No-free-lunch-theorem: A page taken from the computational intelligence for water resources planning and management

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Abstract

The long pursuit to alleviate the global water crisis has been riddled with revolutionary decision-making paradigms, forward-thinking theoretical concepts, and even ground-breaking technologies. This journey, however, is centered around the expectation of discovering what could be seen as the ultimate solution to all water-related problems. These nuances, revolutionary ideas, and cutting-edge technologies raise an ostensibly simple but fundamentally crucial question: Is there or can there ever be a singular universal ideal solution to address the water resources crisis that can potentially ensure the ideas of the sustainable development paradigm? This paper tends to take inspiration from the well-established no-free-lunch theorem (NFLT) to refute the possibility of such a solution in the context of water resources management. Such an interpretation also emphasizes that any remedy intended to address water resources issues must be tailored to the particular circumstances of each case. However, it should be noted that these findings are not intended to undermine the importance of current approaches but rather to emphasize how these concepts or technologies should be used as an inspiration to curate an ad-hoc version of the said solution that can reflect local requirements or constraints.

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1. Introduction

Arguably, one of the most prominent obstacles to securing global sustainability is the threat of the impending water crisis looming over residential, commercial, industrial, and agricultural water-consuming sectors (Zolghadr-Asli et al., 2017a; Mishra et al., 2021a; Vollmer & Harrison, 2021). The root of the current exacerbated water crisis can be sought through the water balance components. Recent studies predict that such trends will continue into the foreseeable future as global water demands continue to rise (Lund Schlamovitz & Becker, 2021; Salehi, 2022). Conversely, the quantity of freshwater available at any given time in a particular location is somewhat limited. The resulting unbalance between these components creates water deficit-related issues. The problem is more prominent in regions such as the Middle East, which have long struggled with an ongoing water crisis, where the intake components of the hydrological cycle, such as precipitation, cannot counterbalance the amount of withdrawn water (Bozorg-Haddad et al., 2020). As a result of this, it is estimated that around 4 billion people are experiencing a severe water shortage for at least one month annually (Mekonnen & Hoekstra, 2016). In the meantime, 2.2 billion people currently do not have access to safe drinking water (Lord et al., 2021). It is worth noting that, through altering the components of the hydrological cycle, climate change is another critical factor that continuously exacerbates the situation.

As stated earlier, water has a wide variety of consumers ranging from the residential and agricultural to industrial and energy sectors. As such, when it comes to water resources planning and management, it is quite crucial to reflect on each stakeholder’s requirements, ranging from the portion of water demands, the water quality constraints, or the variation in the water demand time series. Additionally, it is worth noting that there are cases in which two or more separate entities share jurisdiction over a specific water resource. Historically speaking, the dispute over shared water has caused conflicts, whether internally or among different nations (Zolghadr-Asli et al., 2017b). All in all, these are a few examples to highlight the intricacies that are associated with modern water resources planning and management.

Over the years, different decision-making paradigms, administrative frameworks, state-of-the-art technologies, and scientific concepts have been proposed and theorized that aimed to take the whole industry one step closer to a more well-rounded and effective water resources planning and management standard. The recurring theme in all these attempts was to provide a long-lasting, economically feasible solution with minimum environmental impacts (Zolghadr-Asli et al., 2021a). With the advent of the water-energy-food (WEF) nexus concept in recent years, these frameworks have been trying to acknowledge how the actions of other sectors, such as the agriculture or energy industry, can be reflected in the water industry (e.g., Liu et al., 2017; Mukherji, 2022). Furthermore, as the concern over climate change has been growing in the scientific community, these attempts have been gravitated toward this direction to account for such problems and mitigate any potential adverse impacts (e.g., Enayati et al., 2021; Molajou et al., 2021; Soleimanian et al., 2022). Though it may not be a novel concept per se, integrated water resource management (IWRM) was another theoretical concept that gained traction over the years as a basic guideline to achieve sustainable development in the context of water resources management (e.g., Kafy et al., 2021; Ngene et al., 2021). The gist of this concept was to promote the idea that achieving true sustainability would not be possible without acknowledging the role of other natural resources (e.g., air, soil) and how preserving the ecosystem, mitigating the environmental impacts, and socio-economic evaluation should be incorporated into water resources management schemes (Biswas, 2008). Alternatively, resorting to out-of-the-box engineering-based solutions such as interbasin water transfer (Zhuang, 2016; Rollason et al., 2022) or water augmentation via seawater desalination or recycling water (Crutchik & Campos, 2021) are other known practical approaches to remedy the water shortage-related problems on a local scale.

In light of these nuances, revolutionary ideas, and cutting-edge technologies, one needs to raise a seemingly simple yet crucially fundamental question; Is there or can there ever be a singular universal ideal solution or remedy to cope with the water resources crisis that ensures sustainability in the context that was depicted under the sustainable development paradigm?

From a broader perspective, there are two general opposing schools of thought as one approaches this question. Firstly, there are those who debate the very existence of such solutions. The gist of such ideology, for instance, can be summarized beautifully in the famous quote from the British statistician, George Box, who said "All models are wrong, but some are useful" (Skogen et al., 2021). The implication behind such a statement is that while simplified representations of the reality that we call models are innately incapable of capturing the whole essence of a phenomenon, there is still useful information that can be extracted from them. Note that the intention here is not necessarily to undermine the importance or, arguably even the capacity of these models, but rather to merely acknowledge their shortcomings to capture the entirety of a complex problem in a simplified and somewhat limited representation.

Another example that comes to mind that essentially echoes this idea at its core is the concept of post-modern science (PSN). The philosophy behind this idea was to debate why often in real-world cases, such as most global environmental-related issues, where there are notable uncertainties surrounding the problem, there are multiple stakeholders with opposing interests, the stake is high, and decisions are urgent, tradition scientific-driven paradigms cannot adequately handle the issue at hand (Funtowicz & Ravetz, 1991). Again, it could be argued that this concept highlights how, rather than why, the conventional way of interpreting a problem by seeking a singular unifying solution is failing in practice, most notably in the context of complex environmental issues. Conversely, there is this counter-argument that at its core asks what if there can be a technology, a theoretical concept, or perhaps a decision-making paradigm in the future or perhaps via modifying current variations of these, one can create this ultimate solution to these complex problems in water and environmental sciences.

In this paper, we tend to delve into this theoretical discourse and shed light on less-explored angles of this subject from a fresh perspective. The cornerstone of this argument would be based on one of the most fundamental principles in computational intelligence science called the no-free-lunch theorem (NFLT), a concept that will be explored further in the next section.

2. No-free-lunch theorem in a nutshell

NFLT is arguably one of the most fundamental computational intelligence principles. Although it was theorized formally in the late 1990s (Wolpert & Macready, 1997), the theoretical inspiration behind this idea can be traced back to the mid-18th century, when the Scottish philosopher David Hume highlighted the limits of inductive inference in observation-based studies (Adam et al., 2019). In essence, the core idea behind the NFLT is to advise caution about the generalization of an observed pattern or principle in a limited sample or data set. In the context of data-driven models, the NFLT is an impossibility theorem that states a general-purpose, universal strategy can never exist in perpetuity (Gómez, D., & Rojas, 2016).

When it comes to data-driven models, for any given computational task, be it optimization, data mining, simulation, predictions, or machine learning, there are typically multiple viable options. While these alternatives vary from one another in terms of underlying principles, prerequisite conditions for input data structures, or computational structure, they seemingly offer to execute the same task and provide reasonably similar solutions. Moreover, oftentimes, the computational structure of data-driven frameworks, such as computational intelligence-based optimization algorithms or machine learning models, would be equipped with a number of parameters to provide much-needed flexibility to better match the unique features and requirements of a given problem. One can potentially improve the performance of a given algorithm for a specific problem by tuning these parameters.

In light of the above information, the NFLT, from a practical point of view, has two major implications, which are as follows (Yaghoubzadeh-Bavandpour et al., 2022):

I. There can never be a singular data-driven model or algorithm that can consistently outperform all the other alternatives in all possible questions; and

II. For any given data-driven model or algorithm, there can never be a singular optimum parameter setting that can lead to the best performance for all possible questions.

All in all, these show how algorithm selection and parameter fine-tuning are crucial in data-driven models. In other words, for any given problem, one must opt for the most suitable algorithm and fine-tune its parameters to best cater to the given situation.

3. Interpretation of NFLT in the context of water resources management

One way to interpret the general idea behind the NFLT is to acknowledge that while there can be a number of feasible options that can, in and of themselves, potentially be a viable and effective solution to a given problem, none can be by default assumed to be the suitable match that can guarantee the optimum outcome. In a sense, a problem's unique features dictate a solution's suitability. However, one can redefine the NFLT principle in the context of water resources, and in extend environmental management. In that case, one can draw rather interesting conclusions that showcase how modern decision-making paradigms or state-of-the-art technologies in this industry should be perceived in general.

Similar to what was explored in the previous section, the implications of following this logic in the context of water resource management would be twofold:

I. Firstly, this principle highlights the notion that while there can potentially be many formidable solutions available for any given problem in this field that can eventually lead to acceptable results, no general-purpose, universal strategy *can ever exist* that outperforms other alternatives in all cases and conditions. The term "can ever exist" in the previous statement has a critically crucial implication. The idea being that while it is implied that the results obtained in proposed research studies are often attained in a case study-based situation, there was always this feeling, or even insinuation, that such frameworks, ideas, or technologies can potentially be seen as the "ultimate solution" to the ongoing water crisis with minimum to no adjustment. At the very least, the idea of an "ideal solution" was always an enticing-enough theoretical concept to strive for in such situations. This principle, however, refutes the notion that these results can never be over-generalized in any shape or form. The point being that while such resolutions, whether they are represented as a decision-making paradigm, a theoretical concept, or a newly introduced technology, can have acceptable performance or even arguably result in near-optimum solutions on case-by-case bases, there can never be a guarantee that they can lead to the same result even in cases with similar underlying tones; and

II. Secondly, the best *relative* performance for any of these proposed solutions can be obtained if and only if the said approach is tailored to the specific conditions of a given case. The idea behind recognizing relativity in the previous statement is to highlight how the performance and, in turn, acceptability of any option can vary based on how the said options are set up, reflecting on the notion that tailoring a tentative solution to fit the unique requirement of a problem can potentially led to more rewarding outcomes. The said concept is equivalent to the fine-tuning procedure for computational intelligence-based algorithms. The point is that even a seemingly suitable approach needs additional personalization to fit a given problem's unique requirements.

As to why the NFLT concept can resonate effortlessly within the context of water resources management can be sought in the multi-dimensional and multi-stakeholder nature of water resources. As one of the most fundamental infrastructures of a society, often water resources systems, and water resources in general, needs to be justified on multiple fronts that are bound by factors ranging from the technical side of things to economic, cultural, environmental, socio-political, or legislative-related constraints (Bozorg-Haddad et al., 2018; Graf & Pyszny, 2021; Zolghadr-Asli et al., 2021c). Add to this the fact that, when it comes to water resources, more often than not, one needs to accommodate multi-stakeholders with often conflicting interests (Ganji et al., 2007; Fallah-Mehdipour et al., 2011; Kazemi et al., 2022). All in all, the combination of these can potentially create a complex situation for water resources planning and management, where meeting the needs of one stakeholder or leaning toward a specific criterion may come at the cost of relinquishing other fronts of the described problem. This can be manifested practically in various forms and different problems ranging from water allocation to controlling the water quality of both surface and groundwater resources. The ultimate goal in all these cases would be to attain a solution that can accommodate all the stakeholders' requirements and account for the said criteria. As the NFLT dictates, however, it is *theoretically* impossible to satisfy all these factors to the fullest without compromising on one or multiple fronts.

To better reflect on this notion, it is best to review some practical cases to demonstrate the validity of this school of thought. An interesting illustration of this idea would be the case of recycled water in Kuwait. Like many Middle Eastern nations, Kuwait has long struggled with an ongoing water crisis (Darwish & Al Awadhi, 2009). To accommodate these ever-increasing demands, in addition to limited available conventional resources, they have resorted to desalinating brackish aquifer water (Alhumoud et al., 2003). In a conscious attempt to remedy the situation, in the mid-1950s, the government made an effort to invest in wastewater recycling so that repurposed water could be used in the agriculture industry (Alhumoud et al., 2003). If proven successful, the said augmentation resource could have also been used to meet the urban non-potable sector as well. This practice has been proven to be successful in cases such as Belgium, France, the UK, and Germany (Lazarova et al., 2003). Surveys, however, revealed that Kuwaiti citizens are not keen on such projects, to the point that even enticing financial options such as bringing down the price for the customers would not convince them to implement these resources in their day-to-day uses (Dolnicar & Schäfer, 2009). Despite the fact that such projects may seem appealing on paper, at least from a technical side of things, cultural and religious motivations would hinder the success of this alternative in a practical case (Etale et al., 2020). As such, while this option may check all the boxes to remedy the water crisis and may very well be considered as such under different circumstances, it cannot be seen as a viable option in this particular case.

Another textbook example of such a situation would be the case of Gotvand Dam, Iran. Iran can be classified as a semi-arid to an arid region. As such, like regions with similar situations, it often resorts to infrastructure-based solutions, such as constructing dams to cope with water shortage problems (Shinde et al., 2011). One of the primary ideas behind dams is to regulate the spatiotemporal distribution of stream flows so that the stored water can be tapped at the time of need. While dams have long been considered one of the main pillars of water resources security in semi-arid to arid regions, designing, layout, and operating these systems would rely heavily on several technical factors (Cech, 2018). As such, each case requires to be carefully engineered to reflect these measures. However, failing to capture any of these factors could have devastating effects, which was the case in Gotvand Dam, Iran. Over the past, Iran has heavily invested in constructing new dam sites to ensure agricultural productivity, increase hydropower generation, and secure urban water supplies. Currently, with 316 small and large dams, and an additional 132 under-construction dams which are about to be introduced to its water network, Iran ranks third in the world with respect to the number of dams it has under construction (Madani, 2014). The recklessness of leaning heavily on such a structured-oriented strategy notwithstanding, it is crucial to remember that even if a strategy has proven fruitful in a span of time, the situation could as easily get reversed if the underlying conditions change. In the case of Gotvand Dam, Iran, for instance, soon after the reservoir came in line in 2011, the quality of upstream water and, in turn, stored water started deteriorating drastically. Exposure to several salinization sources, including crop fields' excess runoffs, extreme evaporation from the dam's reservoir, and intrusion of oil-field brine, are among the main cited reasons that may have contributed to this phenomenon (Jalali et al., 2019). Obviously, this singular case cannot undermine the many benefits of dams altogether, as the NFLT highlights, nor the previous successful experiences in this regard could have guaranteed a favorable outcome for the said project.

Another example of this notion would be the Tajo-Segura interbasin water transfer project in southeastern Spain. Considered one of the largest hydraulic infrastructures in Spain, the primary mission behind the Tajo-Segura interbasin water transfer project was to convey water from Tajo Watershed in central Spain to Segura Watershed in southeast Spain, where the water would be used primarily for irrigation and tourism purposes (Ballestero, 2004). Initially, the plan was for the project to stay operational until 2012, when the local communities could adopt farming practices that were more in line with the region's natural water scarcity (Kroll et al., 2013). Getting accustomed to this additional water supply and the financial gains that came with overexpanding the agricultural practices delayed the said deadline, as local farming communities were reluctant to forgo their temporary permitted water rights. To some extent, this has even undermined the desalination projects that were proposed as an alternative to fill the void of a reliable water resource should the said interbasin water transfer project is to be shut down, as the farmers are leaning more toward this resource than desalinated water mainly as the latter has been a more economically affordable option for irrigation purposes (Martínez-Alvarez et al., 2017, 2020). Failing to predict and reflect on this seemingly basic socio-economic behavior, though it may seem a slight misstep from the decision-makers, has led to more significant issues, such as increasing interregional conflicts and water allocation demands, exponential growth in illegal water use, the appearance of new water users who challenge the long-term privileges of large historic water holders, and increasing ecological deterioration, just to name a few (Hernández-Mora et al., 2014). This goes to show how the acceptability of a water resources plan is subject to change over time, and a once prosperous plan can eventually lose its traction if it fails to adapt to the current situation. Again, reflecting on this case from the NFLT perspective shows that while an alternative may seem optimum at a given time, given that some contributing factors are subject to change dynamically through time, it is impossible to maintain the same level of acceptability for that given project.

At the end of this, it should also be noted that none of the above statements is to undermine or dismiss the merits of any of the mentioned projects or the presented alternatives in general, but rather to point out that, based on what is suggested by the NFLT, the idea of a universal solution for water resources, and in extend environmental engineering, can theoretically never exist in any shape or form. The point being that the desirability of a given alternative is subjected to many attributes, including socio-economic, environmental, technical, cultural, and political factors, properties that can also change dynamically over time. As such, the performance and, in turn, acceptance of an alternative may vary drastically from one case to another. This is because, in each case, these factors may be interpreted differently for even the same project as the set priorities may, and in all likelihood, would vary from one case to another. Moreover, based on the NFLT principles, it is crucial to note that to get the best performance out of an alternative, one needs to adjust or, in a sense, fine-tune the said idea to reflect on these localized priorities. The latter procedure can be seen as a way to personalize an alternative to better cope with the unique requirements of a given case.

4. Concluding remarks

In the long pursuit of a remedy to the global water crisis, whether through revolutionary decision-making paradigms, forward-thinking theoretical concepts, or even ground-breaking technologies, there was always this expectation of identifying what could be perceived as the *ultimate solution* to all water-related problems. The said solution was believed to be a blueprint plan that can be applied to all cases with minor to no adjustment, account for every possible angle to that problem, and achieve every perceivable target set for that project ranging from environmental to economic factors. More importantly, the general understanding was that any obstacle to reaching this ideal remedy was exclusively rooted in the practical side of things, meaning that out of the infinite number of feasible solutions that have been or could potentially be identified in the future, there were at least one options that could meet the said description.

However, reexamining this subject from the NLFT principle can perhaps shed light on the futility of this scientific quest. The primary implication of the NFLT principle is to state that there can never be a universal, general-purpose algorithm that can consistently outperform all feasible options in any given case. Moreover, to get the best performance out of any given algorithm, one needs to fine-tune its structure to ensure that it best matches the requirements of a specified problem. Building upon this school of thought, one can now debunk the possibility of such an ultimate solution in the context of water resources management. Such interpretation also implies that any given remedy that tends to tackle water resources problems needs to be modified to better reflect on the unique situation of a given case. Nevertheless, what is important to note here is that such factors may not always be technical in nature but could be rooted in socio-political, economic, or environmental considerations.

With the implication of the NFLT in the context of water resources in mind, it is time to reflect on the necessity of state-of-the-art technologies such as desalination or innovative theoretical concepts such as integrated water management. One might wonder, at this point, whether the NFLT tends to undermine or render these solutions obsolete, as it implies that no general-purpose, universal solution can ever exist to remedy all water problems. While it is true that none of these can be seen as the ultimate solution to the water crisis, on the contrary, the principle behind these solutions is indeed universal. The point is that while the implication of these ideas or technologies may need to be adjusted to reflect on specified requirements of a given case, they can work as a broad guideline to identify the optimum solution for the said project. Ultimately, the idea here is to use these concepts or technologies as an inspiration to curate an ad-hoc version of the said solution that reflects on local conditions. The said solution, while inheriting the central concept from these general ideas, is personalized enough to cope with the unique requirements of a specific case.

Statements & Declarations

Ethical Approval

The authors declare all data and materials, as well as software applications or custom codes, are in line with published claims and comply with field standards.

Consent to Participate

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