

RESERVOIRS SILTING IN MOROCCO

BY D. LOUDYI, M. CHAGDALI, S. BELMATRIK AND K. EL KADI ABDERREZZAK

The Kingdom of Morocco is an arid country that relies heavily on water supplied by reservoirs (Figure 1). Long periods of drought, spreading over several years, are common. In the 1960's Morocco launched a vast dam building program to help solve the issues of water scarcity and rainfall variability which affected thousands of farmers and the agricultural based economy. Morocco now counts 140 large dams (meeting the ICOLD definition) with an overall capacity of about 17,600 million cubic meters (Mm³), 13 hydraulic water transfer structures and more than 100 small dams and hill reservoirs. The

main objective of reservoirs is to secure primarily domestic water supply for large urban centers, to store water for irrigation, to mitigate flood risk and finally to generate hydropower. Demand for domestic and industrial water supply is increasing at a rate of 8% per year. Reservoirs supply 66% (as of 2016) of the water demand (80% in 2020)^[1]. About 1,500,000 ha are irrigated. The annual production of hydropower is 2,527 GWh (10% of the total production), out of a total potential capacity estimated at 5,100 GWh.

Silting of Moroccan dams: facts

The latest monthly monitoring surveys for Moroccan reservoirs showed that, at the end of June 2018, the storage rate of the 55 largest reservoirs was 66% against 50% at the same period in 2017 and 45% in 2016. These fluctuations are due to the variability of rainfall and temperature, but also to the accumulated sediment in the reservoirs. The silting phenomenon has caused a loss of nearly 10% of the total storage capacity of reservoirs, which represents a volume of 1,740 Mm³. Reservoir sedimentation translates into a storage capacity loss of nearly 75 Mm³ per year according to the Moroccan State Department in charge of water, which is equivalent to losing the average storage space of one reservoir every year. The total storage capacity loss may reach 150 Mm³/year in the near future if any mitigating measures are not undertaken, depriving about 15,000 ha of agricultural land of irrigation^[2].

The rate of siltation varies between 0.03 Mm³/year in Dkhila reservoir to 14.3 Mm³/year in Al Wahda reservoir (Table 1). It was noted that for most of Moroccan dams (older than 30 years) the dead storage has been already filled or will be in very near future^[3]. The accelerated pace of water development requires a thorough knowledge of erosion, sediment transport and siltation of dam and hill reservoirs. These natural phenomena, which depend on climatic conditions, landform and vegetation cover, are accelerated and intensified by human activities such as land use, cultural practices, grazing and deforestation.

Most Moroccan basins are characterized by a strong erosion rate (→ 2,000 t/km²/year, a peak value of 5,900 t/km²/year in the Nekor basin)^[4,5]. Among the nine river basins of Morocco (Figures 2 to 5), the annual specific degradation indices evaluated at the level of different watersheds show that the country has seven geomorphological regions whose erodibility decreases from north to south. Dams built in the Moulouya basin (North of Morocco) are in a critical situation because of the siltation losing on average 39% of reservoirs' storage capacity. They are followed by reservoirs in Tensift basin, Souss-Massa Draa basin and Loukkos basin.

Figure 1. Map of Morocco and general information^[1]

Population: 34 million (60% urban) - 2014's census
 Area: 710,850 km²
 - Desert 50%
 - Forest 12%
 - Agriculture land 12% (84% rain fed, 16% irrigated)
 Coastline: Atlantic (3,000 km), Mediterranean (500 km)
 Economy: Agriculture, Mining, Tourism, Industry

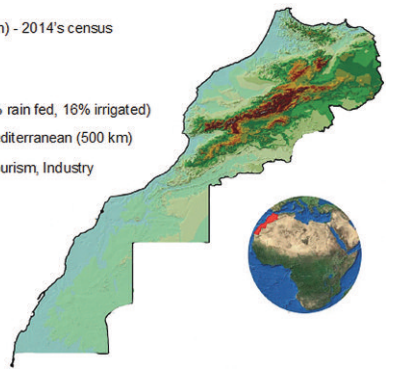


Table 1 Silting rates in a selection of Moroccan reservoirs^[3]

Dam	Basin	Service year	Initial capacity (Mm ³)	Total sedimentation volume (Mm ³)	Silting rate (Mm ³ /year)	Lost storage capacity (%)
Oued El Malleh	Bouregrag-Chaouia	1931	18	14.9	0.2	83%
Sidi Driss	Oum Er Rbia	1984	7	5.5	0.35	78%
Al Khattabi	Loukkos	1981	43.3	31.7	1.1	73%
Mohamed V	Moulouya	1967	725.8	486.2	11.5	67%
Dkhila	Souss Massa Draa	1986	0.7	0.46	0.03	67%
Allal Al Fassi	Sebou	1990	81.5	48.5	2.4	59%
Nakhla	Loukkos	1961	9	4.8	0.1	53%
Lalla Takerkoust	Tensift	1979	78.7	26.1	0.8	33%
Ibn Battouta	Loukkos	1977	43.6	14.5	0.4	33%
El Kansera	Sebou	1966	294.4	77.9	1.8	26%
Aoulouz	Souss Massa Draa	1991	110	21.0	1.1	19%
Hassan Eddakhil	Ziz	1971	380	69.7	1.7	18%
Bin El Ouidane	Oum Er Rbia	1953	1,484	292.0	5.0	18%
Sidi Mohamed Ben Abdellah (after elevation)	Bouregrag-Chaouia	1974 (2007)	508.6 (974.8)	76.9 (55.3)	2.2 (9.5)	15% (6%)
Youssef Ben Tachfine	Souss Massa Draa	1972	320	21.1	0.6	7%
Al Wahda	Sebou	1996	3,730	208.2	14.3	6%
Al Massira	Oum Er Rbia	1979	2,785	87.1	2.3	3%

Figure 2. Map showing the nine river basins and main rivers in Morocco. Red circles: cities where basin agencies are located.

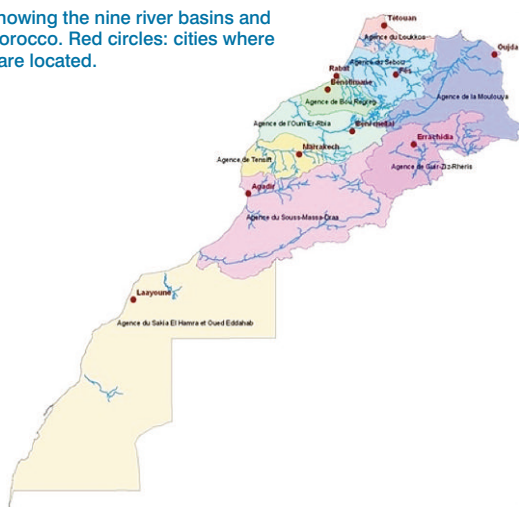


Figure 7. National management program for the afforestation of primary twenty-two watersheds of large dams^[11]

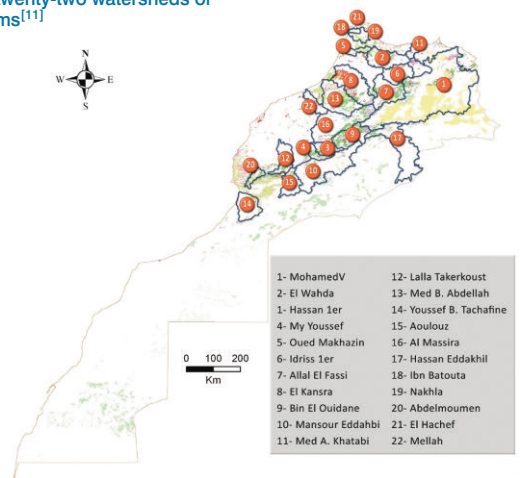


Figure 3. Dkhila dam (service year: 1986, height: 37 m, initial reservoir capacity: 0.7 Mm³, sedimentation rate: 0.03 Mm³/per year), Issen River, Souss Massa Draa basin (Google Earth)



Figure 4. Al Massira dam (service year: 1979, height: 82 m, initial reservoir capacity: 2,785 Mm³, sedimentation rate: 2.3 Mm³/year), Oum Rbia River, Oum Rbia basin

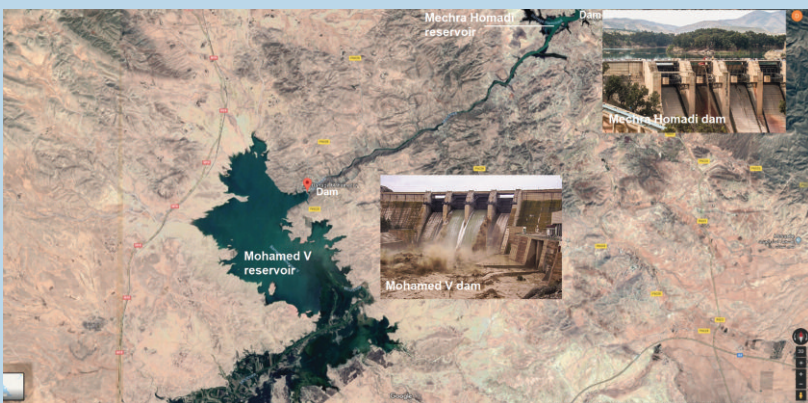


Figure 6. Mohamed V dam (service year: 1967, height: 64 m, initial reservoir capacity: 728.5 Mm³, sedimentation rate: 11.5 M³/year) and, downstream, the Mechra Homadi dam (service year: 1955, height: 57 m, initial reservoir capacity: 42 Mm³, sedimentation rate: 1 Mm³/year), Moulouya River, Moulouya basin (adapted from Google earth)

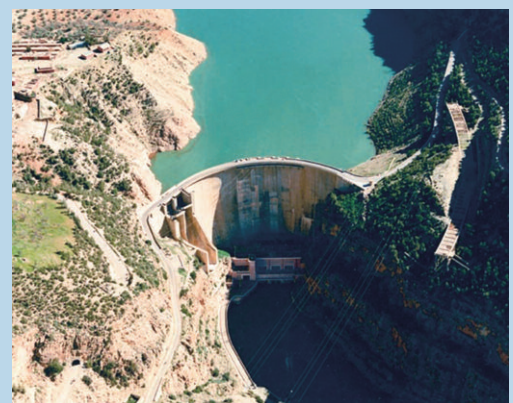


Figure 5. Bin El Ouidane dam (service year: 1953, height: 133 m, initial reservoir capacity: 1,484 Mm³, sedimentation rate: 5 Mm³/year), Oum Er Rbia River, Oum Er Rbia basin

The situation of reservoirs in the North and Rif's mountains is very serious due to the high level of erosion and the hilly slopes. One such case is the Oued El Malleh dam, constructed in 1931 and now almost completely silted up. In the Oum Er Rbia basin, Sidi Said Maâchou dam, the oldest modern dam in Morocco (completed in 1929) is in a similar situation. This dam has lost its storage function to become exclusively a compensation dam for the turbines of Daourat plant which supplies drinking water to the

western part of Casablanca, the industrial hub and economical capital of Morocco. Dkhila (Souss Massa basin) and Sidi Driss (Oum Er Rbia basin) dams are also in the same situation. In the absence of immediate interventions, Al Khattabi (Loukkos basin), Allal Al Fassi (Sebou basin) and Mohamed V (Moulouya basin) reservoirs would be completely silted up by 2024, 2027 and 2032, respectively.

Solutions and mitigating measures

Eighty-eight (88) large dams (64% of the total number of dams) are now more than 20 years old^[6]. Given that the economic life cycle of a dam in Morocco is 50 years, fourteen major hydraulic structures have exceeded their lifetime. The situation is critical, which explains the launch of new dam projects to replace "end of life" ones. The Moroccan State Department in charge of water aims to build 59 dams by 2030. Since 2015, the construction of 35 dams of

different sizes, with an overall storage capacity of 3,064 Mm³, has been launched. These new dams will help ensure continued water supply for domestic and industrial uses in remote areas which suffer from water shortage, increase the irrigated area (the Green Morocco Plan has a goal of reaching 70% of irrigated arable lands by 2030), mitigate the flood risk, and produce hydropower energy.

With the support of World Bank, a RESCON team (see the paper by Efthymiou *et al.* in this issue describing the RESCON tool) worked in 2001 with Moroccan engineers and managers to determine the needs for mitigation measures at several reservoirs. The RESCON approach was applied to ten existing reservoirs with the objective of identifying optimal sediment management strategies that are both technically and economically feasible^[7]. The selected dams ranged from relatively small, with a reservoir capacity of 5.6 Mm³, to large, with a reservoir capacity of 1,500 Mm³. An interesting outcome of this work was the sensitivity of the RESCON tool results to the assumed unit cost of dredging (cost provided by Moroccan engineers vs cost calculated by the RESCON program). For instance, when the default dredging costs calculated by the RESCON program (which were higher than US\$ 4/m³), the optimal sustainable management strategy shifted from dredging to flushing for three of the reservoirs. More details are given by Palmieri *et al.*^[7].

At present, solutions are being put in place, aiming to reduce the negative impact of sedimentation on reservoir storage capacity. Apart from the construction of new dams, the Department of Water, in charge of the supervision of dams, uses either technical or natural methods to mitigate against the silting process. The elevation of hydraulic structures is carried out when technically feasible. This solution was put in place for four dams: Lalla Takerkoust, El Kansera, Oued El Malleh and Sidi Mohamed Ben Abdellah. In addition to the sizing of dead storage, flushing operations are carried out during flood periods to remove part of the sediment through the bottom outlets. However, flushing operations remain limited because of the water scarcity and growing needs for water supply and irrigation. Density current venting under low flow discharges is applied to only few dams which are equipped with bottom outlets (e.g. Ibn Battouta, Youssef Ben Tachfine, Aoulouz, Hassan Eddakhil)^[8]. Building of upstream check structures (weirs and small dams) has been initiated since 1980 to help to trap sediments upstream of large dam



Dalila Loudyi is Professor in hydrology and hydraulics at the Department of Water and Environmental Engineering at the Faculty of Sciences and Technics of Hassan II University of Casablanca. She is leading a research team working on water resources

management, numerical modelling, urban water and climate change. She was selected by the Moroccan Ministry of Higher Education as a National Contact Point in environment, in 2010, to promote the use of the Seventh European Framework Program (FP7) for research and development at a national level. She is a member of the Leadership Team of IAHR MENA Committee.



Mohamed Chagdali is Professor in physics and fluid dynamics at Ben Msik Faculty of Sciences of Hassan II University, Casablanca, Morocco. His research activities cover fluid dynamics and sediment transport.



Salah Bel Matrik is a Chief Engineer and General Secretary of the river basin Agency of Bouregreg and Chaouia, Morocco. He is in charge of water resources planning and management. He has over thirty years of experience in legal, administrative and technical aspects of the public hydraulic domain.



Kamal El kadi Abderrezak is Expert at the National Laboratory for Hydraulics and Environment of the Research and Development (R&D) division of Electricité de France (EDF). His sphere of research includes flood propagation, dike breaching and sediment transport in open channels, with focus on processes and numerical modeling. He also teaches fluid mechanics, open channel flows and sediment transport at Ecole Polytechnique, Polytech Nice Sophia, and ESTP. He is member of the IAHR Europe Regional Division.

reservoirs. Sediment dredging is another effective solution for silting control. However, its cost remains very high and water and agroforestry operators do not reuse the extracted sediments. The removal of 1m³ of sediment now costs 50 Moroccan Dirham (MAD), approximately US\$ 5. This solution was implemented at the Sid Driss dam and the Mechra Homadi dam (Figure 6). The latter was constructed in 1955 with an initial storage capacity of 42 Mm³ that has been drastically reduced over time (silting rate of 1 Mm³/year). The dam reservoir was in a critical situation by the end of 1990 (storage capacity of about 10 Mm³), so that dredging operations were

conducted in 1994 (removing 3 Mm³) and between 2003 and 2009 (removing 5.4 Mm³), costing in total 120 million MAD (US\$ 12 million)^[7]. The dam was also equipped with bottom outlets.

The Department of Water is in favor of afforestation, which remains an ecological method that both protects soils against erosion and preserves the efficiency of hydraulic infrastructures. A National Watershed Management Plan (PNABV)^[9] was adopted in 1996 as a strategic framework setting priorities for interventions and proposing approaches as well as financial and institutional mechanisms for implementing erosion control for twenty-two high-priority watersheds. Morocco aims to reforest catchments covering 1,500,000 ha at a rate of 75,000 ha/year. Since 1996, 650,000 ha have been reforested in eighteen watersheds (Figure 7). Morocco has also increased the rate of bathymetric survey of reservoirs by a Differential Global Positioning System (DGPS) system. Twenty reservoirs are surveyed per year compared with only eight reservoirs per year in the period from 1991 to 1998. Other methods to measure sedimentation include sediment monitoring at gaging stations (bed load and suspended load), aerial surveys, radioisotope methods and the use of degradation prediction relationships for upstream basins^[10]. These measures are undertaken by different departments according to their legal jurisdiction and location. The main stakeholders involved in silting control of reservoirs are: the State Secretary in charge of Water, the High Commissioner for Waters, Forests and Combating Desertification, the Hydraulic Basin Agencies and the National Office for Electricity and Drinking Water ONEE - Water branch. ■

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