

## Research Article

### **Bioinspired Engineering and Complex Systems Engineering: A Theoretical Framework for Water Management**

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**Abstract:** This study reviews the state of the art of different existing modeling tools applied in management water systems. Initially, is carried a conceptual review of several modeling systems, applied by the scientific community to model phenomena presented in reality. Emphasizing the modeling tools that serve to describe non-linear systems with high levels of complexity, such as Bio-inspired engineering and Complex Systems. Among the tools described are artificial intelligence, bio-inspired algorithms, artificial neuronal network, evolutionary algorithms, fuzzy logic, data mining, Bayesian networks, genetic algorithms, emerging systems, ant colony, particle swarm and cellular automata. Then, a review of scientific articles is carried out, showing how these tools have been used for water management systems, for example, making decision in water resources systems, consumption prediction models, quantity, flow, water quality, also for analysis of water pollution sources and wastewater treatment systems, among others. Then, it presents some future guidelines, in which it proposed that these modeling tools could be very useful for the planning and environmental planning of watersheds. Finally, it concluded that these tools have used to solve problems of water resources optimization but very little in the water environmental planning of a river basin.

**Keywords:** Decision making, forecasting models, modeling, neural networks, optimization, water management

## INTRODUCTION

There is the concept of explaining a conceptual abstraction of reality or interpretation of reality (Maldonado and Gómez, 2010), through the formulation, evaluation and application of mathematical models. There is a variety in the types of models and their classifications, among which one can mention the heuristic models (based on explanations of the causes), empirical (based on direct observations), deterministic (as cause and effect relationship without consider response uncertainly embodiment), stochastic (considers the random nature of some characteristics of the process being modeled, which takes into account uncertainty), agglutinated (considering the characteristics of the control volume that is concentrated on one point), distributed (has a spatial variation of the characteristics of the domain, parameters and process variables) (Dominguez, 2000; Refsgaard and Abbott, 1996; Fernández Mejuto *et al.*, 1997), management or collaborative (identifies the information to be used and resources involved for making decision). In this latter type of model, two or more decision makers are involved to the representation of a specific reality that it is desired to model, for the making decision according to the objective function, data, indices, sets and restrictions (Alarcón *et al.*, 2009). This leads to a simplification in some cases of

the real system or the analyzed problem, which can be represented in a linear way or gaussianity (Gaussian distribution) with analytical resolution or numerical methods, that is, a reductionism in the behavior of a phenomenon, patterns or system performance. The objective of this study is to establish a theoretical framework of Bio-Inspired Engineering and Complex Systems Engineering in water management, applied to water environmental planning in a water basin.

## MATERIALS AND METHODS

The method applied in the construction of this manuscript, according to the analysis and scope of the results, was of the explanatory type, since this type of study, has as objective to determine the origins or causes of a certain set of phenomena (Vergel, 2010; Hurtado, 2000). The bibliographical search used several documentary sources and descriptors in the thematic of interest.

## RESULTS AND DISCUSSION

**Conceptualization of bio-inspired engineering and complex systems engineering:** The decision problems and variables (certain or uncertain) for constructing a model, can be simple (if there are few important

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variables), complex (if there are many) or dynamic (if decisions are interrelated over time), with factors such as decision variables (controlled), exogenous (out of range), intermediate (relationship between decision and external variables), performance measures (objectives) and constraints or limitations (Bonini *et al.*, 2000). A model approach may contain qualitative variables (dichotomous and polyatomic) and discrete quantitative variables (present interruptions in the scale of natural values/numbers) and continuous (integer value in a specific interval of the scale of values/real number) as independent variables (Kaveh *et al.*, 2015; Mori and Mahalec, 2015; Soler *et al.*, 2012; Southworth *et al.*, 2004; Domokos and Scheuring, 2004).

However, there are phenomena or abstractions and/or conceptualizations that in reality present complexity, such as non-linearity and non-Gaussian, which leads to the fractality and to the emergency, as a tool to explain a phenomenon; Linear Programming, transforms an optimization problem in an iterative process in which after an initial feasible solution are generated other possible solutions to find the optimal, which is very applied in engineering, flow network, management inventories and optimize mixtures (Borges, 2013); Artificial Intelligence or Artificial Intelligence Bio-Inspired, Engineering with which has been achieved facilitate robustness (system to continue operating under prescribed conditions), distribution and adaptability (system fit its parameters according to the conditions), that is, a solution to the problems of optimization (solution in certain constraints), regression or classification by a qualitative analysis of nonlinear systems and characterization of complex systems, through the abstraction of the operation of known and possible natural systems, or more precisely of artificial life. As for non-conventional computing and complex problem solving, he has integrated the work of fuzzy logic with artificial neural networks and evolutionary computation, giving rise to soft computing. These previous ones, generate an understanding of phenomena through the self-organization and the emergency (they are elements of the system in a certain state and they interact of a certain form) and there, to perceive a complex set of parts, learning, deciding of autonomous and intelligent form to solve the problem by engineering complex systems (Gómez and Maldonado, 2011; Maldonado and Gómez, 2010).

Artificial Intelligence or Emerging Engineering, provides through the theory can be established computational models, trying to formalize the knowledge and considering a practical embodiment of an abstraction of the studied phenomenon, using a paradigm called agent, which perceives and acts in environment to be developed based on a knowledge, with the most convenient decision making, emergent way to solve the problem (generates solutions in top-down decomposition, using an analytical approach),

with cooperation, learning and adaptation, such as search of the strategic path for the design, planning and control of a system. The main applications of artificial intelligence in engineering are in the optimization of processes and production, logistics, fault diagnosis, making decision and planning (Benítez, 2013; Gómez and Maldonado, 2011).

Bio-inspired Engineering by Bio-inspired algorithms, are a type of algorithm that seeks to solve a problem analyzed by abstracting an evolutionary process (Gómez, 2015). It can be applied to design routes, structures, market prediction, pattern recognition and problem solving with non-linear equation systems, among others; these types of algorithms present advantages like: Generic solutions and with few restrictions, offer several solutions, original and very efficient; and as disadvantages, randomness, parameters are not systematically optimized and present problems of premature convergence (Borges, 2013). Bio-inspired techniques for solving complex problems related to optimization, search, route programming, space allocation, pattern discovery and making decision can be metaheuristics, evolutionary computation, immune computing, swarm intelligence, neural computation and computation with membranes (Gomez, 2011). Specifically, the techniques include evolutionary algorithm, genetic programming, evolutionary strategies, differential evolution, genetic algorithms, fuzzy systems, neural networks and ant colonies (optimization swarms or particle swarm optimization, inspired by the collective behavior of insect colonies), among others (Benítez, 2013; Gomez and Maldonado, 2011; Maldonado and Gomez, 2010).

The artificial neural network is an information processing paradigm inspired in the mode and structure as the brain processes information using a computer model in parallel compound of adaptive processing units with high interconnection between them. The main uses of this network are for the resolution of optimization problems (individual non-linear), classification of information and associative memory (Cano Esquibel, 2014; Cárdenas Cardona, 2012). The advantages of this technique are that they are training through examples; they allow rapid identification, analysis of situations and diagnosis in real time, among others (Borges, 2013). Evolutionary algorithms are stochastic methods that have applied to the problem of search, optimization and learning and partially mimic the biological mechanisms of evolution and natural selection (Armendáriz *et al.*, 2014).

Evolutionary strategies used to solve hydrodynamics problems of high complexity, not only evolve to the variables of the problem, but also the very parameters of technique, that is, auto fit, considering individuals as numeric floating point vectors (Armendáriz *et al.*, 2014; Cárdenas Cardona, 2012). Evolutionary Programming: Intelligence is an adaptive

mechanism, emulates specific genetic operators and performs an abstraction of evolution at the species level; it is an adaptation of genetic information of individuals across generations by mutation. This concept involves information exchange between individuals (Armendáriz *et al.*, 2014; Cárdenas Cardona, 2012).

Fuzzy Logic is used to treat uncertain or inaccurate knowledge, which does not require a mathematical model of the system but fail to express control informally and linguistic labels based on expert knowledge, i.e., the rules are taken by experts to later adapt and learn rules for the manipulation of the system (Gómez and Maldonado, 2011; Ponce, 2010). Data mining is to extract information from the data, give them a sense and draw useful conclusions from them, by describing patterns in large datasets (Benítez, 2013).

Bayesian Networks is a probabilistic model of a function of joint probability distribution, to establish relations of cause and effect in probabilistic reasoning systems and integrates uncertainty and expert systems. These networks can be multinomial, continuous and mixed or conditional Gaussian. Genetic Algorithms or Genetic Reproductive Plans, emulate natural selection on a set of individuals to seek the best solution iteratively to a given problem, i.e., it uses the encoding parameter modeling system, which in turn is the genotype which corresponds to a solution of the problem (one or several objectives), optimizing local minimum or maximum in an objective function (Benítez, 2013; Armendáriz *et al.*, 2014; Ponce, 2010). The applications in engineering are in the design, optimization and segmentation of images and the search of the best strategies (Cárdenas Cardona, 2012).

On the other hand, the analysis of the real world or a complex situation leads to the construction of a model, to understand, explain, or explain fundamental processes of the phenomenon studied and to analyze emergencies, dynamics, processes, elements and other aspects that cannot see. Emerging systems in which complex problems are solved and exhibit a high degree of intelligence combining simple and inexpensive intelligent subsystems, such as neurons (Benítez, 2013). Engineering Complex Systems, is an interaction of many elements that interact in a nonlinear way according to relatively simple rules and a global control, i.e., they operate far from equilibrium, in order to self-organize and adapt to changing environments and fraught with uncertainty; including attributes of autonomy (control their own behavior and take their own decisions based on the information), scalability (is the ability to operate with few agents), flexibility (no agent is indispensable for the functioning of the system), adaptability (the system must adapt to a changing environment by the interaction of agents), evolvability, auto-organization (it is the ability of a system to increase its complexity, stabilize and perform

a task without requiring the intervention of any expert agent), resilience, robustness (the information processing and making decision is decentralized), durability, among others. The paradigms of computer architectures and models, have created techniques to model, approach and simulate complex systems based on biological metaphors, such as cellular automata, modeling and agent-based simulation (Gómez and Maldonado, 2011; Maldonado and Gómez, 2010; Cárdenas Cardona, 2012; Kar, 2016).

Collective Intelligence or swarm intelligence is an art of Bio-inspired algorithms and Engineering Complex Systems, for the organization, through collective behavior and coordinated a set of behaviors and intelligent behavior, i.e., this technique emulates when individuals solve their problems linked to survival, in a distributed and parallel way and are capable of carrying out intelligent tasks such as finding the shortest path between two points, constructing complex structures and sharing tasks among themselves (Gómez, 2015; Cárdenas Cardona, 2012). The development of algorithms to explain this technique, are subdivided into Optimization by Ant Colonies (they are heuristic methods to approximate solutions to combinatorial optimization problems, multiobjective and multivariable), particle swarm (a set of alternatives or potential solutions to the problem is modeled (multiobjective and multivariable) as members of the swarm in a multidimensional space of possible solutions) and cellular automata (this is a set of objects on a region capable of acquiring certain states as time elapses). The application in the engineering area, establishes task planning, network routing, sequential ordering, simulation of natural systems, among others (Cárdenas Cardona, 2012; Elbeltagi *et al.*, 2005; Kaveh and Talatahari, 2009).

#### **Applications of bio-inspired engineering and complex systems engineering in water management:**

Computational methods of Bio-inspired Engineering and Complex Systems Engineering, used in the processes of decision making in water resources management under the complexity of the system, the robustness of the results, consider: stochastic programming, multicriteria, games theory, series of games, linear programming, diffuse programming, (Li *et al.*, 2009; Xu and Zhou, 2013; Yan *et al.*, 2015; Li and Guo, 2014; Shi *et al.*, 2014; Read *et al.*, 2014; Ito *et al.*, 2001) and other prediction models as regression analysis, series time, index prediction, artificial neural network, support vectors, hybrid neural network models, Bayesian networks, that consider the uncertainty in the structure and results of the model, as well as water quality risk, adaptive management to uncertainties and the knowledge of the basin (Zeng *et al.*, 2014; Taormina *et al.*, 2012; Bakhtiari and Bougila, 2014; Zhao *et al.*, 2014).

We used the Bio-Inspired Engineering, with the technique of fuzzy logic in drought forecasting, control water loss and zoning in the distribution networks of drinking water, analysis, drinking water quality and network management of water supply, as well as river water management models in terms of quantity and quality of water, which results in the allocation of pollutant loads in minimum and maximum limits, ecological impact, as well as making decision as to restrictions or permits to discharge pollutants with aspects of economic optimization (Carvajal Serna, 2013; Babea, 2010).

Work has been done on the prediction of water consumption and river flows, in the assessment of the quality of drinking water, in the control of water treatment processes, management of waste water treatment plants, groundwater purification and identification of sources of water pollution in terms of dioxins and sediments in rivers with the technique of Artificial Neural Networks, (Babea, 2010). Other results of studies by Hamoda *et al.* (1999) and Grieu *et al.* (2005), have established that the performance of PTARM can be predicted through a neural network and also other studies such as Hamed *et al.* (2004), Mjalli *et al.* (2007) and Tomenko *et al.* (2007) have shown, that neural networks have outperformed the regression models used in wastewater treatment plants (West and Dellana, 2011). In addition, Dogan *et al.* (2009) and Singh *et al.* (2009) using neural networks for the prediction of river water quality in watersheds have conducted studies. However, a cumulative error effect over a period of several years also has been found in Beck (2005), which, although generating a considerable approximation in cumulative predictions over multiple time periods, is highly significant and influential in quality of water in the river basin (West and Dellana, 2011). Another application has been in the analysis and diagnosis of a wastewater treatment plant (activated sludge technology), due to the high variability of the concentrations of parameters of the raw (tributary) wastewater and the knowledge of the performance of the processes and biological unit operations present in the wastewater treatment plants. Therefore, it did an analysis using neural networks, to discover dependencies between the process variables and the actual behavior of the wastewater treatment plants and potential application to other wastewater treatment plants (Hong *et al.*, 2003). Neural and statistical linear models have applied for the application of water management in watersheds, taking into account effluents from wastewater treatment plants and non-point sources (rainfall runoff).

Bayesian Networks technique, has been worked on probabilistic prediction of quality water, episodes of flooding in rivers, reservoir levels, anaerobic treatment in wastewater, eutrophication studies, water supply management, control of wastewater treatment plants,

impacts due to climate change in surface water bodies and in making-decision processes in water management, specifically in quality and environmental, social and economic impacts (Mediero, 2007); with the Evolutive Algorithms technique, used in distribution water, fluvial and hydrological models, urban drainage, water supply, calibration of hydrological models, watershed modeling, wastewater treatment systems, for the optimization of making decisions and model efficiently water management (Lerma *et al.* 2015; Dumedah, 2015).

Investigations has been conducted by Afshar *et al.* (2009) and Farmani *et al.* (2006) using genetic algorithms to minimize construction costs in the optimal design of wastewater collection systems (Rani *et al.*, 2013) with the Genetic Algorithm technique; other studies conducted by researchers such as Seleshi *et al.* (1994) on serial dependence of wastewater processes and prediction of discharge points, only BOD and SST parameters (West and Dellana, 2011). In watershed planning, studies were conducted by Chen and Yeh (1997), where genetic algorithms for multi-objective planning were included to establish the system cost and the detention effect at basin level. In addition, Harrell and Ranjithan (2003) applied genetic algorithms to identify tank designs and land use in watersheds. The combined use of genetic algorithm models and simulation can be seen in many basin management studies, Perez-Pedini *et al.* (2005), combine a distributed hydrological model with GA for urban basin to determine the optimal location of best management practices based on infiltration for the management of rainwater (Rani *et al.*, 2013; Ketabchi and Ataie-Ashtiani, 2015).

Some research has focused on the design of the wastewater system, which is needed to define the performance and impact of the combination and separate sewer systems, not only in terms of physical capacity and performance overflow, but also in terms of loads generated in the receiving body, with the Collective Intelligence technique (Izquierdo *et al.*, 2008; Tan *et al.*, 2008).

#### **Future guidelines for bio-inspired engineering and complex systems engineering in water management:**

The trends of change in engineering aspects, especially in the environmental theme and particularly in the environmental planning of water resources, establish the interaction and application of computational techniques used in design, calibration of models, systems operation and planning of hydric systems (Maier *et al.*, 2014), as a significant alternative for the optimization of making decision, future investment and intervention in the basin, with a view of the analysis of the situation with the knowledge and information of the water resource, from the field of seasonal water planning, with interrelated medium-term objectives

with relevant short-term actions, taking into account stakeholders and/or actors, constraints, potentialities, conditions and perspective of strategies, inherent risks, investments, among other aspects.

In that sense, the Bio-Inspired Engineering and Engineering Complex Systems can be potentially interesting tools in the search for a planning and environmental planning of watersheds, as they are able to solve problems with significantly difficult mathematical properties due to abstraction real world of the basin, taking into account: the selection and definition of decision variables (including objectives and constraints), evaluation of objectives and limitations of the values and optimal solutions in making decision; generating simulation models that adapt to the application contexts and reduce the problem (Maier *et al.*, 2014; Roach *et al.*, 2015), exploring more optimal options for solving the problem of water environmental planning.

A working need is to understand the relationship between the properties of the problem to be solved, the type of computational technique applicable to the problem (influence of the parameters that controlling the sensitivity, convergence and changing behavior of parameters) and the performance of the applied technique, i.e., because some techniques work better in certain types of conditions problem, applying attributes as autonomy, scalability, flexibility, adaptability, evolution, self-organization, resilience, robustness, durability, among others.

## CONCLUSION

Bio-inspired Engineering and Complex Systems Engineering, attempt to replicate in their techniques the biological organisms to represent a real optimal solution, which can be a way of being applied in the management of water resources used in making decision at strategic level, especially in aspects of planning, which have still been little explored. The application of these computational techniques has been focused on very specific problems of optimization (calibration of water distribution models, allocation of environmental flow, operation of reservoirs and potable and residual treatment water systems) in water resources, but little or rather nothing, in the water environmental planning of a river basin. According to the above, it may show that there is no causal relationship between computational techniques, environmental planning and making decision in watersheds using Bio-Inspired Engineering and Engineering Complex Systems.

What is interesting is to integrate the particular or atomized intelligence to solve a specific problem in a river basin and social collaboration to find a criterion of a group of users, whose intelligence could be integrated, recognizing potentialities for the analysis of

relationships and interactions, to facilitate robustness, flexibility and self-organization.

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## CONFLICT OF INTEREST

The authors inform they do not have any conflict of interest that may have influenced the development of the manuscript.

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