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An automated and rapid method for identifying dam wall locations and estimating reservoir yield over large areas

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ABSTRACT

Global demand for water, food and energy has seen the construction and planning of large dams continue at a steady pace in many parts of the world. However, the process of 'exhaustively' examining all potential dams sites within an area as part of an initial scoping study is still largely undertaken using manual methods. This paper describes DamSite, a series of novel algorithms that construct 'virtual' dam walls at every pixel along every channel within a catchment, including saddle dams where required by the terrain. By repetitively calculating dam and reservoir dimensions, reservoir yield and dam costs along a river network and for incrementally higher dam walls at each location it is possible to identify both optimal dam wall locations and optimal dam wall height at a given location. The DamSite model was tested in two catchments in northern Australia and accurately pin-pointed previously identified potential dam locations.

1. Introduction

The global demand for water, food and energy has seen interest in large dams and their planning and construction continue at a steady pace in many parts of the world. Zarfl et al. (2015) for example, identified more than 3700 major dams designed primarily for hydropower production, either under construction (17%) or planned for construction (83%) around the world, predominantly in developing economies. However, the interest in large dams is not limited to developing economies or hydropower production. In Australia for example, there has been a resurgence of interest in the construction of large dams, primarily to supply water to 'greenfield' irrigation areas to enable economic development and affect social change, principally in the country's sparsely populated north (PMC, 2015). Elsewhere it is estimated that approximately 25 million hectares and 7 million hectares of 'greenfield' area could potentially be developed for irrigation in Brazil and China, respectively (Aquastat, 2015).

The process of investigating a potential dam site typically involves an iterative process of increasingly detailed studies, sometimes occurring over as few as 2 or 3 years but often over 10 or more years. Given the large costs and time involved and the likelihood of many potential dam sites in a catchment, an important stage of assessing the surface water resources of a catchment is a 'pre-feasibility assessment'. This typically involves an initial desktop investigation that exhaustively looks at 'all' potential dam sites in an area. The better potential dam sites are then usually short-listed for a more detailed desktop investigation before a site is selected for a 'feasibility analysis', which involves increasingly detailed and expensive ground based investigations. Through this process it is possible to confidently select the most appropriate dam sites on which to undertake more detailed and costly ground based investigations.

However, the process of 'exhaustively' examining all potential dams sites in an area as part of the initial stages of a pre-feasibility analysis is still largely undertaken manually, for example based on visual examination of a digital elevation model (DEM) and satellite imagery or aerial photography. Then for the more promising sites hydrological models and/or data are developed to assess the performance of a dam at selected locations - inevitably a time consuming and somewhat subjective process.

In the scientific literature a number of studies detail methods for the regional scale identification of areas with promise for rainwater and water harvesting and micro and small farm scale water storages (e.g. Weerasinghe et al., 2011; Pachpute et al., 2009; Ramakrishman et al., 2009; Winnaar et al., 2007) or for

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optimising the location and sizing of storage units in urban drainage settings (e.g. Behera et al., 1999; Zoppou, 2001; Travis and Mays, 2008, Marques et al., 2015). Only one study (Baban and Wan-Yusof, 2003), however, is known to the authors that details an automated method for the rapid identification of topographically and hydrologically suitable locations for large dam structures over large areas. That study and others examining micro and small farm scale water storages, all used composite index techniques, which involve spatial overlay of relevant GIS data to produce a summed ranked layer. These approaches, rather than identify specific locations for dam walls, indicate the general areas more suitable for construction of water storages. These techniques work well for criteria that are easily represented spatially, such as broad scale geology, runoff generation, social and environmental effects and proximity to current and future water demands. While composite index techniques are useful for capturing broad scale considerations in siting of dams, they do not explicitly model processes and factors relevant to the performance of individual large dams (e.g. yield or cost of construction), which are dependent upon the complex 'inter-play' between the following factors:

- topography, e.g. through the dimensions of the dam wall, reservoir volume and surface area to volume relationship;
- hydro-climatology, e.g. through the quantity and inter and intra annual variability of inflows to the reservoir and net evaporation from the reservoir;
- reliability with which a particular yield can be achieved.

Consequently composite index methods are limited in their ability to evaluate the relative promise of specific sites, primarily because they do not calculate potential dam and reservoir dimensions and hence yield, which is typically the key measure of dam performance. While this may be less of a problem for identifying areas suitable for micro and farm scale water storages that are distributed across a landscape, it is problematic for large potential dams, of which a limited number are likely to be constructed in an area, and for which dam performance is site specific and needs to be explicitly assessed.

In this paper we describe DamSite, a series of algorithms that provide a flexible means of identifying and ranking potential dam wall locations across a landscape from most to least promising, by i) calculating potential dam and reservoir dimensions, and ii) calculating yield at a given reliability for every potential dam within a catchment or region.

To demonstrate its use, DamSite is applied to the Finniss and Adelaide catchments adjacent to Darwin in northern Australia (Fig. 1). This area was chosen because its rivers are largely unregulated and there are known potential dam sites that have been previously investigated and so can be used to assess the performance of the DamSite model.

This manuscript first describes the 'case study area', i.e. the catchments in which the DamSite model is demonstrated. In the next section the methods are outlined. Section 4 presents the results of the DamSite model applied to the study area, and is followed by a discussion and summary comments.

2. Case study area

The case study area encompasses 16,950 km^2 of land, most of which is underlain by the Pine Creek Orogen, which is comprised of sandstone, siltstone, shale and dolomitic rocks and which vary from flat to moderately strongly folded. Plateaus and strike ridges of sandstone form the main positive topographic features, whereas siltstone, shale and dolomite areas tend to have low relief with limited outcrop. Sandstone, the most common rock, is hard with little or no primary porosity. The degree of fracturing varies considerably from area to area and the geological suitability of the rock would need to be assessed by on-site investigations.

Relief is modest (250 m maximum elevation) and hills and rugged ridges alternate with undulating plains and alluvial plains (Fig. 1). Alluvial sequences are generally poorly developed, though alluvial floodplains cover an extensive area along the coastal northern edge of the study area, and are underlain largely by marine sediments that have been deposited in the last 10,000 years since the end of the ice age (CSIRO, 2009).

Across the case study area there is a distinct north-south gradient in mean annual rainfall, ranging from over 1600 mm in the north to 1250 mm in the south. About 95% of rain falls during the wet season months (i.e. November to April). Morton's areal potential evaporation (APE) (Morton, 1983) is high all year round, but is highest in October and November immediately prior to the on-set of the wet season.

Runoff coefficients vary from about 15% to 40% of rainfall. Rainfall and runoff vary considerably from year to year. The coefficients of variation of annual rainfall and runoff averaged over the study area are about 0.18 and 0.6 respectively (Fig. 2).

The study area contains two large existing dams, Darwin River Dam (325 GL capacity) and Manton Dam (16 GL capacity) (Fig. 1). The rest of the rivers in the study area are unregulated. The Northern Territory Power and Water Corporation, which is responsible for water services across the Northern Territory, has commissioned numerous studies on potential dam sites in the Darwin region over the last few decades. In 1979 a pre-feasibility analysis of future sources of water for Darwin (SMEC, 1979) identified 12 potential dam and weir sites in the vicinity of the city (Fig. 1). On the basis of these investigations, three of these sites were short-listed for more detailed investigations in the early 1990's (Paiva, 1991a, b). They were: Marrakai (Paiva, 1991a; GHD, 1990; Stewart and Baker, 1987), Mount Bennett (Paiva, 1992; Ullman and Nolan, 1990) and Warrai (Paiva, 1991b; Paiva, 1990). These three potential dam sites will be referred to as the 'short-listed' sites and their locations are shown in Fig. 1.

3. Methods

The methods section is comprised of three parts. Section 3.1 describes a new computationally efficient spatial analysis technique for quantifying large numbers of dam and reservoir dimensions across large areas. Section 3.2 describes a method for quantifying the attractiveness of a topographic constriction for dam construction and outlines a method for ranking the favourability of potential dam sites. Section 3.3 outlines a staged method for calculating reservoir yield.

The DamSite model is comprised of two separate pieces of software: DamSite Spatial and DamSite Behaviour. The algorithms presented in Sections 3.1, 3.2 and 3.3.1 are implemented in DamSite Spatial. DamSite Behaviour is described by Section 3.3.2.

3.1. Spatial analysis to calculate dam and reservoir dimensions

Candidate dam sites are considered at every DEM cell along the drainage network defined by a minimum catchment area, set at 10 km^2 for this study. There are established GIS techniques for calculating reservoir surface areas and volumes for a single dam site and wall height, however, they do not scale well to being performed for many wall heights for every cell along every channel in a catchment. In order to perform billions of reservoir and dam dimension calculations in a practical amount of time a new efficient method for automatically calculating dam and reservoir dimensions from a DEM was developed (i.e. Section 3.1). A prototype