Journal of Hydrology 533 (2016) 567–580

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A framework model for the dimensioning and allocation of a detention basin system: The case of a flood-prone mountainous watershed

Annalisa Bellu [a], Luís F. Sanches Fernandes [a], Rui M.V. Cortes [a], Fernando A.L. Pacheco [b],*

[a] CITAB-UTAD – Centre for Research and Technology of Agro-Environment and Biological Sciences, University of Trás-os-Montes e Alto Douro, Quinta de Prados, 5001-801 Vila Real, Portugal

[b] CQVR-UTAD – Chemistry Research Centre, University of Trás-os-Montes e Alto Douro, Quinta de Prados, 5001-801 Vila Real, Portugal

ARTICLE INFO

Article history:
Received 19 April 2015
Received in revised form 22 August 2015
Accepted 20 December 2015
Available online 29 December 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of Richard Philip Silberstein, Associate Editor

Keywords:
Flood management
Watershed scale
Detention basin
Peak flow attenuation
Multi-criteria decision analysis
Optimal siting

SUMMARY

A straightforward approach in flood management is the attenuation of peak discharges through an appropriate detention system. In this study, a flexible framework model was developed to optimize the dimensioning and site selection of a flood mitigation system based on detention basins. The general workflow can be summarized by three separate but interrelated modules: (*i*) the hydrologic module, which back tracks the detention basin contributing area based on the application of engineering formulae to historical information on local river floods and associated hydrometric data; (*ii*) the geomorphologic module, implemented in a Geographic Information System, which indicates all the potential locations with adequate contributing area as required for the detention system, by analyzing the flow accumulation within the river basin; and (*iii*) the environmental module, which comprises the implementation of a multi-criteria decision analysis for the selection of best location(s) for the detention basin system, addressing three different objectives: to minimize diffuse pollution; to minimize point-source pollution; to optimize landscape integration (by minimizing the dam height). The framework model was applied to the flood-prone Vez River, which is the main tributary of the Lima River in Northwestern Portugal. Although the expectations as regards diffuse and point-source pollution are optimistic, results show that detention of the largest flood in this river could only be accomplished with one very large dam or a number of decentralized large dams. Decentralizing the detention system with multiple basins installed in various branches of the Vez River did not reduce the mean dam height, because the catchment is located in a region of craggy topography and high annual rainfall. An extensive reforestation of the basin headwaters would increase evapotranspiration reducing runoff. Eventually, this would expand the alternatives for flood mitigation, namely through the construction of sustainable flood detention basins.

1. Introduction

Urban flooding is a dramatic problem worldwide, with tremendous consequences on economy, society and environment. In 2014, severe floods occurred in Europe have caused more than a hundred deaths and billions of Euros of economic loss (Mildenhall et al., 2015). In a reaction to this problem, flood risk assessment has become a central matter for the European Union (Flood Directive; EC, 2007), being reported in a large number of publications (Correia et al., 1998; De Moel et al., 2009; Dráb and Říha, 2010; Evrard et al., 2010; Geilen et al., 2004; Langhammer, 2009; Lastra et al., 2008; Merz et al., 2010; Nedkov and Burkhard, 2012; Nijssen et al., 2009; Santos et al., 2011; Seibert et al., 2014). The current understanding is that flood management, comprising risk assessment and the implementation of mitigation measures, requires coordination at the catchment scale to be effective (Brandolini and Cevasco, 2015; Brandolini et al., 2012; Cevasco et al., 2015; Warner et al., 2013).

Likewise other countries, Portugal deals recurrently with floods. According to Zêzere et al. (2014), the number of disastrous floods occurred in Portugal from 1865 to 2010 was 1621 causing a total of 1012 deaths and a partial of 522 victims due to a single flash-flood event in the Tagus region in 1967. In compliance to the 2007/60/EC Directive (EC, 2007), transposed to the Portuguese Decree-Law 115/2010 (Ministério do Ambiente e do Ordenamento do Território, 2010), the Portuguese Agency for the Environment (APA – Agência Portuguesa do Ambiente) identified 22 flood-prone regions in various hydrographic basins of mainland

---

* Corresponding author. Tel.: +351 259 350 280; fax: +351 259 350 480.
E-mail address: fpacheco@utad.pt (F.A.L. Pacheco).
URL: http://www.utad.pt (F.A.L. Pacheco).

http://dx.doi.org/10.1016/j.jhydrol.2015.12.043
0022-1694/

Portugal. The corresponding cartograms can be accessed from http://sniambportal.apambiente.pt/diretiva60ce2007/. Two of these zones are located in the Lima River basin (Northwest of Portugal), which is the smallest and the wettest of five Portuguese international watersheds and will be used as study area in this work.

A fundamental principle on flood management is the attenuation of peak flows, frequently accomplished by an appropriate detention system like a Flood Retention Basin (FRB). An FRB provides peak flow attenuation by temporarily storing a certain volume of stream water, but the outcome can be attained with an array of very different damming structures. Recently, existing FRBs have been assembled into six types with the purpose to assess their flood-control potential beside other possible uses (Scholz and Sadowski, 2009; Scholz and Yang, 2010). The proposed FRB types, which span from highly engineered structures to natural wetlands, are characterized for 40 parameters (Yang et al., 2011). The most relevant are related to structure (e.g., dam height and length; outlet arrangement), hydrology, topography (e.g., floodplain elevation), and ecosystem protection (presence of aquatic and land animal passages). Besides characterizing existing FRBs, the proposed classification had the purpose to assist engineers and planners during the design stage of a new flood detention system (Yang et al., 2011). In addition to FRB characterization, including dam sizing, a central issue in flood attenuation planning is the selection of suitable locations for detention basins within the catchment, although not many publications have addressed this topic. In this context, Travis and Mays (2008) used discrete dynamic programming to assist optimal location and sizing of a detention basin network within a hypothetical watershed. The constraints to the optimization algorithm were developed in terms of basin geometry, infiltration, water quality, storm-water volume and land cost functions. Palmeri and Trepel (2002) as well as Zhang and Song (2014) dealt with best site selection models for wetlands. In the work of Palmeri and Trepel (2002), a land score system based on 6 factors (geology, climate, environment, hydrology, society and economy) was implemented in a Geographic Information System (GIS) and used to produce a detention basin suitability map. Having selected the most suitable areas and given the local environmental and boundary conditions a formula was proposed to estimate the wetland surface area so efficiency in pollution abatement is achieved. As regards the study by Zhang and Song (2014), the CTI index (logarithm of catchment area divided by tangent of catchment slope) was used to set up a ranking sequence for sub-basin priority, which removes the area of human habitation from consideration. Subsequently, a multi-objective optimization matrix was designed to maximize flood control, economic benefits, and ecosystem functions. Additionally, an attempt was made to localize the biotic population during the restoration process, choosing vegetation types that have both ecological and economic functions. Finally, wetland restoration benefits were quantified to verify the methodology. The DamSite method of Read et al. (2012) is more engineering oriented because it uses a suitable digital elevation model to assess all locations on a river network and test dam walls of varying heights to build a comprehensive dataset of relevant attributes including catchment area, runoff, reservoir volume, reservoir surface area, dam height, dam width and dam face area.

A major negative effect of detention basin systems is the trapping of sediments behind the damming structures. This condition hampers the natural conveyance of sediments and lets sediment deprived water downstream the dam to develop a greater erosive action causing channel incision (Kondolf, 1997). Moreover, the mining of inert materials in the riverbed may further contribute to the increase of erosion. Apart from being a sink to sediments, artificial lakes created by the installation of dams are also receivers of nutrients transported in runoff from upstream areas, especially of phosphorus and nitrogen (Santos et al., 2015c; Pacheco et al., 2015b). As noted in Figueiredo et al., 2012, a quality gradient is expected from more pristine waters in the highlands to waters with increasing pollution in the lowlands, because of a commonly observed altitudinal zoning of land uses whereby forests are located around the headwaters while agriculture and population are concentrated at lower altitudes where soils are more productive (e.g., Rhoades and Thompson, 1975). Apart from this topographic influence, the degradation of lake water quality will depend on whether the upstream areas have been disturbed by forest management (Hutton et al., 2008), wildfires (Santos et al., 2015b) or land use conflicts (Valle Junior et al., 2014a, 2015a). An important environmental sequel of nutrient enrichment is eutrophication that threatens the lake ecosystem and endangers the most sensitive species (Santos et al., 2015a).

As mentioned above, the number of studies on sizing and siting of detention basin systems in watersheds is scarce. Even scarcer are studies that link sizing to flood history in the watershed and siting to optimal locations of the detention basins around the catchment headwaters where pressures to water quality are usually less important. This study is a contribution to fill in this gap. To that end, a new framework model is presented based on a workflow of three sequential modules: the hydrologic, geomorphologic and environmental modules. The hydrologic module (HM) back tracks a minimum detention basin contributing area (A) based on the application of engineering formulae to historical information on local river floods and associated hydrometric data. Then, the A value is used as input to the geomorphologic module (GM), which is a siting method embedded in a GIS environment. The output from GM comprises outlet locations of sub-catchments with an area equal to A. Because A is a minimum contributing area, these outlets are located the closest as possible from the catchment headwaters. The various sub-basins are finally processed in a spatial decision support system based on Multi Criteria Decision Analysis (environmental module – EM), which selects a best sub-basin or group of sub-basins based on the assessment of environmental indicators. Because sub-catchments are located around the catchment headwaters, the outputs from EM are expected to optimize water quality protection. With the purpose of testing the framework model, a discussion on its application to a flood-prone watershed is presented, namely to the Vez River basin, a sub-catchment of the Lima River basin. It is worth noting that selection of suitable areas for detention basin installation using the present framework model corresponds to a first choice. A final decision on the construction of the damming structure requires deeper analyses from the geotechnical point of view and must be based on risk assessment and cost-benefit analyses taken into account the existing normative and laws, which were not tempted in this study.

2. Study area

The Lima River is a transnational water course rising in the San Mamede massif (Spain) at the altitude of 950 m.a.s.l. The main stream flows along 41 km before entering Portugal between the Peneda and Gerês Mountains, and reaches the Atlantic Ocean in Viana do Castelo after a total path of 67 km (Fig. 1). The Portuguese portion of Lima River watershed covers approximately 1140 km^2 (46% of the entire basin). The Lima catchment area is characterized by a temperate climate and by a mean annual precipitation of 1780 mm, varying from 900–1000 mm near the coastline to 3500 mm in the inland mountainous areas. The mean river discharge at the mouth gauging station of Lima River is 3298 $h\,m^3/yr$ (value obtained from a flow record available at http://snirh.apambiente.pt). The natural hydrologic functioning of this stream