Ecological Indicators 93 (2018) 470–480

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Multicriteria decision analysis framework for hydrological decision support using environmental flow components

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ARTICLE INFO

Keywords:
Hydrology
Climate change
Decision support systems
Indicators of hydrologic alteration
Environmental flow components
Multicriteria decision analysis

ABSTRACT

Assessing the quantity and quality of water available in water stressed environments under various potential climate and land-use changes is necessary for good water and environmental resources management and governance. We present a novel approach with which to assess water quantity in the Luanginga basin, a subbasin of the upper Zambezi River, using existing results of hydrological modelling based on climate change scenarios, hydrological indicators, and multicriteria decision analysis. Flexible input criteria and open-source software are used to the greatest degree possible. Scenarios are represented through a combination of model input data and parameter settings in the hydrological model, and preferences are represented through criteria weighting in the multicriteria decision analysis. The resulting methodology, combining hydrological indicators with MCDA, is thus adaptable, in terms of both application platform and subject matter. The method results were largely as expected. When a decision maker expressed a preference for wetter conditions, the RCP 4.5 scenarios were generally deemed most suitable, and thus ranked highest. When drier conditions where preferred, the RCP 8.5 scenarios, resulting in less streamflow and less frequent flood events, were ranked highest. Validation of the results is not possible, due to the methodologically exploratory nature of the research being undertaken. The promising results do, however, allow for further research that builds upon the work undertaken here, to be envisaged.

1. Introduction

Assessing the amount of water available in water-stressed environments under various potential climate and land-use changes is necessary for good water and environmental resources management and governance. On the whole, Africa is viewed with high confidence as being subjected to increased stress on water availability, in particular in areas already affected by water stress today (Niang et al., 2014). More specifically, southern Africa is projected to become drier with climate change (Serdeczny et al., 2016). Kling et al. (2014) well summarize the results of existing models of the upper Zambezi in particular, concluding that, although uncertainty exists, the consensus of existing research results is that runoff is likely to decrease, perhaps by up to 40% by 2050, due to a combination of decreased rainfall and increased temperature. In view of this, it is key to allow for adequate natural resources planning. The present research aims to contribute to work on water availability in the upper Zambezi, and so aid stakeholders in making critical planning decisions as to how water is managed in the future.

1.1. State of the art

A decision support system (DSS) can be defined as a software system that provides five functionalities: a database and processing environment; a knowledge and information system; modelling analysis frameworks; socioeconomic analysis; and a communication framework (e.g. public web platform) (GWP, 2013). According to Georgakakos (2006), “the role of DSS is to leverage current scientific and technological advances in developing and evaluating specific policy options for possible adoption in” water resources management.

Currently, the Integrated Land Management System (ILMS) software package developed and provided by FSU Jena covers all of the functionalities listed above, to varying degrees, apart from that of socioeconomic analysis. The database and processing environment are provided through the use of the SASSCAL Information System (SASSCAL-IS) platform. The IS also provides a basis for the knowledge and information system category, as well as the communication framework. The modelling analysis framework functionality is covered in ILMS by the various J2000 hydrological models available. What remains undealt

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https://doi.org/10.1016/j.ecolind.2018.04.057
Received 2 June 2017; Received in revised form 22 April 2018; Accepted 23 April 2018
1470-160X/

with, at least in the SASSCAL-IS context, is the development and support of a socioeconomic analysis functionality, which is out of the scope of the current, hydrologically focussed, research, but which we aim to develop on the basis of the research presented here.

In terms of African, and in particular southern African, indicators of hydrologic alteration analysis, some previous research does exist. Of specific interest here is the work by Martínez-Capel et al. (2016), who undertook an indicators of hydrological alteration (IHA)/environmental flow component (EFC) analysis on the Zambezi-Chobe River in Namibia. In contrast to that study, however, where the environmental flow component output was used as input to the WEAP21 hydrological decision support system, the present research, by applying the IHAs/EFCs to a multicriteria decision analysis, uses environmental flow components differently.

Some research applying IHAs/EFCs as input for multicriteria decision analysis has already been undertaken. Martin et al. (2015), using the Ecological Limits of Hydrologic Alteration (ELOHA) hydrological assessment indicators set, used the EFCs as a basis for the evaluation of social preferences into watershed management planning exercises. Porse et al. (2015) use EFCs derived from the indicators of hydrologic alteration framework to compare different potential reservoir storage possibilities, bearing in mind the different objectives of different user groups. As such, expanding the interpretation of the EFCs to a wider scope, including but not limited to the original ecological scope, as is planned in the SASSCAL-DSS, appears to be a feasible goal.

With regards to the application of the Preference Ranking Organization Method for Enrichment of Evaluations, or Promethee, method, used here, in water resources management, Bezhadian et al. (2010) state that 14.4% of all papers published that made use of the Promethee method in some way, up to the point of the review, focussed on the topic of "Hydrology and Water Management". This topic denotes "sustainable water resources planning, water management strategies assessment, and irrigation planning", corresponding to the sphere of the research presented here.

Use of the Promethee MCDA method in combination with hydrological modelling data is thus a feasible combination, as is the use of the IHA/EFC framework with MCDA. Where the approach presented here innovates, however, is in the use of the combination of hydrological modelling results, hydrological indicators, and MCDA to evaluate the suitability of different climate change scenarios for different stakeholder groups (albeit hypothetical ones).

1.2. Objectives

So as to enable improved data collection and analysis regarding issues such as water vulnerability, and a myriad of other related topics, as well as to enhance organisational cooperation of researchers, governance, and stakeholders within and regarding the region, the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) initiative was undertaken.

One goal of the SASSCAL project, and the objective of the research presented here, is to develop and provide an integrated decision support system with which decision makers (DMs) within a given catchment can obtain objective information regarding potential changes in water flow quantity and timing. The results of this research thus far are presented here.

2. Materials and methods

The hydrological decision support system developed here uses output from existing, validated hydrological models as the basis of the calculation of a range of hydrological indicators based upon indicators of hydrologic alteration and environmental flow components calculated for a historic time series (pre-impact), and a set of model simulations based upon a selection of climate change scenarios (post-impact). These indicators, obtained using the Indicators of Hydrologic Alteration software package, a process developed, documented, and maintained by The Nature Conservancy (2009), are then used as input for a multicriteria decision analysis undertaken using an open source MCDA software package, diviz. The results of these analyses will provide decision makers with an indication as to how various hydrological indicators within a catchment may be altered under different future scenarios, as well as providing a ranking of how each scenario best suits different DM preferences. A more detailed description of the method and its various components applied here follows.

2.1. Methodological overview

The work presented in this paper is based on the results of a catchment-scale hydrological model of the Luanginga catchment of the Zambezi River by Meinhardt (2017), involving model calibration and validation, and subsequent modelling of the Luanginga using several sets of climate projection data for the study region. The results of this prior research form the basis of the present research, as they were then used as input with which to obtain a set of environmental indicators. These indicators were obtained using the Indicators of Hydrological Alteration software. This program aims to provide the user with a detailed breakdown of how streamflow dynamics are altered between a pre- and post-impact period. Although usually applied for projects such as dam construction, there is no great issue with using post-impact data consisting of streamflow generated under a specific climate change scenario. The final step of the process involves using a set of indicators output from the IHA program as input to the Promethee II MCDA in the diviz modelling environment. These indicators fill the role of the criteria to be assessed in the MCDA, under a selection of scenarios and preference values. What follows is an overview of the concepts used.

2.2. Summary of catchment and hydrological data used

The data that the present research is based on consist of the results of the J2000 hydrological model applied using climate forcing data from four different downscaled Representative Concentration Pathway (RCP) datasets, consisting of two scenarios from two models (ECHAM 4.5/8.5, and EC-EARTH 4.5/8.5). A flood component was developed specifically for use in the Luanginga catchment, an area subject to seasonal flooding. For full details of the hydrological model used, see Meinhardt (2017). For further information on the J2000 model and applications thereof, including in southern Africa, see, for example, Krause (2001, 2002), Fischer et al. (2009), and Helmschrot et al. (2014).

The majority of the Luanginga subbasin is located in Angola, and the rest in Zambia (Fig. 1). Since it is one of the smallest catchments in the Zambezi Basin, flooding often occurs shortly after heavy rainfall (World Bank, 2010). Due to its relatively remote location, there is very little human development and human influence upon the river, with no dams or hydropower plants, or plans for any, along the river (World Bank, 2010). The low levels of development and human impact on the river thus provide suitably 'natural' streamflow values, and thus too, EFC values, with which to undertake an MCDA that is not subject to much, if any, uncertainty due to human factors in the area itself.

2.3. Indicators

Indicators of hydrologic alteration were used here as they are shown by Olden and Poff (2003) to be effective in representing a wide range of flow regime information without using an overly large selection of indicators, stating that IHAs "capture the majority of the information provided by the population of indices available to researchers". Despite indications that fewer indicators could be used, the present study, due to its aim of providing a generally applicable methodology, rather than geographically specific results, applied the range of IHAs/EFCs.

Use of the IHA framework has a number of other advantages.