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Proposal of a hydric index to support industrial site location decision-making applying a fuzzy multi-attribute methodology

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ABSTRACT

This paper proposes a practical water resources-related index methodology (Hydric Index for Location of Industrial Facilities – HILIF) to provide preliminary guidance for location-based decision-making processes for new industrial sites, based on the likely effects on water resources in river watersheds, as applied to the conceptual phase of a project design. The framework of HILIF is established on the integration of three hydric factors: consumptive water availability, river carrying capacity, and flood vulnerability and effects of the drainage project. The proposed methodology for the application of HILIF is founded on Multi-Attribute Decision Making (MADM) using fuzzy logic (fuzzy MADM) to combine seven indicators into nine possible recommendation levels. Additionally, in order to illustrate the HILIF methodological approach, a case study of a project design using a cyclical analysis based on a hypothetical scenario was developed. In this context, three alternative sites (AA, BB, and CC) were considered for a nitrogen fertilizer plant in the Contas River Basin in the state of Bahia, Brazil. The results demonstrate that the HILIF methodology can support the conceptual project design by identifying the most adequate site alternatives for an industrial location within an integrated hydric perspective. In addition, the possibility of implementing modifications during the initial conceptual project was observed through cyclical analysis using multiple rounds for the same locational alternatives. For the present case study, the locational alternative preferred by project designers (Alternative CC) shifted from a classification of Not Indicated (NI) in the first round of HILIF application to a Fairly-Good Recommendation in the second round after modifications in the initial conceptual project. Thus, Alternative CC became nearly as adequate as Alternative BB, which was the best alternative site in terms of water, classified as a Good Recommendation in the first HILIF round. On a complementary basis, the results generated by the application of HILIF can also be utilized to support further complex studies for licensing proposes within the context of Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA).

1. Introduction

1.1. General concepts applied to HILIF

The use of water is indispensable for various industrial purposes, such as cooling and heating processes, incorporation as a raw material in products, as a cleaning agent and solvent, and for the disposal of effluents. Water availability is now a major challenge in the field of global sustainability because water is not equally or adequately distributed in terms of quantity and quality in many regions. Considering only manufacturing activities (industries), water use is expected to increase by 400% from 2000 to 2050. Accordingly, industrial corporations have begun to incorporate studies of water availability into their planning and management processes. Additionally, many analytical tools and practical actions are being developed to help companies evaluate the complex relationships between water impacts and their

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production activities (Ruini et al., 2013; Wintgens et al., 2013; Mueller et al., 2015; Reddy et al., 2015; Walsh et al., 2015). In this context, water planning, Integrated Water Resources Management (IWRM), and Decision Support Systems in River Basin Management (DSS in RBM), which combine different hydrological and water management models, represent important technical procedures to support decision makers in selecting alternatives for distinct objectives in the field of water management (Jonoski, 2014; Pedro-Monzonís et al., 2016; Zhang et al., 2016).

The industrial locational decision-making process comprises a complex multi-criteria analysis that includes conceptual project planning associated with a new enterprise and considers not only traditional factors (such as engineering, transportation costs, economics, and politics) but also environmental issues (biotic, physical, and socio-economic), especially water resources. Hazards to facilities (e.g., floods) and environmental externalities of industrial operations (e.g., water withdrawal, consumption, and effluent discharge) are examples of crucial factors that must be assessed before the development of an industrial facility due to their potential impacts, mainly at a local scale. As a result of rising interest from customers and governments concerning environmental regulations and protection, companies are obliged to include environmental sustainability in their decision-making procedures, including site location choices (Briassoulis, 1995; Mulatu et al., 2010; Treitl and Jammernegg, 2014).

In scientific literature, it is vastly substantiated that indices associated with multi-criteria methods are capable of summarizing, aggregating, and diffusing complex data among different stakeholders (Juwana et al., 2012). In the area of hydrology, Valipour (2016) presents an example of the use of indices applied for the determination of future scenarios of land use for irrigation. Singh et al. (2009) show that the combined use of indicators, composite indices, and multi-criteria (or attribute) methods has been increasingly recognized as a useful approach to environmental policy development and public communication in corporate organizations, including industrial activities. In this context, Garcia et al. (2016) exemplify an application of a multi-criteria model to support balanced decision-making analysis involving stakeholders and shareholders to address corporate sustainability management strategies. Other examples of multi-criteria analysis applications to address environmental corporate policies are observed in evaluations of environmental impacts of road corridor alternatives (Geneletti, 2005) and environmental impacts of industrial processes alternatives (combined with Analytic Hierarchy Process (AHP) methodology) (Sólnes, 2003; Horodnic, 2015).

The use of the Multi-Attribute Decision Making (MADM) technique within a fuzzy logic approach (fuzzy MADM) can support indices to consolidate and improve final analysis results applied to an environmental perspective. The concept of MADM refers to making decisions within conditions of finite (few) multiple attributes. Environmental decisions are often complex, involving a finite number of stakeholders with distinct interests. As such, MADM methodologies are broadly applied worldwide in environmental studies and projects, including water resource management. Thus, with the goal of performing MADM studies, environmental decision makers are involved in many cases with four types of technical inputs, representing sets of quantitative and qualitative attributes: a) modeling and monitoring study results; b) risk assessment; c) cost-benefit analysis; and d) stakeholder preferences. The use of fuzzy logic allows the user to work with the concept of partial truth (unlike Boolean logic), which simulates the subjectivity condition of human nature in terms of decision-making. Additionally, fuzzy logic creates a more serene transition between categories of membership functions (e.g., between two levels of stature height "tall" and "short", there is an intermediary transitory subcategory "medium" that is not "tall" or "short") (Chen and Hwang, 1992; Kiker et al., 2005; Shepard, 2006; Chung and Lee, 2009; Lermontov et al., 2009; Juwana et al., 2012; Comino et al., 2014; Jonoski, 2014; Kim and Chung, 2014; Huang et al., 2015). These two intrinsic concepts compose the main motivation that led the authors to adopt fuzzy-logic techniques associated with MADM in HILIF.

The present study relies on multi-criteria analysis, applying a fuzzy MADM technique for the development and application of a water resources-related index called the Hydric Index for Location of Industrial Facilities (HILIF). The HILIF methodology aims to support locational decision-making processes of new industrial sites at the conceptual design stage, considering the likely effects on water resources. In terms of application, the HILIF methodology is expected to be utilized as a new procedure to contribute to environmental management of project designs, especially during the conceptual phase, with the goal of reducing both potential future environmental impacts on water, as well as to promote industrial project designs that adhere more closely to local river watershed characteristics. Therefore, through the use of a cyclical analysis, the most inappropriate locational alternatives and the associated operational technologies are promptly rejected by the HILIF methodology; the project design is then expected to become more environmentally oriented (in terms of river watershed use) as it is being developed (Secron, 2015).

Thus, assuming that water is a crucial input for an industrial facility during the entirety of its useful life (installation and operation), the primary contribution of the HILIF methodology to a state-of-the-art facility is to integrate three hydric factors, or branches of hydrology, within a unique decision-making interface: Consumptive Water Availability, River Carrying Capacity (Zhu et al., 2010; Zhang et al., 2011; Xiao-qing et al., 2012), and Flood Vulnerability and Effects of the Drainage Project. These factors or branches, in terms of water, encompass the most important general aspects that can substantially influence location analysis for an industrial site, independent of the type of industry. In turn, the influence of each hydric factor will depend on both the physical and the environmental characteristics of a given watershed and the particularities of the proposed industrial project. Subjects such as water consumption, effluent dilution (Park and Uchrin, 1988), and flash floods are common worldwide concerns for new industrial conceptual projects; these are covered by the three hydric factors proposed.

Currently, hydric studies applied to industrial project designs and their implications in the environmental engineering area are typically assessed in isolated studies, without a systemic assessment integrating the effects resulting from the water context into the decision-making processes. This ends up generating some weaknesses in incorporating environmental and hydric variables, both in the industrial site location process and in the development of projects. HILIF offers a new approach, with the possibility of establishing a holistic view of water environmental impact through the quantification of the influence of each factor (and the global result) in a determined industrial locational alternative. Thus, a set of metrics involving indicators covering three hydric factors was created, and HILIF presents a final result, with the objective of reducing the combined effects of all the hydric factors into a single index. This reduction process focuses on: a) facilitating the visualization of the influence of each hydric factor on the decision-making process, b) integrating the decision-making process around a single calculation methodology (taking into account the combined and resulting influence of each hydric factor, and c) increasing the possibilities of decision-making alternatives by stakeholders. Therefore, HILIF summarizes the total influence of water aspects on an industrial locational decision-making process. It is also expected that a well-located industrial site can also promote a better condition both for the future operational life of the industrial plant and for the surrounding environment (watershed and local communities).

1.2. The importance of legal and good informal environmental practices, and the relationships among industrial project design, site location, and HILIF

Environmental Impact Assessments (EIAs) have largely been applied