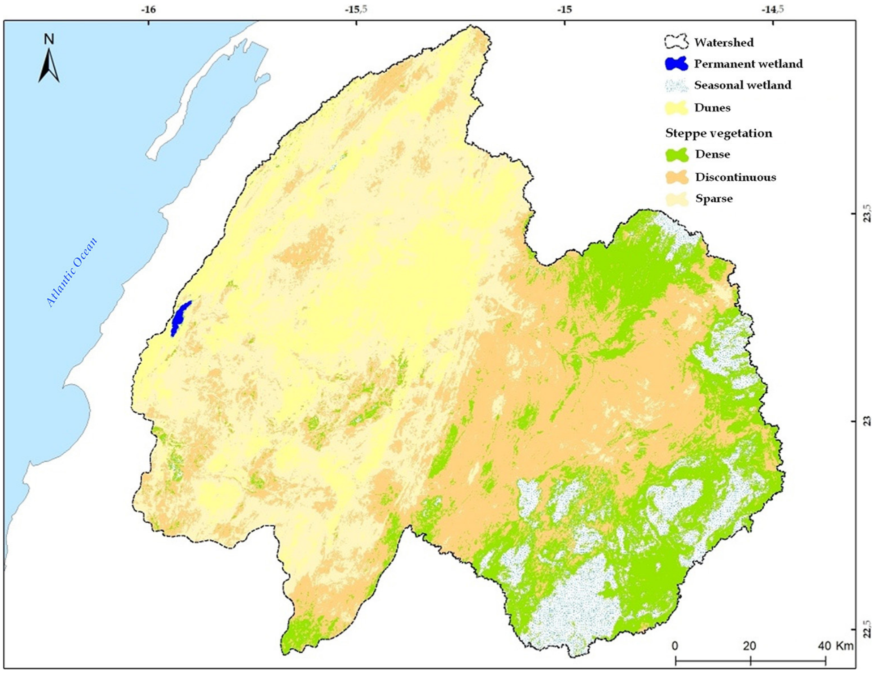


Fig. 3. Land use types (habitats) in the Imlili watershed

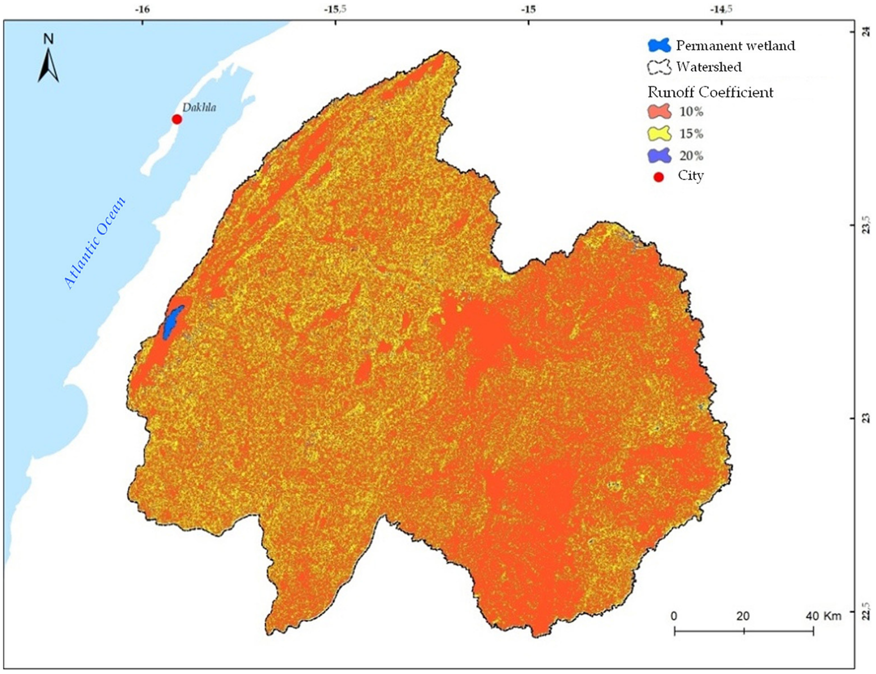


Fig. 4. Variation of the runoff coefficient in the Imlili watershed

mm respectively. The average volume of water (for the period 1981–2015) that is assumed to reach the wetland is 23.2 mm^3/year; it would be 2.9 mm^3/week for the period ‘September–October’ and 4.929 mm^3/week for the wettest month (weeks 36–39). Given that the topography of the catchment area is characterised by a low gradient (Fig. 6) and a dominance of sandbanks, the concentration time is high (74.86 mn) and the flow velocity during showers is low. This means that after heavy rainfall, the fraction of rainwater that reaches the sebkha would mainly come from the edge of the wetland. The rest of the rainfall is expected to infiltrate into the wadi underflows and/or to evaporate over time; the numerous

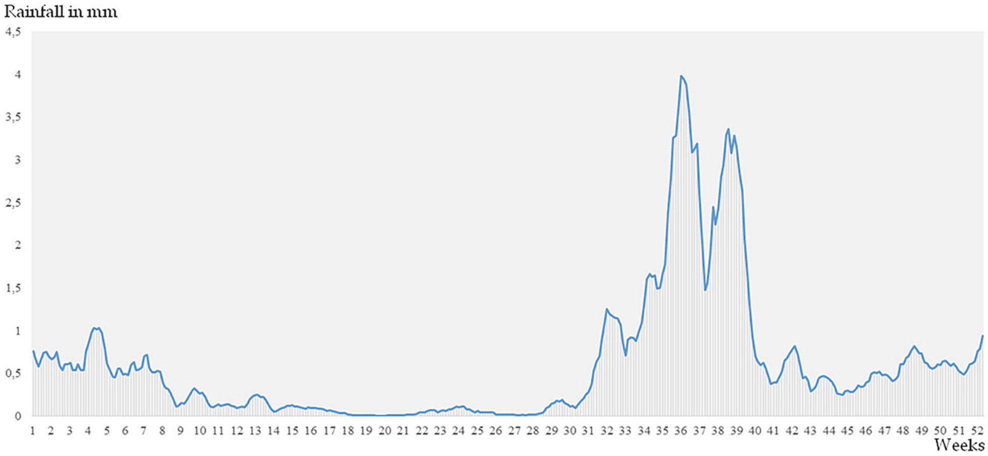


Fig. 5. Determination of the wettest period in the Imlili watershed

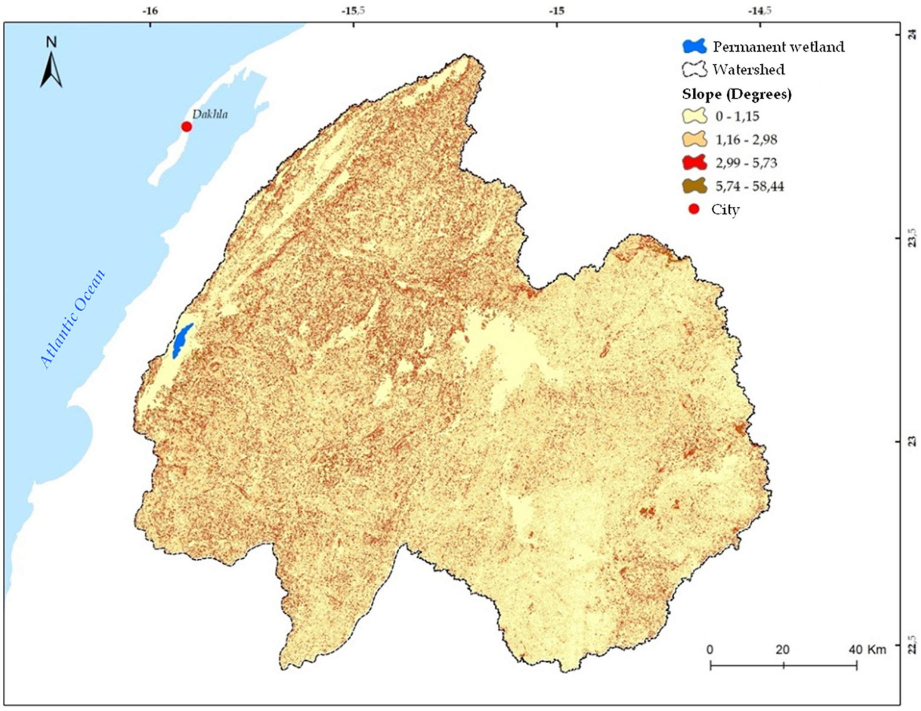


Fig. 6. Slope variation in the Imlili wetland catchment area

small depressions visible in the wadi beds accumulate this water over short periods and are supposed to participate in this infiltration. This means that precipitation would contribute more to the recharge of the water table, which converges almost entirely on the wetland aquifer, rather than its filling by surface runoff.

Peak flow

The extreme flows estimated according to several return periods give an overview of the exceptional floods (Fig. 7); they deserve consideration both for the susceptible water masses that arrive at the wetland and for the materials they may drain from the catchment (sand and silt, gravel, organic material, etc.). Despite the low slope of the wadi beds, these large floods are likely to sweep away many sandy obstacles and a good part of their water would reach the sebkha. They would be responsible for a significant transport of materials (sand, sometimes silty) towards the bottom of the thalwegs, or even to the wetland. Nevertheless, the flow will not be able to break certain impassable obstacles, which are favourable to the stagnation of rainwater upstream of the wetland and therefore to the recharge of the sebkha aquifer.

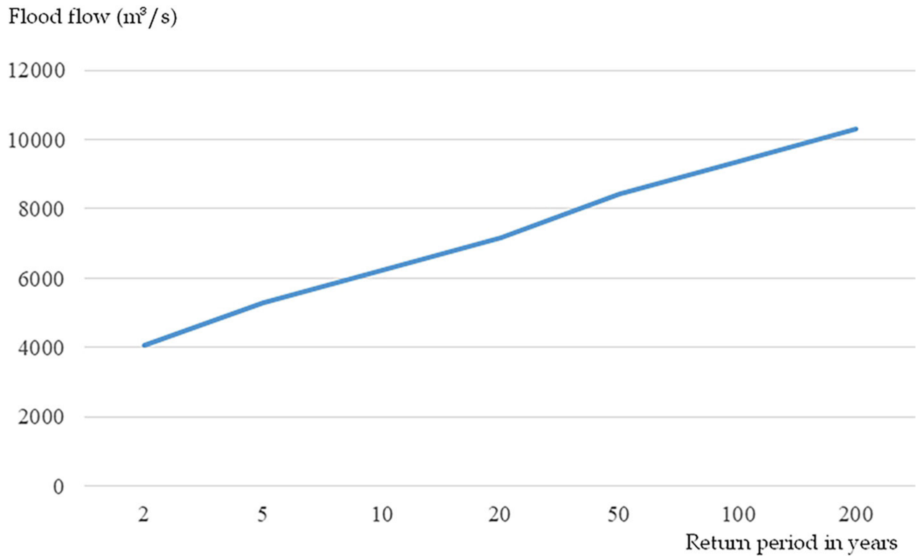


Fig. 7. Variation of peak flows according to return periods

DISCUSSION

It is well known that the permanence of the Imlili wetland is due to the emergence of groundwater via shallow cavities in the shallows. Given the low gradient and the silting up of the runoff surfaces, almost all of the rainwater is lost in the subsoil; a small part of the surface water masses generated by major storms would reach the wetland. However, episodic recharge of the wetland by surface water is attested to by traces of flooding (several decimetres high) and runoff observed in the field, by local witnesses and visitors, and by the vegetation of the wetland (Ibn Tattou, 2020). These surface inputs would particularly occur in early autumn (Fig. 5), as the wetland receives little rainfall during spring and summer (weeks 09–31).

The permanent character of the wetland would therefore be linked to the emergence of the surface water table, whose reserves are assumed to be relatively large, even during recent drought phases. This means that rainwater is not totally lost through evaporation and that it is largely recovered by the surface aquifers, thanks to the permeability of most of the land (Cenozoic deposits) and the sandy soils. In addition, during floods, rainwater submerges part of the wetland, including the cavities that emerge from the water table, and would contribute to the recharge of the underlying aquifer.

CONCLUSIONS

The contribution of this article lies in the simulation of the watering mechanisms of the Imlili wetland, in particular the permanence of the groundwater emergences that give it its character of permanent sebkha. The contribution of rainwater to the hydrological functioning of Saharan wetlands, generally underestimated due to the climate, is revised upwards for the Imlili sebkha, considering its rapid infiltration into the subsoil.

In addition, the catchment area has been extended to include the Wad Al Faj network, whose modelling may escape the digital field model. Indeed, in the depression drained by this network to the north of the wetland, the flow areas are poorly defined, especially as they may be blocked by temporary sandy obstacles.

This extension, even if we admit that its surface contributions to the Imlili wetland are low, has the merit of integrating the contribution of this network to the water table recharge, without neglecting its possible surface contributions to the wetland during heavy rainfall.

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