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► **To cite this version:**

Mounir Karim, Mehdi Maanan, Mohamed Maanan, Hassan Rhinane, Henri Rueff, et al.. Assessment of water body change and sedimentation rate in Moulay Bouselham wetland, Morocco, using geospatial technologies. *International Journal of Sediment Research*, 2018, 10.1016/j.ijsrc.2018.08.007 . hal-01866182

**HAL Id: hal-01866182**

**<https://hal.science/hal-01866182>**

Submitted on 21 Oct 2021

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## **Assessment of water body change and sedimentation rate in Moulay Bouselham wetland, Morocco, using geospatial technologies**

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**Abstract:**

Coastal lagoons have significant biodiversity and ecologic and socio-economic interest. Several resident and migratory birds live in coastal lagoons as well as fish and other aquatic biota. Over the years, lagoons worldwide have been subject to considerable sediment deposition coming especially from soil erosion due of agricultural activities, and the lagoon's inflows have resulted in an accelerated sedimentation which can drastically affect the aquatic ecosystem balance. A new, fast, and cost-effective approach was developed, using water surface change as a proxy, to evaluate the sediment deposition rate. In the current research, this methodology was applied in the Moulay Bouselham Lagoon in Morocco, and a combination of Landsat 8 and Landsat 5 imagery acquired at four points in time over 30 years (1985–2015) was used. Following geometric correction and enhancement, the interpretation of the acquired images provided important insight on the current conditions of the water surface change using the Normalized Difference Water Index (NDWI). Several iterations were done to determine a suitable threshold for effective water surface detection. In order to validate the automatically extracted water surface features, many band combinations of Landsat and Sentinel 2 were used as references to run the accuracy assessment. The results show that the Moulay Bouselham Lagoon lost 17.60% (106 ha) of its water surface area, and 530,000 m<sup>3</sup> to 1,060,000 m<sup>3</sup> of its water volume during the last three decades. Converting water surface loss into sedimentation returned a rate of 0.58 cm/yr. These results have been confirmed by previous field work using sedimentological approaches. Proper management should be applied to sustain the vitality of this lagoon environment.

**Keywords:** Environmental monitoring; Remote sensing; GIS; Spatial analyst; Human/nature interaction; Sustainability planning.

## **1. Introduction**

Wetlands are crucial ecosystems and resources for human kind (Hu et al., 2017). In addition to their ecosystem services supporting agriculture, fishing, and the tourism industry, wetlands provide a significant ecological and biologic services where natural habitats host rich flora and fauna (Affian et al., 2009; Hatvany, 2009; Mateus et al., 2016; Pérez-Ruzafa & Marcos, 2012; Sun et al., 2017; Zhang et al., 2017). Coastal lagoons are considered wetlands but with their features, mainly inflow and outflow dynamics with oceans, providing another dimension in terms of species presence (Pérez-Ruzafa et al., 2013). Facing the population shift near to the coastal areas, population growth, and human needs, signs of degradation of water quality and quantity of these ecosystems have become undeniable. Much of these coastal wetland areas have undergone or are undergoing adverse changes in their environmental conditions, partly or largely due to human activities (Kalloul et al., 2012; Maanan et al., 2014). Since the beginning of the 20th Century, the world lost around 64-71% of its wetlands (Davidson, 2014). Filling and sedimentation are defined among the main causes of wetland degradation (Zedler & Kercher, 2005). Many past studies highlighted accelerated sediment accumulation over the years (Bowen & Johnson, 2017; Dinis et al., 2006; Tsai et al., 2010). The filling process threatens the ability of wetlands to store and hold water (Luo et al., 1997) which can have a drastic and negative impact on wetland economic and ecologic services (Pérez-Ruzafa et al., 2013).

Moulay Bousselham Lagoon, located on the northern African coast, is no exception to these changes. The lagoon is in an area under development where the population has increased by 150% over the last 25 years (Maanan et al., 2013). It is the outfall, through the natural Drader River, for its watershed and through the artificial waterway Canal Nador of a larger watershed located in its southern part. Both of the basins are known for high agricultural activity where most of the fresh water is diverted for irrigation. The lagoon suffers from both direct and

indirect water pumping which reduces the amount of inflow water supplied to the Moulay Bouselham Lagoon.

To prevent ecological losses and degradation, a better understanding of the evolution and the behavior of the water body of the Moulay Bouselham Lagoon is needed. To improve understanding, a fast and accurate delimitation of the water body is fundamental for wetland resources evaluation, management, and protection (Xiao et al., 2014). Using traditional field survey techniques can be a challenging task in terms of water body delimitation depending on the nature of the field. These tasks also are costly and time consuming. However, relying on remote sensing technology and data can help to overcome these difficulties.

Monitoring and assessing changes based on spatial technologies is a powerful and crucial tool that has been used in several studies to study wetlands (Brivio & Zilioli, 1996; Munyati, 2000; Ozesmi & Bauer, 2002; Rebelo et al., 2009; Zhao et al., 1999) and more specifically to assess water body changes (El-Asmar et al., 2013; Frihy et al., 1998; Hui et al., 2008).

Due to its great socioeconomic and ecological resources, the Moulay Bouselham Lagoon has long aroused the interest of the scientific community (Beaubrum, 1976; Carruesco, 1989) and more recently in the two last decades has been part of the projects CASSARINA (Flower, 2001) and MELMARINA (Flower & Thompson, 2009). Most of the past studies concerning the Moulay Bouselham Lagoon have been based on field work and observations (Appleby et al., 2001; Kraïem et al., 2001; Labbardi et al., 2005; Peters et al., 2001; Ramdani et al., 2001, 2009; Thompson et al., 2009). Several other studies used spatial technologies (Ahmed et al., 2009; Ibara et al., 2015; Maanan et al., 2013; Shukla et al., 2017) to characterize and analyze environmental and ecological changes within the wetland. These studies often focused on the water contamination due to anthropic activities and how it impacts the ecological and biological balance of the ecosystem.

The main subjects treated, in the current paper were, the behavior and change of water quantity within the Moulay Bousselham Lagoon. Remotely sensed data and spatial technologies technics were used in order to achieve the following objectives: (1) to characterize water body changes during a period of three decades (1984 - 2015), and (2) to propose a method to estimate the sedimentation rate.

## **2. Materials and methods**

### *2.1. Study area*

Moulay Bousselham Lagoon covers 35 km<sup>2</sup> (Alaoui et al., 2010) and is a “Ramsar” (Ayadi et al., 2014) wetland on the northern Moroccan coast (longitude: 6°16’32” W and latitude: 34°50’57” N). The site has been declared as a “Site of biological and ecological interest” following a ministerial order by the local government in 1978 due to its significant biosphere. Furthermore, with its 11 habitats (Benhoussa et al., 1999), it is home to considerable biologic and ecologic activities as many endemic and migratory species live in the lagoon (Kraïem et al., 2009). Figure 1 shows the Moulay Bousselham Lagoon, its drainage basin and land uses and sampling locations in this basin. This coastal wetland is composed of two distinct and unequal water bodies (Fig. 1). Merja Zerga is the main water body which occupies a major part of the lagoon. A secondary one Merja Kahla, lays north of Merja Zerga. The lagoon receives its water mostly from the daily exchanges with the Atlantic Ocean following a semidiurnal tidal cycle. In addition to the ocean-lagoon water exchanges, two important water inflows are feeding the main water body with fresh water. The Nador Canal, an artificial waterway constructed in the early fifties, feeds the lagoon from the south. Oued Drader is a natural river that feeds the lagoon from the east. The climate in the lagoon is dominated by two distinct seasons. A cold and wet season where the temperature is low and precipitation is relatively high, starting in October and ending in April (Thompson et al., 2009). Then a hot

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**i.e. Ramsar** is an intergovernmental convention providing a framework for the conservation and wise use of wetlands and their resources

dry season takes over afterwards with marginal precipitations and high temperatures that reach their peaks in July and August (30C°). The annual precipitation can reach 750 mm depending on the year.

## *2.2. Data sets*

Three main types of data sets were used: satellite images, bathymetric (lagoon depth), and hydrological measurements (tidal level). Cloud free Landsat images covering a period of thirty years were acquired from the U.S. Geological Survey (<https://earthexplorer.usgs.gov>). All selected Landsat scenes were acquired between August and September assuring nearly similar weather conditions (Table 1). The images were selected during similar tide magnitudes in order to avoid tidal fluctuations affecting the water body surface change. An additional Sentinel 2 image, in accordance with Landsat acquisition conditions, was acquired for validation. Tide data were acquired from online sources that use XTide. XTide is a tide prediction program commonly used in scientific work (Berthot & Pattiaratchi, 2005; Kilcher & Nash, 2010; Verhoeven et al., 2014). The lagoon's bathymetry depends on the location; it rarely exceeds 1 m within the lagoon while it can reach 2 m within the inlet (communication channel between the ocean and lagoon) (Thompson et al., 2009). Ayache et al. (2009) suggested that the peak water depth within the lagoon varies from a minimum of 5 cm in the borders and a maximum of 2 m in the central part. Alaoui et al. (2010) agreed that the mean depth is 1 to 1.5 m and 0.3 to 0.5 m, respectively, for Merja Zerga and Merja Kahla. Ramdani et al. (2001) suggested that the average depth of Merja Zerga ranges between 3 and 80 cm. Finally the value chosen value as the mean depth, 50 cm, has been reported by Kraïem et al. (2001) and Labbardi et al. (2005). Due to its size and the fact that the fresh water inflows don't drain directly into it, Merja Zerga was selected as the central interest of the current study.

### 2.3. *Surface water change detection*

#### 2.3.1 *Image preprocessing*

The first step of the pre-processing phase consisted in projecting Landsat scenes to the local projection coordinates system. No additional geometric treatments were required as the scenes matched perfectly with a georeferenced basemap. The second step was the radiometric calibration consisting of the conversion of the Landsat digital numbers to top-of-atmosphere (TOA) radiance. Using Exelis Visual Information Solutions software (ENVI 5.1), which can automatically read Landsat metadata files and provide radiometric calibration with the Band Interleaved by line with a “scale factor” equal to 0.10. These parameters are required for the execution of the last step. Finally, the chosen method for atmospheric correction was the Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH model) (Fig. 2). Following instructions made available on the ENVI website, the key parameters used for the FLAASH model are listed in Table 2.

#### 2.3.2 *Satellite-based water index*

Over the years several studies have used remotely sensed data and water indices for water detection in urban, rural, coastal, and inland regions (El-Asmar et al., 2013; Han et al., 2014; McFeeters, 2013; Singh et al., 2015; Zhang et al., 2011). The choice of the right water index depends on the nature of the study area. Considering the facts that the selected images were cloud free and there are no built up areas near to the water borders (Gautam et al., 2015; Xu, 2006), the Normalized Difference Water Index (NDWI) was chosen. The NDWI was first introduced in the mid-nineties by (McFeeters, 1996) where the author affirms that this method uses the green light wavelengths to maximize the water features reflectance and uses the near-infrared (NIR) where water absorbance peaks and records the highest reflectance of soil and terrestrial vegetation. In the near-infrared the signal between water and non-water features is more marked. Using this approach, water features have positive values while soil and terrestrial vegetation tend to have negative values (McFeeters, 1996). In addition to the

current criteria selection, the NDWI has often a high value in accuracy assessment (Rokni et al., 2014). The NDWI is computed as follows

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

where Green and NIR stand, respectively, for the green wavelengths and near-infrared wavelengths. The green match bands 2 and 3 accordingly for Landsat 5 and 8, while NIR match bands 4 and 5 accordingly for Landsat 5 and 8.

#### *2.4. Sedimentation rate*

The balance of water inflows and the filling speed determines the lagoon dynamics and allows estimation of the sedimentation rate. The sediment quantity is very sensitive to environmental changes and human development. Many techniques have been used over the years to estimate the sediment deposition rate, such as coring. They are accurate but expensive and time-consuming. Using remote sensing instead, can be faster and easier to estimate the sedimentation rate.

To compute the sediment deposition rate, using only remotely sensed data, the following formula below was proposed. The equation is based on a water volume approach. To simplify calculation in the proposed model, two key assumptions are applied (Fig. 3): First, due to the Depth-Volume-Area correlation, the lost water volume within the lagoon during the period 1984-2015 was replaced by an equal amount of sediment. This means that the sediment volume must be computed. The Sediment volume equals the sediment depth times playa area (Tsai et al., 2010). Second, the sediment is assumed to be equally spread all over the lagoon. In addition to these assumptions, the morphology of the bottom surface can be approximated by a very gentle slope, which relatively increases going from the border to the principle channels in the center of the lagoon.

$$SDR = \frac{ABS (V_e - V_r)}{A_e} * \frac{1}{p}$$

where ABS = the absolute value function; SDR = The sediment deposition rate in m/yr;  $V_r$  = the water recent volume from 2015 in  $m^3$ ;  $V_e$  = the water earlier volume from 1984 in  $m^3$ ;  $A_e$  = the water earlier area from 1984 in  $m^2$ ; and  $p$  = numbers of years.

Following the foregoing equation, the volume of water loss during the studied period first was computed. The volume, in  $m^3$ , was calculated from the absolute value of the difference between the recent and the earlier area multiplied by the average mean depth. Then the result was divided by the earlier water area in  $m^2$  to get the value of the sediment deposition depth during the last three decades. Finally, to get the mean sedimentation rate per year, the latter result was divided by the period covered by the current study.

### *2.5. Accuracy assessment*

Accuracy assessment techniques were used to evaluate the quality of the automatically extracted information using remote sensing data. First to evaluate the surface change, the Kappa coefficient and the overall accuracy which are two well documented and known methods (Congalton, 1991; Wilson & Sader, 2002; Yuan et al., 2005) were used. To do the accuracy assessment, band combinations of Landsat images were visually interpreted in order to create reference maps and a 100 ground truth points for each date. An additional reference map was developed from a band combination of the Sentinel 2 image for 2015. Furthermore, the area evaluation was supported by the calculation of the absolute error which is the difference between the automatically extracted areas using the NDWI and the areas from the reference maps. Similar accuracy assessment was used in Rokni et al. (2014) and Yuan et al. (2005).

### **3. Results and discussion**

#### *3.1. Water body change*

Due to its dominant size, changes in the Merja Zerga basin were the main focus of the current study. The area covered by water in the lagoon clearly has been shrinking over the years. In Fig. 4, the water surface evolution shows a loss in water surface of about 17.60% going from 602 ha in 1984 ha to 496 ha in 2015. Figure. 4e showed a peak in the water surface area in 1995 which reaches 953 ha. Despite this peak, a decreasing trend can be easily deduced from the evolution of the extracted water surface areas.

For the water body changes accuracy assessment (Table 3), the overall accuracies and the kappa coefficients range, respectively, from 0.89 to 0.94 and 0.78 to 0.88. These values ensure the reliability of extracted water bodies. Moreover, this conclusion was supported by the calculation of the absolute error. For 2015, the absolute error values were respectively, 10.91 and 16.74 ha for the reference map from the Sentinel 2 image and the Landsat image. The Sentinel 2 image has a spatial resolution of 10 m which is better for visual interpretation. For the years 1984, 1995, and 2003, the values for the absolute error were, respectively, 42.63, 16.68, and 16.74 ha. This range of values of absolute error are tolerable considering the areas of the water body in the studied wetland.

The shape of the water body is adapting to the ecosystem morphology change. In 1984, most of the water was concentrated in the southern and eastern parts of the lagoon while in its center; only the permanent channels were filled in water Fig. 4a. This water body shape can be explained by the development of a sandpit at the mouth of the lagoon (Carruesco, 1989). This sediment body has been aggrading throughout the years in parallel with the coastline periodically blocking the inlet. Blockages obviously limit the exchange between the ocean and the lagoon.

Considering that the ocean mainly supplies water to the lagoon (Thompson et al., 2009), these blockage episodes reshape the water body and its spatial distribution. The narrow inlet channel which provides the sea-lagoon exchange was completely blocked in 1983 (Carruesco, 1989). These episodes have been recurrent through the centuries and only happened on several occasions during the Twentieth Century (Ayache et al., 2009). Once the inlet of the lagoon is blocked, the wetland receives the water mostly from its freshwater inflows namely Oued Drader River and Nador Canal. The water spatial distribution fits perfectly with the freshwater outfalls, where most immersed areas are located in the south and east of the lagoon. These morphologic modifications highly impact the water chemistry. In this case, the salinity level lowers and the lagoon changes into a freshwater lake. Ayache et al. (2009) reported that the water salinity conditions have a large impact on the fish community, especially the migratory species. Following the blockage episodes, which generally lasted a few months (Carruesco, 1989), the inlet is mechanically removed by the local fishermen who do need a narrow channel (communication between lagoon and the ocean) for their fishing activity in addition to other uses (UCL, 1994). The inner part of this latter channel is used as a daily fishing port.

The estimated water area for 1995 shows that the water had regained all the available space. In addition to the immersed areas in 1984, those near the inlet became filled with water Fig. 4b. The constant ocean-lagoon exchanges assure a permanent submersion of the wetland. Some blockage episodes associated with storms occur on rare occasions. Since the active maintenance previously mentioned is on-going, these incidents are short-lived events and only last a few days according to the local community. These momentary interruptions have not been documented. Once the entrance is cleared, the rapid water replacement due to the large tidal oscillation reported by Thompson et al. (2009) limits the salinity decrease.

Starting from 1995, the water body begins to shrink from the south and the east borders without showing a major modification in its shape. The lagoon lost approximately a third and half of its immersed areas, respectively, from 1995 to 2003 and from 1995 to 2015. This water surface evolution shows a progressive and relatively fast reduction in terms of immersed areas. As shown in Fig. 4c and 4d the water surface shrinking is a localized loss where it's likely to be linked to the lagoon freshwater inflows. The lost water area in the southern part of the wetland is likely due to the progradation of the deltaic structure induced by the Canal Nador discharge (Ahmed et al., 2009; Ayache et al., 2009; Carruesco, 1989). The deltaic structure appeared in the mid-fifties when the artificial waterway was constructed and kept developing afterwards. Its size has reached 3 km<sup>2</sup> (Carruesco, 1989) and 6.6 km<sup>2</sup> (Ayache et al., 2009) respectively in 1983 and 2000. In 2015, this deltaic body has been estimated to reach 9.8 km<sup>2</sup> in size (Fig. 5).

In the eastern part of the Merja Zerga, despite the presence of a delta at the outlet of the natural Drader River, the water surface loss is attributed to the hydrology conditions. In Morocco, as in the most developing countries, anthropogenic pressure overwhelms environmental considerations and water management is no exception. Following the demographic expansion around the region and facing growing resource demands, the Drader River and its tributaries have been subjected to heavy and continuous pressure to satisfy the population and their activities. Agriculture was set to be the primary activity of the local community and dominates the land use (Fig. 1), especially on both sides of the Drader River. Fields, especially permanently irrigated lands, that have developed around the lagoon are a good indicator of the rapid human expansion. The lagoon watershed is shared by anthropogenic activities and the natural environment where another indicator of this development can be spotted. This indicator is the shape of the western and southern boundaries of the forest which has smoothly been modelled by the expansion of the

agricultural parcels. Drader River water has heavily been used for irrigation. Thompson et al. (2009) reported that an important but unknown amount of water is extracted by a pumping station near to the outlet of the Drader River. In addition to that, in 2015 around the eastern natural inflow, the permanently irrigated areas have reached approximately 3800 ha. Since the construction of the Canal Nador, the sedimentation in the lagoon has been modified. The artificial waterway was constructed in 1953 as part of plans to reduce the flooding problem that frequently occurred in Gharb basin (Alaoui, 2009; Carruesco, 1989). This basin is drained by the Sebou River. The Sebou River basin covers an area of 38,380 km<sup>2</sup> and it is highly known for its intensive agricultural activities (Ayache et al., 2009). The Canal Nador has partly reduced the flooding problem through draining irrigation water. As a consequence, a huge amount of water ends in the lagoon. The average Nador Canal sediment discharge has been estimated at 450,000 t/yr (Carruesco, 1989). A large part of this discharge is attributed to agricultural waste.

### *3.2. Sedimentation rate*

According to the formula previously presented, the extracted areas from each image and the mean value of bathymetry of the lagoon were used to compute the volume of water and then calculate a mean value of the sedimentation rate. Historic values of the sedimentation rate were used to validate the results. The estimated sedimentation rate depends on the location of the sediment core sampling. For example, near the outlet of the freshwater sources, the sedimentation rate is greater than in the central part of the lagoon (Carruesco, 1989). Using the volume-based approach a value of 0.58 cm/yr was found. This value agrees with the values found in previous scientific work where Maanan et al. (2013), Appleby et al. (2001) and Carruesco (1989), respectively, estimated it at 0.65, 0.6, and 0.4 cm/yr using radionuclide methods (<sup>137</sup>Cs and <sup>210</sup>Pb, cesium 137 and lead 210).

The current paper has proved that estimating the recent sedimentation rate based on the water volume approach is a time saving and cost-effective method. This approach uses the water area as a proxy to calculate the volume as well as the water depth. It can be a powerful tool for worldwide wetland monitoring and wetland preservation. This method depends on two major parameters: a good estimation of water depth and satellite image availability. This method can be a substitute for the radiometric determination and core sampling methods which are known to be time-consuming and costly.

#### **4. Conclusions**

The key for a coastal ecosystems' longevity is proper management and continuous monitoring. The monitoring is controlled by financial constraints. Furthermore, traditional monitoring based on field sampling often is time consuming. Thus, the current study demonstrated that the use of remotely sensed data and GIS based techniques allow a fast and fairly accurate method to assess the water surface shape change and estimate the sedimentation rate in a coastal wetland. The current study shows that, in addition to natural factors, the shape of the Merja Zerga is constantly changing under anthropogenic influences. Human intervention assures the continuity of the ocean/lagoon exchange that keeps the sea water coming and helps maintain an important immersed area. Even with this maintenance, the lagoon keeps shrinking and is progressively losing significant immersed area each year. Moreover, the spatial distribution of water in this ecosystem can indicate the water's origin. Regarding the estimation of the sediment deposition rate, the approach proposed is highly time saving and low cost. However, there are some limitations to its application. Further evaluations should be done in different natural coastal and inland ecosystems as well as artificial reservoirs to test and adapt the proposed approach.

#### **Acknowledgements**

The authors gratefully acknowledge Prof. Hongwei Fang (Editor-in-chief, International Journal of Sediment Research) and Prof. Charles Melching (Associate editor, International Journal of Sediment Research) and two anonymous reviewers for their scientific suggestions and constructive comments. The authors also thank Prof. Carol Robins for proofreading this paper.

## References

- Affian, K., Robin, M., Maanan, M., Digbehi, B., Djagoua, E. V., & Kouamé, F. (2009). Heavy metal and polycyclic aromatic hydrocarbons in Ebrié Lagoon sediments, Côte d'Ivoire. *Environmental Monitoring and Assessment*, 159(1–4), 531–541.
- Ahmed, M. H., El Leithy, B. M., Thompson, J. R., Flower, R. J., Ramdani, M., Ayache, F., & Hassan, S. M. (2009). Application of remote sensing to site characterisation and environmental change analysis of North African coastal lagoons. *Hydrobiologia*, 622(1), 147–171.
- Alaoui, A. M. (2009). *Environnement et paléoenvironnement d'un écosystème côtier : la lagune de Moulay Bouselham, côte atlantique marocaine* (Doctoral dissertation, Bordeaux 1).
- Alaoui, A. M., Choura, M., Maanan, M., Zourarah, B., Robin, M., Conceição, M. F., Andrade, C., Khalid, M., & Carruesco, C. (2010). Metal fluxes to the sediments of the Moulay Bouselham Lagoon, Morocco. *Environmental Earth Sciences*, 61(2), 275–286.
- Appleby, P. G., Birks, H. H., Flower, R. J., Rose, N., Peglar, S. M., Ramdani, M., Kraïem, M. M., & Fathi, A. A. (2001). Radiometrically determined dates and sedimentation rates for recent sediments in nine North African wetland lakes ( the CASSARINA Project ). *Aquatic Ecology*, 35(3-4), 347–367.
- Ayache, F., Thompson, J. R., Flower, R. J., Boujarra, A., Rouatbi, F., & Makina, H. (2009). Environmental characteristics, landscape history and pressures on three coastal lagoons in the Southern Mediterranean Region: Merja Zerga (Morocco), Ghar El Melh (Tunisia) and Lake Manzala (Egypt). *Hydrobiologia*, 622(1), 15–43.
- Ayadi, H., Le Bars, M., Le Grusse, P., Mandart, E., Fabre, J., Bouaziz, A., & Bord, J. P. (2014). SimPhy: A simulation game to lessen the impact of phytosanitaires on health and the environment - The case of Merja Zerga in Morocco. *Environmental Science and Pollution Research*, 21(7), 4950–4963.
- Beaubrum, P. C. (1976). La lagune de Moulay Bouselham: Etude hydrographique et sédimentologique. *Bulletin Institut Scientifique Rabat*, 1, 5–38.
- Benhoussa, A., Dakki, M., Qninba, A., & El Agbani, M. A. (1999). Habitats d'un site Ramsar cotier du Maroc, la Merja Zerga: Approches typologiques et cartographique. *Humedales Mediterráneos*, 1(1999): 75-82 SEHUMED, Valencia (Spain), pp.75–82.
- Berthot, A., & Pattiaratchi, C. (2005). Maintenance of headland-associated linear sandbanks: Modelling the secondary flows and sediment transport. *Ocean Dynamics*, 55(5–6), 526–540.
- Bowen, M. W., & Johnson, W. C. (2017). Anthropogenically accelerated sediment accumulation

- within playa wetlands as a result of land cover change on the High Plains of the central United States. *Geomorphology*, 294(1), 135-145.
- Brivio, P. A., & Zilioli, E. (2014). Assessing wetland changes in the Venice Lagoon by means of satellite remote sensing data. *Journal of Coastal Conservation*, 2(1), 23–32.
- Carruesco, C. (1989). *Genèse et évolution de trois lagunes du littoral Atlantique depuis l'holocène : Oualidia, Moulay Bou Salham (Maroc) et Arcachon (France)* (Doctoral dissertation, Bordeaux 1).
- Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37(1), 35–46.
- Davidson, N. C. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, 65(10), 934.
- Dinis, J. L., Henriques, V., Freitas, M. C., Andrade, C., & Costa, P. (2006). Natural to anthropogenic forcing in the Holocene evolution of three coastal lagoons (Caldas da Rainha valley, western Portugal). *Quaternary International*, 150(1), 41–51.
- El-Asmar, H. M., Hereher, M. E., & El Kafrawy, S. B. (2013). Surface area change detection of the Burullus Lagoon, north of the Nile Delta, Egypt, using water indices: A remote sensing approach. *Egyptian Journal of Remote Sensing and Space Science*, 16(1), 119–123.
- Flower, R. J. (2001). Change, stress, sustainability and aquatic ecosystem resilience in North African wetland lakes during the 20th century: An introduction to integrated biodiversity studies within the CASSARINA Project. *Aquatic Ecology*, 35(3–4), 261–280.
- Flower, R. J., & Thompson, J. R. (2009). An overview of integrated hydro-ecological studies in the MELMARINA Project: Monitoring and modelling coastal lagoons-making management tools for aquatic resources in North Africa. *Hydrobiologia*, 622(1), 3–14.
- Frihy, O. E., Dewidar, K. M., Nasr, S. M., & El Raey, M. M. (1998). Change detection of the northeastern Nile Delta of Egypt: Shoreline changes, spit evolution, margin changes of Manzala Lagoon and its islands. *International Journal of Remote Sensing*, 19(10), 1901–1912.
- Gautam, V. K., Gaurav, P. K., Murugan, P., & Annadurai, M. (2015). Assessment of surface water dynamics in Bangalore using WRI, NDWI, MNDWI, supervised classification and K-T transformation. *Aquatic Procedia*, 4(Icwrcoe), 739–746.
- Han, X., Chen, X., & Feng, L. (2015). Four decades of winter wetland changes in Poyang Lake based on Landsat observations between 1973 and 2013. *Remote Sensing of Environment*, 156, 426–437.
- Hatvany, M. G. (2009). Wetlands and reclamation. In *International Encyclopedia of Human*

*Geography* (pp. 241–246). Amsterdam Elsevier.

- Hu, S., Niu, Z., Chen, Y., Li, L., & Zhang, H. (2017). Global wetlands: Potential distribution, wetland loss, and status. *Science of the Total Environment*, 586, 319–327.
- Hui, F., Xu, B., Huang, H., Yu, Q., & Gong, P. (2008). Modelling spatial-temporal change of Poyang Lake using multitemporal Landsat imagery. *International Journal of Remote Sensing*, 29(20),
- Ibara, B. O., Dakki, M., Hakdaoui, M., & El Hamoumi, R. (2015). Contribution of hybrid classification on Ikonos Satellite Imagery In Mapping Of Wetland Habitats : Merja Zerga ( Morocco ). *International Journal of Innovation and Applied Studies*, 12(4), 9324.
- Kalloul, S., Hamid, W., Maanan, M., Robin, M., Sayouty, E. H., & Zourarah, B. (2012). Source contributions to heavy metal fluxes into the Loukous Estuary (Moroccan Atlantic Coast). *Journal of Coastal Research*, 279, 174–183.
- Kilcher, L. F., & Nash, J. D. (2010). Structure and dynamics of the Columbia River tidal plume front. *Journal of Geophysical Research*, 115(C5), C05S90.
- Kraïem, M. M., Chouba, L., Ramdani, M., Ahmed, M. H., Thompson, J. R., & Flower, R. J. (2009). The fish fauna of three North African lagoons: Specific inventories, ecological status and production. *Hydrobiologia*, 622(1), 133–146.
- Kraïem, M. M., Hamza, C. Ben, Ramdani, M., Fathi, A. A., Abdelzaher, H. M. A., & Flower, R. J. (2001). Some observations on the age and growth of thin-lipped grey mullet, *Liza Ramada* Risso, 1826 (Pisces, Mugilidae) in three North African wetland lakes: Merja Zerga (Morocco), Garâat Ichkeul (Tunisia) and Edku lake (Egypt). *Aquatic Ecology*, 35(3–4), 335–345.
- Labbaridi, H., Ettahiri, O., Lazar, S., Massik, Z., & El Antri, S. (2005). Étude de la variation spatio-temporelle des paramètres physico-chimiques caractérisant la qualité des eaux d'une lagune côtière et ses zonations écologiques : Cas de Moulay Bousselham, Maroc. *Comptes Rendus Geoscience*, 337(5), 505–514.
- Luo, H. R., Smith, L. M., Allen, B. L., & Haukos, D. A. (1997). Effects of sedimentation on playa wetland volume. *Ecological Applications*, 7(1), 247–252.
- Maanan, M., Landesman, C., Maanan, M., Zourarah, B., Fattal, P., & Sahabi, M. (2013). Evaluation of the anthropogenic influx of metal and metalloid contaminants into the Moulay Bousselham Lagoon, Morocco, using chemometric methods coupled to geographical information systems. *Environmental Science and Pollution Research*, 20(7), 4729–4741.
- Maanan, M., Ruiz-Fernández, A. C., Maanan, M., Fattal, P., Zourarah, B., & Sahabi, M. (2014). A long-term record of land use change impacts on sediments in Oualidia Lagoon, Morocco.

*International Journal of Sediment Research*, 29(1), 1–10.

- Mateus, M., Almeida, D., Simonson, W., Felgueiras, M., Banza, P., & Batty, L. (2016). Conflicting uses of coastal areas: A case study in a southern European coastal lagoon (Ria de Alvor, Portugal). *Ocean & Coastal Management*, 132, 90–100.
- McFeeters, S. (2013). Using the normalized difference water index (NDWI) within a Geographic Information System to Detect Swimming Pools for Mosquito Abatement: A Practical Approach. *Remote Sensing*, 5(7), 3544–3561.
- McFeeters, S. K. (1996). The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432.
- Munyati, C. (2000). Wetland change detection on the Kafue Flats, Zambia, by classification of a multitemporal remote sensing image dataset. *International Journal of Remote Sensing*, 21(9), 1787–1806.
- Ozesmi, S. L., & Bauer, M. E. (2002). Satellite remote sensing of wetlands. *Wetlands Ecology and Management*, 10(5), 381–402.
- Pérez-Ruzafa, A., & Marcos, C. (2012). Fisheries in coastal lagoons: An assumed but poorly researched aspect of the ecology and functioning of coastal lagoons. *Estuarine, Coastal and Shelf Science*, 110, 15–31.
- Pérez-Ruzafa, A., Marcos, C., Pérez-Ruzafa, I. M., & Pérez-Marcos, M. (2013). Are coastal lagoons physically or biologically controlled ecosystems? Revisiting r vs. K strategies in coastal lagoons and estuaries. *Estuarine, Coastal and Shelf Science*, 132, 17–33.
- Peters, A. J., Jones, K. C., Flower, R. J., Appleby, P. G., Ramdani, M., Kraïem, M. M., & Fathi, A. A. (2001). Recent environmental change in North African wetland lakes: A baseline study of organochlorine contaminant residues in sediments from nine sites in the CASSARINA Project. *Aquatic Ecology*, 35(3-4), 449-459.
- Ramdani, M., Elkhiaï, N., Flower, R. J., Thompson, J. R., Chouba, L., Kraïem, M. M., Ayache, F., & Ahmed, M. H. (2009). Environmental influences on the qualitative and quantitative composition of phytoplankton and zooplankton in North African coastal lagoons. *Hydrobiologia*, 622(1), 113–131.
- Ramdani, M., Flower, R. J., Elkhiaï, N., Kraïem, M. M., Fathi, A. A., Birks, H. H., & Patrick, S. T. (2001). North African wetland lakes: characterization of nine sites included in the CASSARINA Project. *Aquatic Ecology*, 35(3-4), 281-302.
- Rebelo, L. M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland

- inventory, mapping and change analysis. *Journal of Environmental Management*, 90(7), 2144–2153.
- Rokni, K., Ahmad, A., Selamat, A., & Hazini, S. (2014). Water feature extraction and change detection using multitemporal Landsat imagery. *Remote Sensing*, 6(5), 4173–4189.
- Ruiz-Luna, A., & Berlanga-Robles, C. A. (1999). Modifications in coverage patterns and land use around the Huizache-Caimanero Lagoon system, Sinaloa, Mexico: A multi-temporal analysis using Landsat images. *Estuarine, Coastal and Shelf Science*, 49(1), 37–44.
- Shukla, S., Jain, S. K., Kansal, M. L., & Kumar, S. (2017). Assessment of sedimentation in Pong and Bhakra reservoirs in Himachal Pradesh, India, using geospatial technique. *Remote Sensing Applications: Society and Environment*, 8, 148–156.
- Singh, K. V., Setia, R., Sahoo, S., Prasad, A., & Pateriya, B. (2015). Evaluation of NDWI and MNDWI for assessment of waterlogging by integrating digital elevation model and groundwater level. *Geocarto International*, 30(6), 650–661.
- Sun, C., Zhen, L., & Giashuddin Miah, M. (2017). Comparison of the ecosystem services provided by China's Poyang Lake wetland and Bangladesh's Tanguar Haor wetland. *Ecosystem Services*, (February 2016), 0–1.
- Thompson, J. R., Flower, R. J., Ramdani, M., Ayache, F., Ahmed, M. H., Rasmussen, E. K., & Petersen, O. S. (2009). Hydrological characteristics of three North African coastal lagoons: Insights from the MELMARINA project. *Hydrobiologia*, 622(1), 45–84.
- Tsai, J.-S., Venne, L. S., McMurry, S. T., & Smith, L. M. (2010). Vegetation and land use impact on water loss rate in playas of the southern high plains, USA. *Wetlands*, 30(6), 1107–1116.
- University College London. (1994). *Hydrology, vegetation and human use of Merja Zerga, Morocco. M.Sc. conservation course, Departments of Biology and Geography*, London.
- Verhoeven, J. T. A., Laanbroek, H. J., Rains, M. C., & Whigham, D. F. (2014). Effects of increased summer flooding on nitrogen dynamics in impounded mangroves. *Journal of Environmental Management*, 139, 217–226.
- Wilson, E. H., & Sader, S. A. (2002). Detection of forest harvest type using multiple dates of Landsat TM imagery. *Remote Sensing of Environment*, 80(3), 385–396.
- Xiao, X., Wdowinski, S., & Wu, Y. (2014). Improved water classification using an application-oriented processing of Landsat ETM+ and ALOS PALSAR. *International Journal of Control and Automation*, 7(11), 373–388.
- Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water

features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14), 3025–3033.

Yuan, F., Sawaya, K. E., Loeffelholz, B. C., & Bauer, M. E. (2005). Land cover classification and change analysis of the Twin Cities (Minnesota) Metropolitan Area by multitemporal Landsat remote sensing. *Remote Sensing of Environment*, 98(2–3), 317–328.

Zedler, J. B., & Kercher, S. (2005). Wetland resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources*, 30(1), 39–74.

Zhang, B., Shi, Y., Liu, J., Xu, J., & Xie, G. (2017). Economic values and dominant providers of key ecosystem services of wetlands in Beijing, China. *Ecological Indicators*, 77, 48–58.

Zhang, F.F., Zhang, B., Li J.S., Shen, Q., Wu, Y., & Song, Y., (2011). Comparative analysis of automatic water identification method based on multispectral remote sensing. *Procedia Environmental Sciences*, 11, 1482–1487.

## **Figures captions**

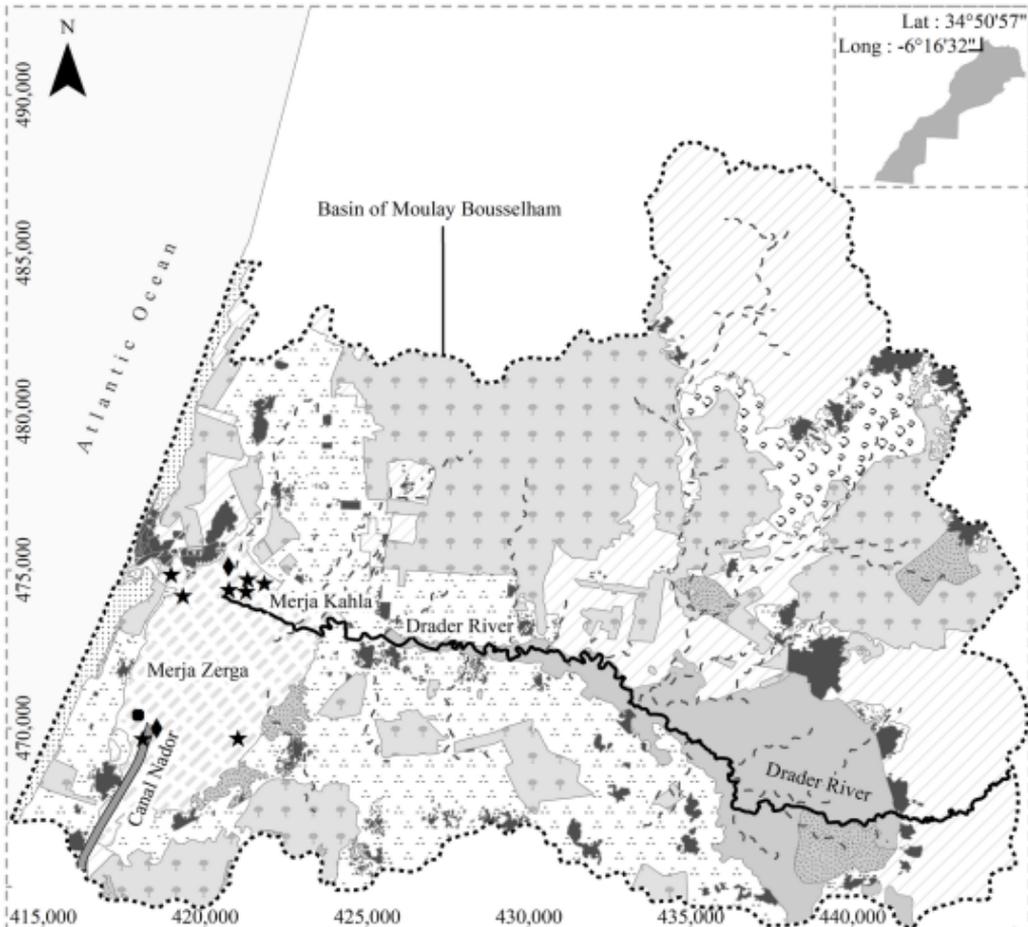
**Fig. 1:** Land use in the Moulay Bouselham basin and core sampling locations

**Fig. 2:** Scheme of the methodology used to compute the sediment deposition rate and to extract the water body change (note: NDWI = Normalized Difference Water Index)

**Fig. 3:** Visual model to estimate the sedimentation rate (adopted from Tsai et al. (2010)).

**Fig. 4:** a, b, c and d represent, respectively, the water body area from 1984, 1995, 2003 and 2015; and e is the diagram of water area fluctuation in hectares (1984-2015)

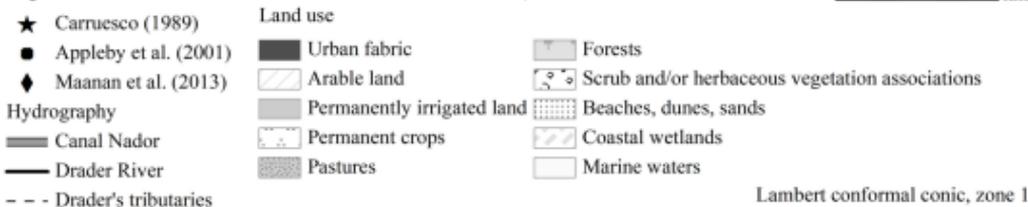
**Fig. 5:** Deltaic cores and sediment loads, Moulay Bouselham Lagoon, Morocco

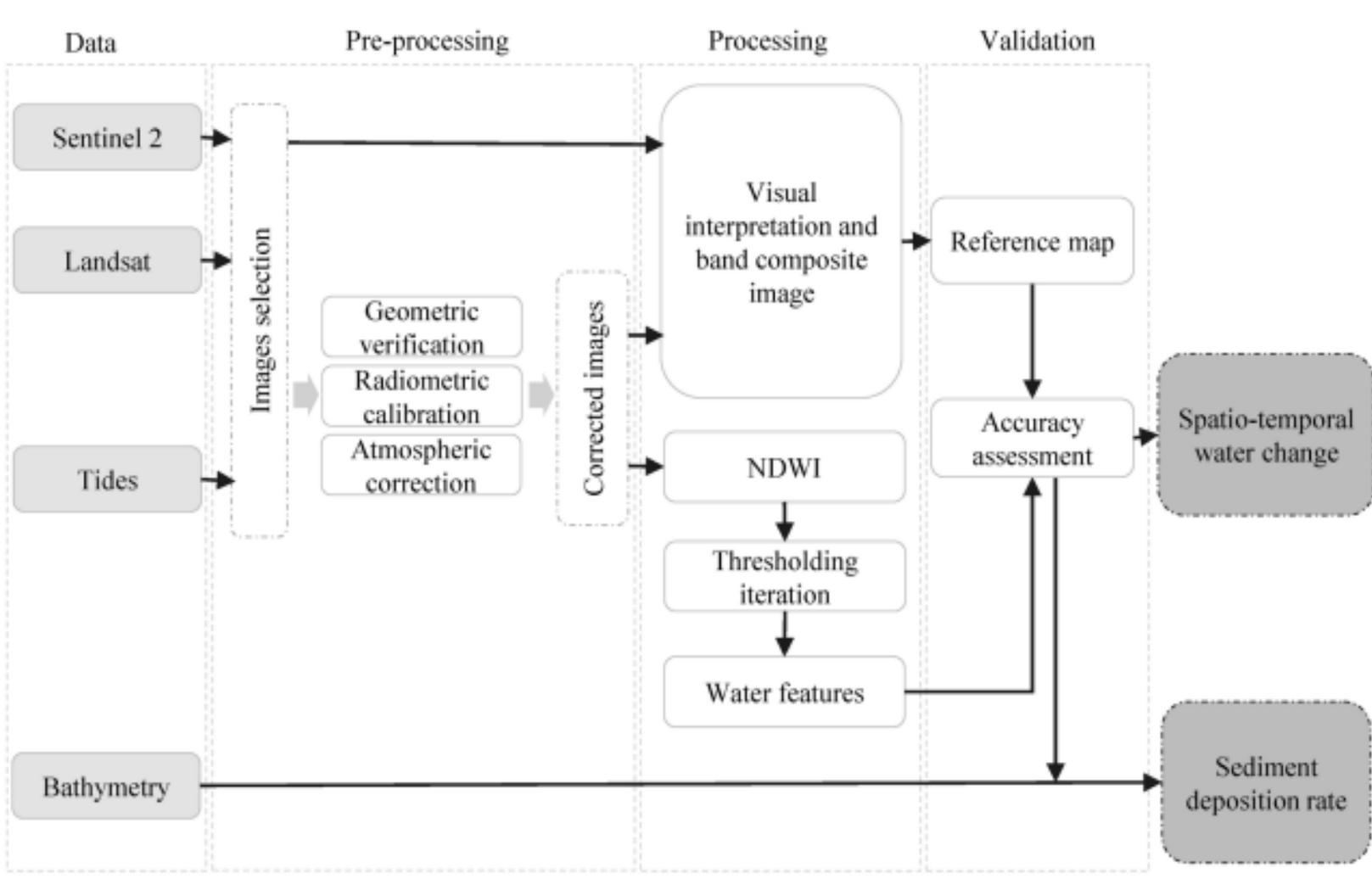


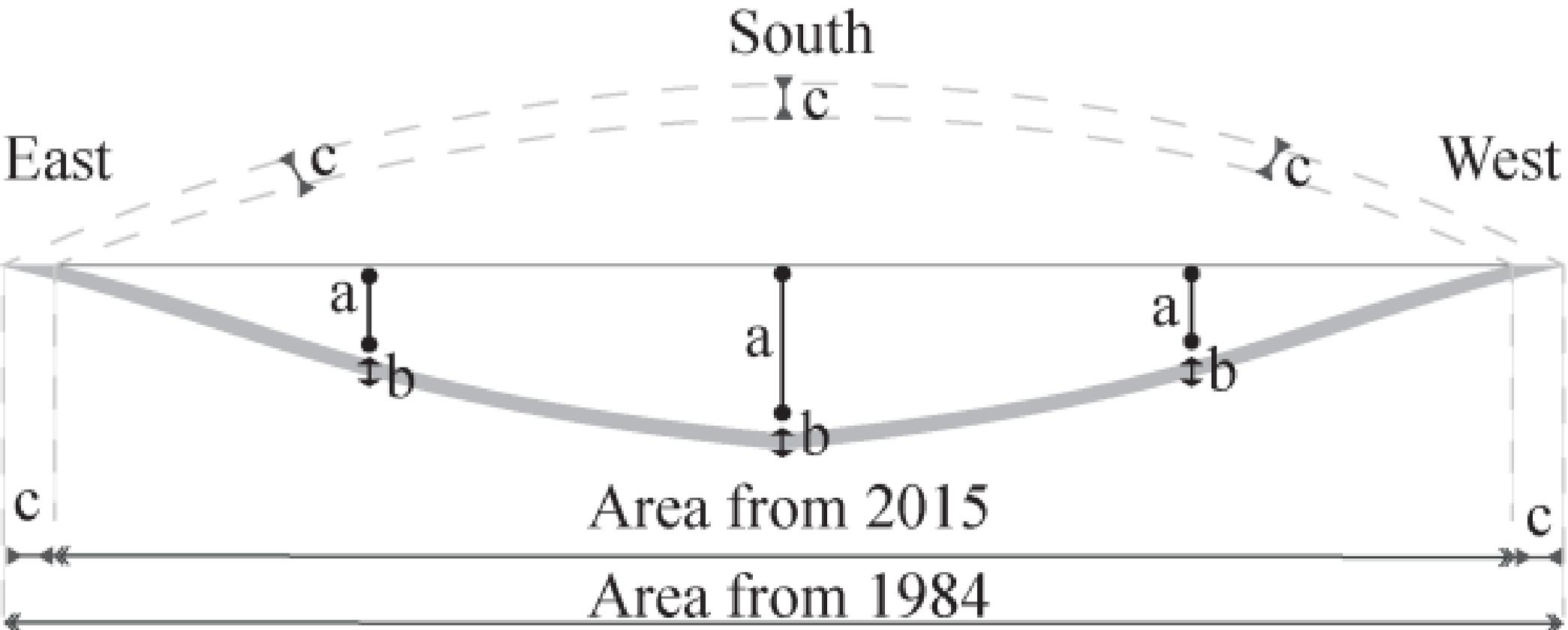
Legend

1:200,000

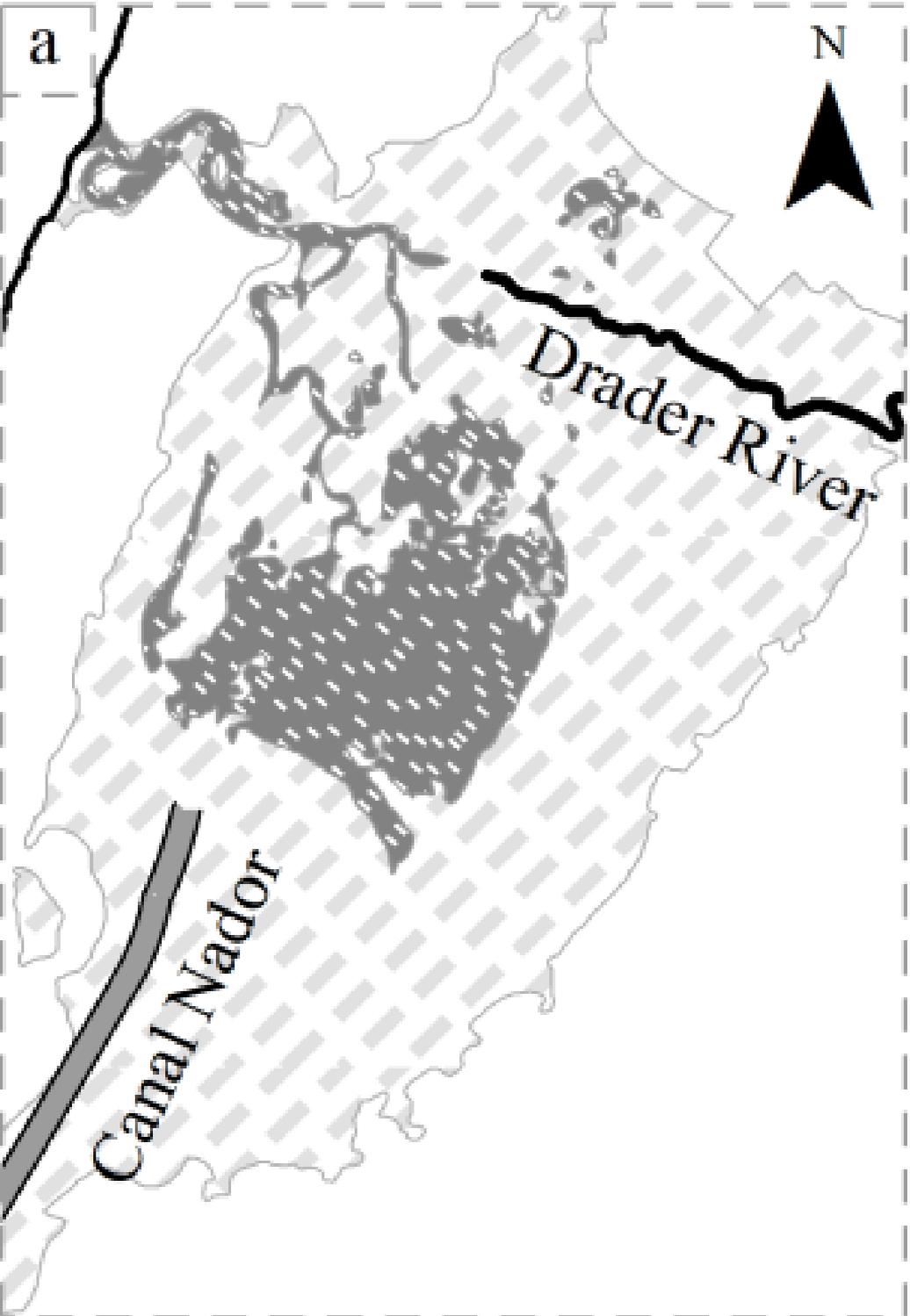
0 1 2 3 4 5 km







$\downarrow a$ : Water depth  $\downarrow b$ : Assumed sediment depth  $\downarrow c$ : Lost area



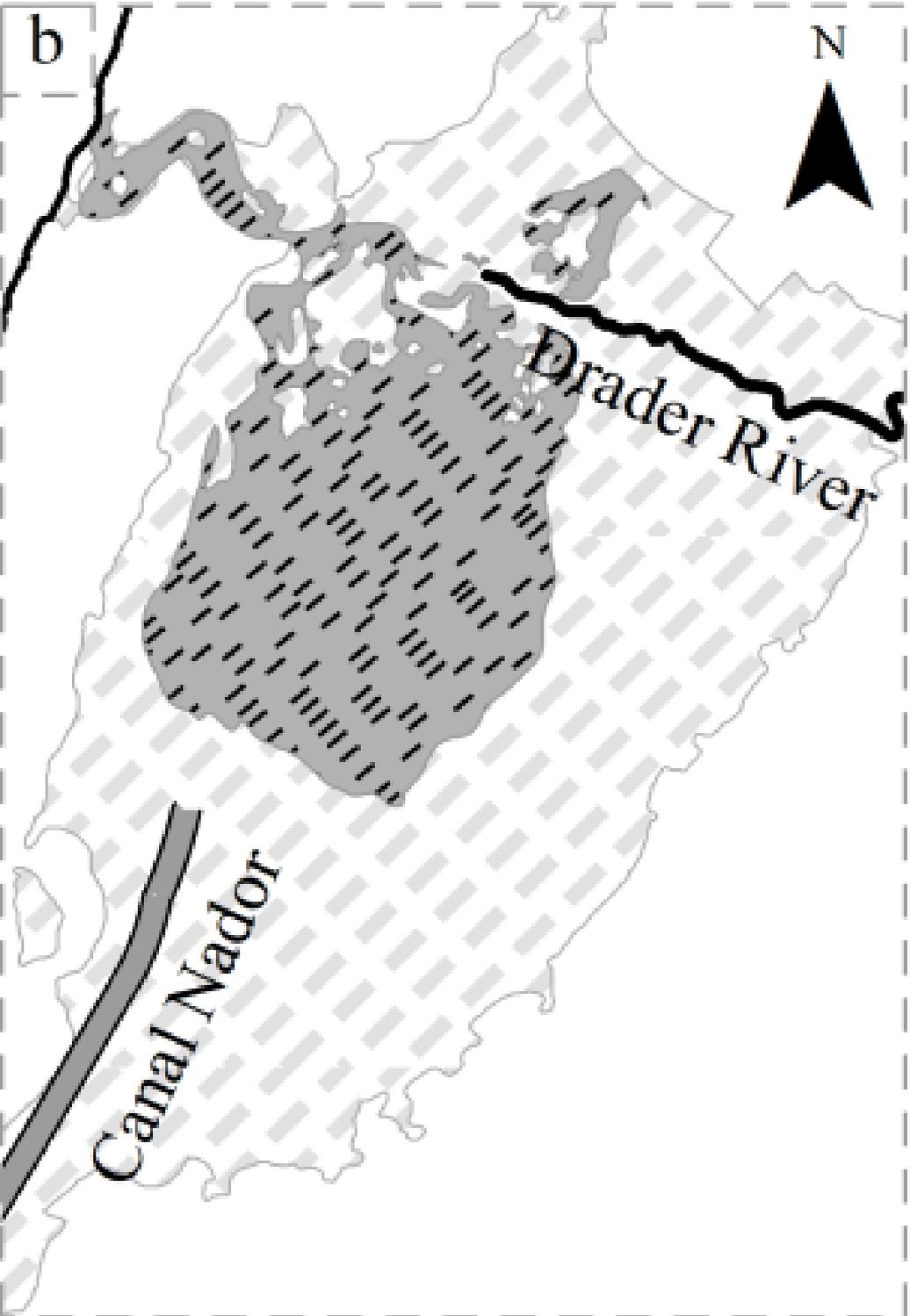
## Legend



Coastal wetlands



Water shape from 1984



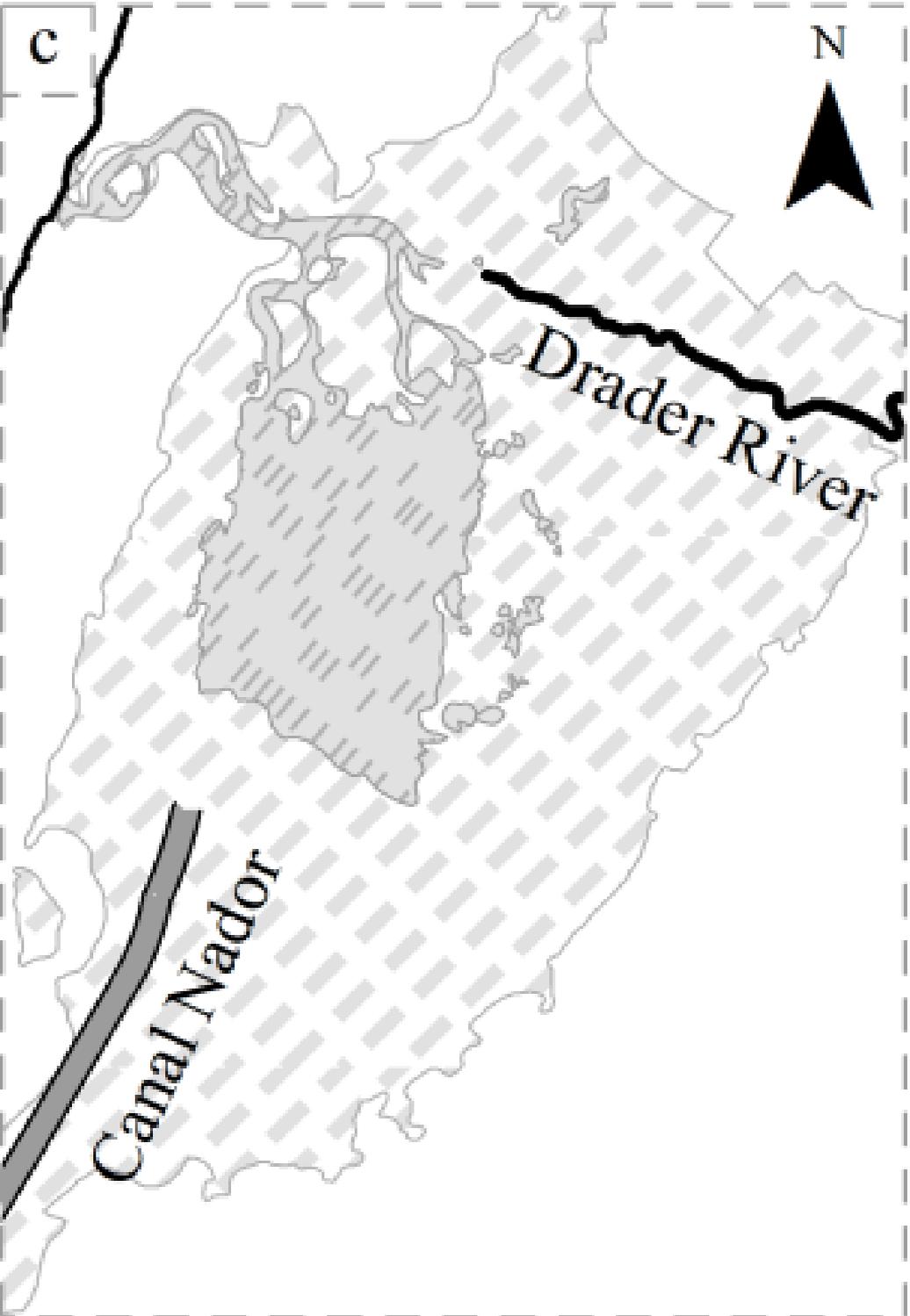
## Legend



Coastal wetlands



Water shape from 1995



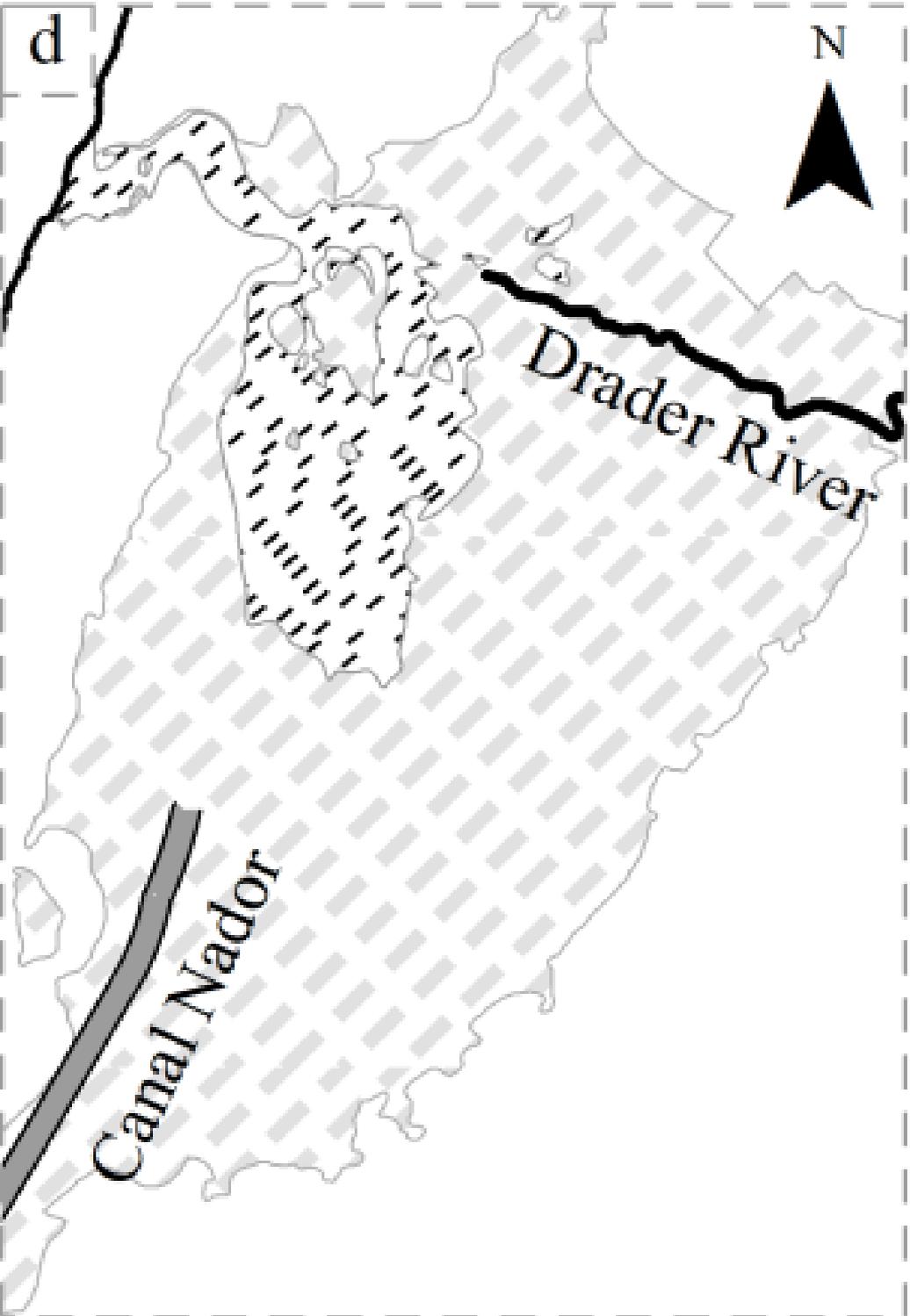
## Legend



Coastal wetlands



Water shape from 2003



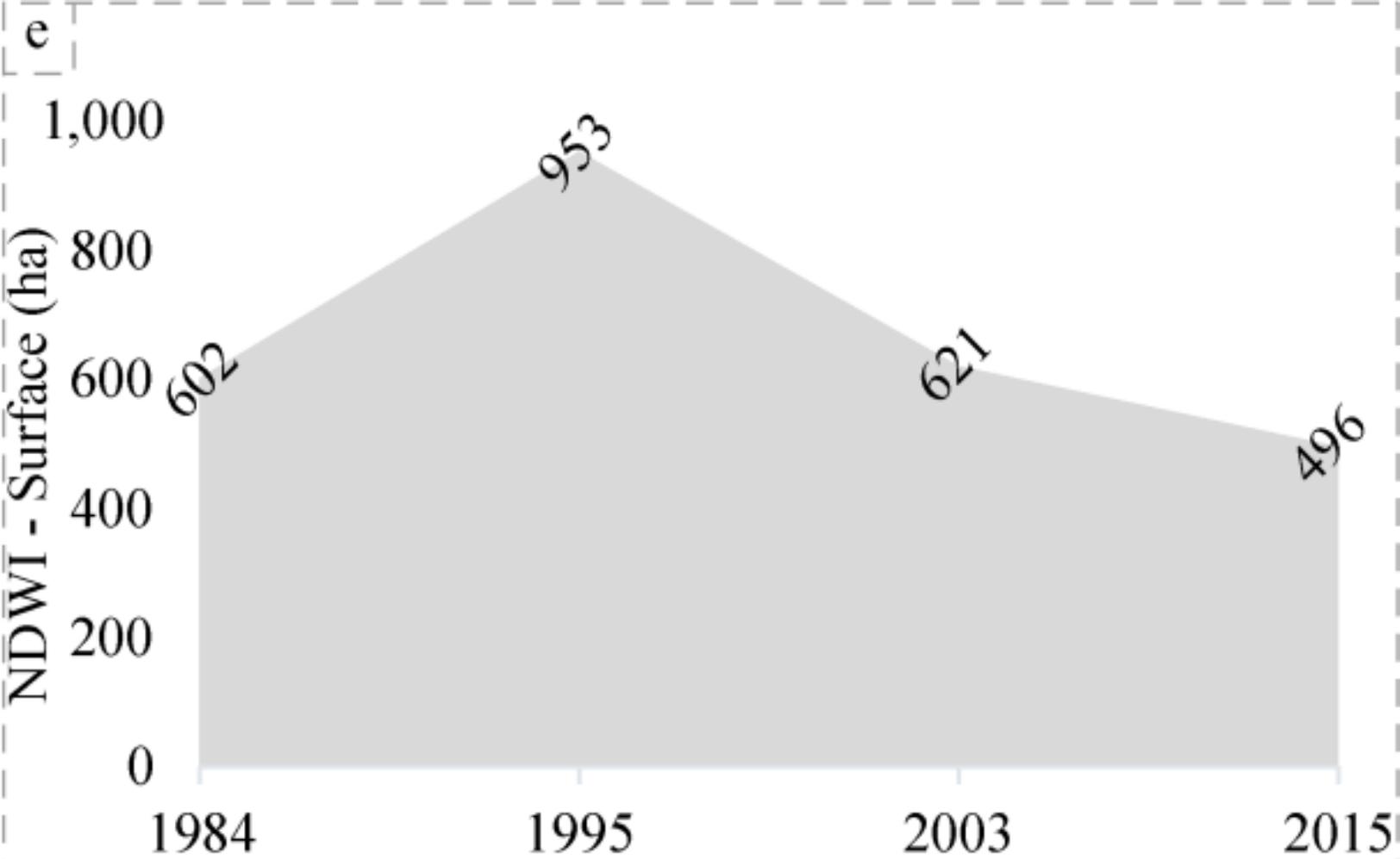
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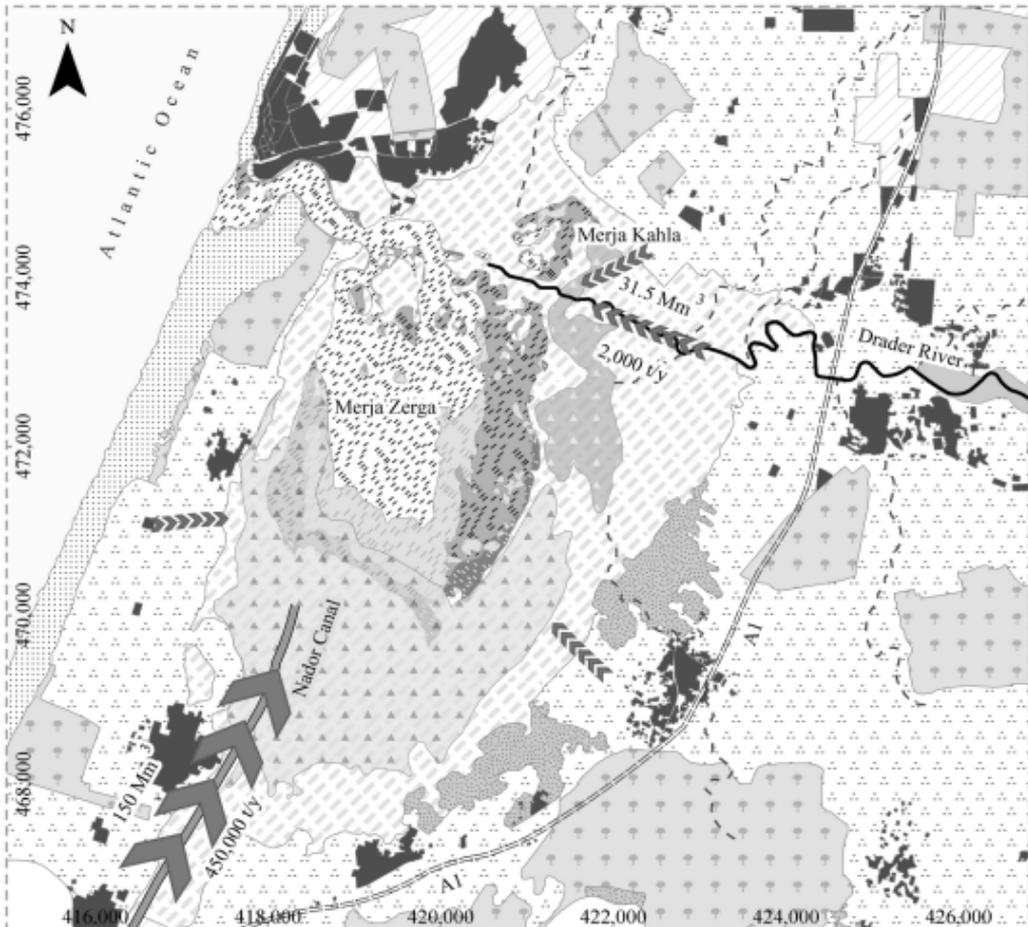


Coastal wetlands



Water shape from 2015





Legend

Sediment load & water flow

Motorway

Hydrography

Canal Nador

Drader River

Drader's tributaries

Land use

Urban fabric

Arable land

Permanently irrigated land

Permanent crops

Pastures

Water shape

2015

2003

Deltaic cores

1995

1984

Drader - 1.5 km<sup>2</sup>

Nador - 9.8 km<sup>2</sup>

Forests

Scrub and/or herbaceous vegetation associations

Beaches, dunes, sands

Coastal wetlands

Marine waters

1:75,000

0 1/2 1 2 3 km

Lambert conformal conic, zone 1  
Land use nomenclature: Corine land cover