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**Reservoir Management in Mediterranean Climates through the European Water  
Framework Directive**

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Abstract

While the problem of sedimentation slowly filling dams and reservoirs is innate to the structures, it is especially significant in Mediterranean climates that rely on reservoir storage to mitigate out-of-phase water availability and demand. Reservoirs and their impounding structures have significant impacts on in-stream and riparian ecosystems. Several preventative and mitigation measures have been designed by engineers to limit sediment accumulation and the ecological impacts of reservoirs. Dam removal has been documented to have significant environmental benefits for restoration of aquatic ecosystems and native fisheries but may also lead to eroded floodplains, impaired downstream habitat and loss of flood control capacity. The European Water Framework Directive (WFD) establishes goals and guidance designating “heavily modified water bodies” and achieving “good ecological potential,” but definitions of these terms are not clearly defined. In addition, sediment management is not explicitly addressed in WFD guidance, thus contributing to limited guidance on how reservoir sedimentation should be managed in Mediterranean climates. As a European Union member state and a Mediterranean-climate country, surface water and reservoir management in Portugal is undergoing several changes through actions to achieve WFD goals. We examine how WFD management guidance for reservoirs and their ecological status is currently being considered throughout Europe and in Portugal specifically.

Final

## Introduction

Dams and reservoirs are constructed on fluvial systems, typically created as impoundments to hold water behind a structure for future use, or for hydroelectric power generation (Palmieri et al, 2001). Fluvial systems convey water and sediment from surrounding uplands. When a fluvial system is impounded by a dam, upstream water slows down and sediment tends to deposit in a reservoir (Figure 1) (Morris & Fan, 1998). Common engineering practice has been to design reservoirs to allow them to fill with sediment slowly, thus giving a finite lifetime to the reservoirs due to loss of capacity from siltation (Palmieri et al, 2001).

Reservoir sedimentation is an increasing problem globally, especially in Mediterranean climates which rely on reservoir storage and experience extreme climatic events, such as floods, that can contribute significant amounts of sediment into reservoirs (Gasith & Resh, 1999). Reservoirs and their associated impoundments impact in-stream and riparian ecology (Gasith & Resh, 1999). We discuss efforts to mitigate these impacts in Europe as guided by the Water Framework Directive (WFD), and we will examine how Portugal has followed this guidance thus far.

## Reservoir Use in Mediterranean Climates

### *Mediterranean Climate Characteristics*

Mediterranean climates are typically distinguished by their predictable contrasting seasons – hot, dry summer followed by cold, wet winters (Figure 2) (Conacher & Sala, 1998). Precipitation variability between years results in periods of drought and torrential rains (Conacher & Sala, 1998). These infrequent, episodic events can significantly

## Final

change river form and ecology (Hecht, 1994 in Kondolf & Batalla, 2005). Mediterranean climates, with their abundant sunshine and mild winters, are historically favorable for human settlement and agricultural production (Gasith & Resh, 1998). Several schemes to store seasonally available water have been developed throughout civilization, with the most common in the 20<sup>th</sup> century being reservoir storage (Conacher & Sala, 1998).

The coastal location of Mediterranean climates contributes to the marine origin of their underlying lithology, and can contribute to weak soil structure (Milliman & Syvitksi, 1992 in Kondolf & Batalla, 2005). Mediterranean landscapes also tend to be geologically active, producing steep relief (Milliman & Syvitksi, 1992 in Kondolf & Batalla, 2005). The combination of this relief and climate results in high erosivity of soils, and subsequent high rates of surface runoff and a greater likelihood of debris flows (Kondolf & Batalla, 2005). Vegetation is adapted to drought, fire, and nutrient-poor soils, which leads to thin ground cover and further contributes to high soil runoff rates (Langbein & Schumm, 1958 in Kondolf & Batalla, 2005). These climatic features all contribute to high rates of reservoir sedimentation in Mediterranean climates (Conacher & Sala, 1998).

### *Reservoir Use*

Reservoir storage is proportionally greater in Mediterranean climates than in other climatic regimes (Thoms & Sheldon, 2000 in Kondolf & Batalla, 2005). Reservoir storage is necessary to mitigate the out-of-phase water availability and demand (Kondolf & Batalla, 2005). Throughout the Mediterranean region, dams are built to ensure freshwater resources are available during seasons of demand.

Final

Intense agricultural production found in Mediterranean climates requires freshwater for irrigation, making rivers particularly susceptible to flow regulation through water diversions and reservoir construction (Gasith & Resh, 1999). In Southern Europe, 58% of water usage is devoted to irrigation, a condition exacerbated throughout the 1990's by subsidies from Common Agricultural Policies (CAP) that led to more land being devoted to agriculture and thus increased irrigation (Figure 3) (Molden, 2006; Scardigno, 2003). The 2003 CAP Reform decoupled subsidies from production and dictated environmental best management practices through cross compliance in part to address this strain on water resources (Scardigno, 2003).

Over 1,450 reservoirs in Europe are used for hydroelectricity production. In France about 13 % of the national electricity production is operated by hydropower, compared to 16% in Spain and 35 % in Portugal (Table 1) (Lehner et al 2001). As Mediterranean climates are more prone to drought, there is significant variation in these numbers from year to year. For example, in Spain the 2005 drought caused a 39.3% reduction in hydropower from 2004 levels (European Environment Agency, 2009). Drought also has a negative impact on conventional power plants that require water for cooling – an issue of particular concern for France which relies heavily on nuclear power (European Environment Agency, 2009). Both the frequency and degree of droughts are expected to increase with climate change. Reservoirs can also mitigate the impacts of seasonal floods downstream of impoundments by storing water upstream, thus reducing flood magnitudes (Gasith & Resh, 1999; Kondolf & Batalla, 2005). Thus in wetter regions, such as the French Atlantic, dams are also built for flood control purposes (European Environment Agency, 2009).

Final

## Environmental Impacts of Reservoirs

### *Hydromorphological and Ecological Impacts*

Reservoirs prevent the transport of sediment as well as water to downstream reaches of a river. The gradual accumulation of sediment in a reservoir tends to be ignored because rivers transport more water than sediment, thus sediment infilling occurs at an imperceptible rate. While water can be easily removed from a reservoir, sediment cannot. Impacts from impoundment construction are well documented, but sedimentation impacts are often overlooked. However, as more reservoirs age, these impacts become more noticeable (Morris & Fan, 1998).

Sediment deposition can compromise the safety of the impoundment structure, from spillway overtopping or cracking under increased pressure from the weight of the sediment. Delta deposition where rivers enter reservoirs can also deplete storage capacity, and cause channel aggradation extending upstream from the reservoir (Figure 4). Vegetation growth in these deposits can increase upstream flood risk, from increased hydraulic roughness and sediment entrapment. Landslides and debris flows can fill reservoirs to near capacity (Figure 5) or in extreme cases cause catastrophic floods that can break a dam. Changes in sediment loading in a reservoir can affect species composition, and if not managed, sedimentation can cause open-water habitat to turn into upland area above the water surface (Morris & Fan, 1998).

Sediment deposition can also accelerate eutrophication of reservoirs through loss of water storage capacity and limiting flow, which subsequently limits dissolved oxygen content of the water column. Where reservoirs are used for irrigation storage for the surrounding agricultural landscape, runoff from these farms may have high nutrient

Final

content. The combination of these factors leads to eutrophic reservoir conditions of increased plant and algal growth in reservoirs (Environmental Health and Safety Online, 2009).

Reservoirs have significant impacts on downstream river reaches (Figure 6) (Petts, 1984). The presence of a migration barrier to anadromous fish often prevents access to upstream spawning habitat (Morris & Fan, 1998). Downstream morphology is often impacted by the loss of sediment transport from upstream (Morris & Fan, 1998). Water that is not transporting sediment will tend to erode the streambed and banks, resulting in increased bed armoring which can compromise ecological habitat and decrease access to spawning grounds (Kondolf & Batalla, 2005). Channel incision can also lower groundwater tables in riparian areas, and in coastal areas this can lead to saltwater intrusion in the groundwater, lending these aquifers useless (Morris & Fan, 1998; European Commission, 2007). Reservoirs prevent transport of organic material, which is a food source for the downstream ecosystem (Gasith & Resh, 1999). Furthermore, reduced sediment discharge contributes to changes in coastal morphology, notably shoreline recession and delta subsidence (Morris & Fan, 1998). Release of polluted sediments from reservoirs can cause channel aggradation and threaten downstream ecology, at times resulting in fish kills (Wohl & Cenderelli, 2000). Loss of downstream pool habitat from reservoir sediment releases can cause long-term loss of fish habitat (Wohl & Cenderelli, 2000).

#### *Reservoir Sediment Management Techniques*

Preventative measures to limit sediment accumulation in reservoirs can be grouped into three categories (Figure 7). The first set of methods is to prevent sediment

Final

from entering the reservoir, such as by placing the reservoir in a catchment with a low sediment yield, or controlling land use practices in the catchment to reduce sediment yield (Annandale, 1987; Palmieri et al, 2001). Water diversions can be constructed to pass floods transporting large amounts of sediment around the reservoir controlled by flood control gates and diversion canals (Annandale, 1987). Reservoirs can also be constructed off-stream of the reservoir (Annandale, 1987).

Sediment discharged into a reservoir can be controlled if sediment carrying capacity of the stream flowing through the reservoir is close to the carrying capacity of the unmodified river (Annandale, 1987; Palmieri et al, 2001). This is difficult to achieve, but can be accomplished during floods using gates in dams or maintaining low reservoir levels during flood periods (Annandale, 1987; Palmieri et al, 2001).

Once sediment has been deposited in a reservoir, it can be removed by dredging or flushing sediment from the reservoir. Dredging is often very expensive and locations for dredge spoil storage are limited. Flushing, or transporting deposited sediment through bottom outlets by increasing flow velocity, can increase reservoir capacity but has limited reliability in semi-arid environments where reservoir capacity can significantly exceed mean annual runoff (Palmieri et al, 2001; Annandale, 1987).

If sediment management is deemed too costly or not feasible for other reasons, retiring reservoirs and their impoundments are proposed alternatives. Dam removal has been documented to have significant environmental benefits for restoration of aquatic ecosystems (Pejchar & Warner, 2001). Ecosystem response to restored hydrologic regime and geomorphic complexity following dam removal has been extensively documented



Final

(Collier et al, 1996). Benefits of dam removal include improved habitat connectivity and water quality (Pejchar & Warner, 2001).

However, impoundment removal can have detrimental impacts on rivers as well. Dam removal can leave terraced sediment deposits in the former reservoir pool susceptible to flood erosion and lateral incision due to the altered longitudinal bed profile created by the reservoir (Collier et al, 1996). Release of reservoir sediment as part of dam removal can create easily eroded floodplains, and impair downstream habitat due to increased pollution or smothering of downstream spawning gravels (Pejchar & Warner, 2001; Palmieri et al, 2001). Flood control provided by the reservoir may be lost following retirement if sufficient mitigation procedures are not put in place (Pejchar & Warner, 2001).

### Reservoir Management through the Water Framework Directive

#### *European Water Framework Directive*

In 2001, the European Union (EU) implemented the Water Framework Directive (WFD) as a new management strategy for achieving “good” ecological and chemical quality status for Europe’s water bodies. The WFD sets goals and processes for attaining this status through basin-level management and implementation of pollution-control measures. Reservoirs are characterized as “artificial/modified” water bodies, meaning they were created from human physical modification for economic activities and thus do not have to be restored to the same level as unmodified water bodies (Figure 8) (Kallis & Butler, 2001).

#### *Heavily Modified Water Bodies (HMWB)/Artificial Water Bodies (AWB)*

Final

According to the Water Framework Directive, in the process of drafting River Basin Management Plans member states may designate surface water bodies as *Heavily Modified* “where they have been physically altered so that they are substantially changed in character” or *Artificial* if they have been “created by human activity” (Figure 9) (European Environment Agency, 2007) The Guidance Document for HMWB and AWB further clarifies:

- “physical alterations mean changes to the hydromorphological characteristics of a water body, and
- a water body that is substantially changed in character is one that has been subject to major long-term changes in its hydromorphology as a consequence of maintaining the specified uses listed in WFD Article 4(3).”

Instead of "good ecological status", the environmental objective for HMWB and for AWB is good ecological potential (GEP), which has to be achieved by 2015. The designation is not necessarily an opportunity to avoid achieving demanding ecological and chemical objectives, since GEP is an ecological objective which may often, in itself, be challenging to achieve (CIS, 2003). MEP biological conditions are derived from the closest natural comparable water type – in the case of reservoirs, a natural lake. If a comparable natural lake is not found, an AWB or HMWB must be found “of the same type” with consideration for the impacts caused by hydromorphological changes of the reservoir in question. “Although the working groups implementing the WFD have tried to give guidance on these definitions...at present little has advanced in terms of understanding what does GEP mean, especially in an ecological context” (CIS, 2006).

Final

More recently, further attempts have been made to define MEP and GEP based on two approaches – one based on biological quality elements, the other based on identification of mitigation measures (known as “The Alternative Prague Approach”) (Figure 10) (Kampa & Lasser, 2009). GEP based on biological quality elements is defined as “a state in which the ecological potential of a water body is falling only slightly short of the maximum it could achieve without significant adverse effects on the wider environment or on the relevant water use or uses,” lacking an assessment of costs of mitigation measures (Kampa & Lasser, 2009). In contrast, “The Alternative Prague Approach” bases the GEP definition on “the biological values that are expected from implementing the identified mitigation measures” that are predicted to have the most significant ecological improvement (Kampa & Lasser, 2009). The primary difference between these approaches is that “The Alternative Prague Approach” defines GEP directly based on mitigation measures, whereas the biological quality elements approach indirectly defines GEP from predictive modeling (Kampa & Lesser, 2009). While these give a framework and alternative approaches for measuring the MEP/GEP, there is little guidance on what actually has to be done by scientists taking samples for the biological elements. Hence, differences in interpretation, methods and approaches are common across different European countries (Borja & Elliott, 2007).

#### *Mediterranean Lakes Reference Conditions*

Mediterranean reservoirs were characterized by the European Commission Joint Research Center Lake Mediterranean Geographical Intercalibration Group to establish reference conditions for lakes and reservoirs. This was done through classification of reservoir types based on their climate and lithology, and establishment of a water quality

Final

characterization protocol using phytoplankton as an indicator of degree of eutrophication in reservoirs (Table 2). The protocol used also called for collection of climate, physio-chemical and hydromorphologic data. The report mentions that additional reference sites and years of data are needed to establish statistically significant reference conditions, and that other biological indicator species such as fish and zoobenthos should be incorporated in the protocol (GIG, 2007).

Most of the reservoirs used to establish intercalibrated reference conditions among Mediterranean countries are used for irrigation and water supply, although most reservoirs in the Mediterranean region are used for hydropower generation. Irrigation and water supply reservoirs have a higher residence time than reservoirs used for hydropower generation, and thus different ecological composition. Hydromorphologic reference condition status was derived from measured chlorophyll-a concentration and Secchi disk measurements in reservoirs. In Mediterranean reservoirs, interannual variability in precipitation can have significant impacts on the available storage capacity of a reservoir. Concentrations of chlorophyll-a were proposed to scale the percent of the storage volume available in a reservoir depending on the eco-type the reservoir is in. Water retention time, maximum depth or annual rainfall, were also proposed as factors on a “matching scale” for biological indicators. A single year (2005) of data was used to determine reference conditions, thus impacts of fluctuating water levels and discharge on species composition were not captured in the characterization (GIG, 2007).

#### *WFD Mitigation Proposals*

While there are no obligatory mitigation measures that member states must implement in order to attain GEP status (even if implementing the Prague approach),

Final

there are several mitigation checklists (generic, specific to water body and specific to type of modification) that are available for reference. Several countries have even consulted water users in applying the Prague method for the establishment of GEP. (Kampa & Laaser, 2009).

Mitigation measures referred to in the definition of MEP hydromorphological conditions are limited to those that would not have a significant adverse effect on the wider environment or the use or uses that are dependent on the modified characteristics (Good Practice, 2006). This suggests that while many mitigation measures may be considered (see Table 3) those most likely to be implemented reflect “the proportionality of costs, financing and the effectiveness of measures as well as the application of exemptions to the HMWB objectives” (Kampa & Laaser, 2009). Under this definition, dam removal is not a possible mitigation measure because of the effect removal would have on the use of the modified characteristics.

#### *Draft River Basin Management Plans*

As part of the WFD process, the competent authorities for each river basin must produce a River Basin Management Plan (RBMP). The timetable for WFD implementation calls for draft RBMPs to be available for comment by 2008 and final RBMPs to be completed by the end of 2009. A significant number of countries are behind schedule, including several Mediterranean climate countries. We reviewed available draft RBMPs from France and Spain, the only Mediterranean countries with available completed draft RBMPs. Of the one available draft RBMP from Spain (Balearas) and six available from France (Rhône Méditerranéen, Loire Bretagne, Rhin Meuse, Seine Normandie, Artois Picardie, & Adour Garonne), we found little mention of

Final

sediment management and no mention of reservoir infill. The draft RBMP for the international river basin (including France) for the River Meuse France (technically not in a Mediterranean climate) does not directly address sediment management. However, the management of sluices, barrages, hydropower facilities and shipping are mentioned as “important management tasks” which suggests indirectly that sediment management will be addressed. The incomplete draft RBMP for the River Ebro in Spain only addresses sediment related to polluted waste despite well documented “sedimentary disequilibrium in the catchment [and] sediment quantity issues (e.g. reservoir siltation, sediment deficit and effects on river coastal systems)” (SedNet, 2009)

The lack of discourse on sediment management in WFD guidance inspired a 2006 roundtable discussion on sediment issues (hosted by SedNet) in which representatives acknowledged that “European legislation insufficiently deals with sediments” and that “sediment needs to be considered as a part of a functioning, healthy ecosystem” (SedNet, 2006). A second SedNet-hosted discussion entitled “Implementation of sediment management issues into the first RBM Plans” is planned for October 2009.

### Portuguese Reservoirs – A Closer Look

#### *Characteristics of Portuguese Reservoirs*

Reservoirs are considered to be an integral part of the Portuguese landscape because of the benefits they provide humans, such as supply, irrigation, hydroelectric power and recreation (Cabecinha, 2009). These structures are not new to the Portuguese landscape as commonly reported (Cabecinha, 2009). Early Portuguese reservoirs, such as the Monto-Novo Dam built by the Romans, were equipped with sediment flushing outlets

Final

sufficient in size to maintain reservoir storage capacity (Schnitter, 1994 in Chanson, 1998).

However, there has been increased construction of reservoirs in the second half of the 20<sup>th</sup> century as Portugal's economy has industrialized (Gomes, 2008). The main use of Portugal's 236 reservoirs is for hydropower, with navigation, irrigation, water supply, and recreation as secondary uses (Table 4) (Figure 12) (SNIRH, 2009; Cabecinha, 2009). Of all electricity generated in Portugal, 35% is from hydropower (Figure 13) (Gomes, 2008). In 2005, hydropower production was reported to be 54% lower than the average and 37% lower than in 2004, reflecting increasingly common drought conditions in the region and increased water allocation in Spain for agricultural purposes (Isandahl, 2006). Portugal has 215 designated heavily modified water bodies (Table 5) (Afonso, 2009). Of these, 98 are reservoirs, and 101 are river reaches downstream of reservoirs (Afonso, 2009). Water bodies included in the "Lakes" category are reservoirs, as Portugal has no naturally occurring inland lakes (Afonso, 2009).

WFD reference conditions for Portuguese Reservoirs were determined using sites with less than 20% of the catchment in agricultural production and the rest in vegetated coverage (GIG, 2007). Studied reservoirs for reference condition characterization are mainly used for hydropower, whereas intercalibrated reference conditions were determined using data from reservoirs used for irrigation and water supply, which experience a different manipulated hydrologic regime than hydropower reservoirs. Only a single year of data was collected, thus the effects of multi-year fluctuating water levels and discharge were not captured in the reference condition (Cabecinha, 2009).

Final

*Environmental Impacts in Mediterranean Climates and Portugal*

Reservoirs manipulate hydrology and seasonal flow variability, which many aquatic and riparian organisms have adapted to in Mediterranean climates such as Portugal's. Alterations to this variability can threaten stream ecology (Junk et al, 1989 in Kondolf & Batalla, 2005). Catchments in Mediterranean climates tend to have high sediment yields, and reductions in this sediment supply below reservoirs results in morphologic change greater than those found in humid-climate rivers (Kondolf & Batalla, 2005). Reservoir-induced stable flow regimes alter riverine processes. Impounded rivers in California have demonstrated this phenomenon through vegetation encroachment into the formerly active channel, further narrowing the channel (Kondolf & Wilcock, 1996 in Kondolf & Batalla, 2005). Exotic species that were once not able to survive under flow variability may be able to thrive under a stable flow regime (Kondolf & Batalla, 2005).

Reservoirs in Portugal frequently experience eutrophication due to high nutrient loads entering in surface runoff from the surrounding watershed, and decreased capacity from sedimentation (Matias et al, 2008). This is particularly a problem in southern reservoirs, such as those in the Tejo basin, due to predominantly agricultural land use (Matias et al, 2008). Thus far, characterization and management of reservoirs has focused on mitigation measures to reduce eutrophication (Cabecinha, 2009).

In the Sado River basin in southern Portugal, hydromorphological and ecological impacts of reservoirs were recorded by Kondolf et al (1997). Seven large reservoirs on the Sado River and its tributaries were constructed for irrigation and hydroelectric purposes. These reservoirs reduce annual flood peaks, and thus reduce flood scour.



Final

Analysis of aerial photography and field observations indicated that woody, exotic, riparian vegetation has encroached on the channel in the absence of floods. Reservoir storage has also enabled floodplains to be converted to agriculture (Kondolf et al, 1997).

*Management Application in Portugal*

Pre-WFD implementation, Portugal had little integrated planning for water infrastructure with consideration for conservation, aquatic ecosystems, and human water use (WWF, 2003). In contrast, the transposing of the WFD into law, has led to a coordinated management effort between the Portuguese Ministry of Environment, the Instituto Nacional d Agua (INAG), and the River Basin District Administration Bureau. While draft RBMPs are still unavailable, the Water Institute has suggested that mitigation measures for altered rivers range from fish passages to the restoration of ecological flow regimes (WFD Comparison 2007).

The WFD establishes guidelines for citizen participation in the river basin management process, but it lacks focus on how local people and water-users should be included in the management of reservoirs. Historically, this culture of community participation in resource management has not existed in Portugal. Government officials and scientists have traditionally been the most active in reservoir management because of their greater access to information than the general public. Since WFD implementation, surveying of local residents in some catchments has begun to incorporate their knowledge about local reservoir systems into management planning (Matias et al, 2008).

Final

### Conclusion

By 2015, member states to the Water Framework Directive are obligated to achieve Good Ecological Potential for heavily modified water bodies. However, considering the many key elements of this process that remain unclearly defined, it is hard to know what GEP will look like, much less how it will be accomplished. Simply establishing meaningful reference conditions for heavily modified water bodies has proven challenging given the ambiguous definitions of comparable natural water bodies and the need for multiple years' worth of data collection. Furthermore, the extent to which reference conditions will even play a role in guiding mitigation efforts is largely unknown considering the influence of cost effectiveness in deciding which measures are ultimately implemented. In this context, the lack of consideration for hydromorphological impacts on river ecology from reservoir construction is especially troubling. For Mediterranean countries in particular, sediment management will have to play a much larger role in final RBMPs for the achievement of Good Ecological Potential to have meaning.

Final

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