Assessing Computational Tools for Artful Rainwater Design: Evaluating Flow Simulations in Smallscale Hydrology

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Abstract: Small-scale hydrology is vital to landscape architecture, particularly in urban environments where water management must integrate functionality with visual appeal. Artful Rainwater Design (ARD) emphasizes creating sustainable, expressive landscapes that celebrate water's dynamic behavior while managing stormwater. This research began with a preliminary evaluation of approximately 20 computational tools, narrowing the focus to three – Flow3D Hydro, Autodesk CFD, and Blender, for detailed analysis. Using the Flow Box test, we measured flow behavior variables such as flow rate adjustments, water drops, splashes, and visualization capabilities to assess each tool's reliability, accuracy, and usability. The findings demonstrate the potential of computational simulations to capture complex water interactions in ARD, providing valuable insights into simulation criteria for designing functional and visually engaging water management systems in small-scale applications.

Keywords: Small-scale hydrology, artful rainwater design (ARD), computational fluid dynamics (CFD), water flow simulation, water flow visualization

1 Introduction

Landscape architecture is an interdisciplinary field that combines art and science (GAZVODA 2002, Nijhuis 2013, HARVEY & FIELDHOUSE 2004), with certain specialists focusing on civil engineering, ecology, or computer science (GAZVODA 2002). The increasing demand for expertise in natural systems, particularly water, has led to the introduction of new resource management and planning techniques (WALL & WATERMAN 2010, MOTLOCH 2000), highlighting the importance of landscape hydrology (FERGUSON 1991).

1.1 Hydrology

Contemporary hydrology investigates how water moves throughout the Earth's surface and atmosphere (DAVIE 2019, SAHA & PAL 2024). Accurate measurements are required to understand these processes and interpret data (WARD & ROBINSON 1967). The problems include streamflow prediction (KHANDELWAL et al. 2020), parameter estimates, watershed model building (ARNOLD et al. 1998), and the application of data-driven modeling (DDM) approaches (ELSHORBAGY et al. 2010). The lack of tools for doing smaller-scale hydrological research complicates the effort, necessitating improved approaches and interdisciplinary collaboration.

1.2 Computational Hydrology

Computational hydrology forecasts and evaluates hydrological processes through simulations and analysis; yet, developing models and validation require significant effort (ASTAGNEAU et al. 2021, ESSAWY et al. 2018). Addressing model uncertainties, integrating inter-disciplinary sciences, increasing real-time data processing, and building reproducible

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procedures are among the challenges (PANICONI & PUTTI 2015, MARIA 1997). Computer simulation, which was picked for this work, is useful for studying complicated water systems when direct analysis is challenging or expensive (LAW 2022, BANKS 1999).

1.3 Artful Rainwater Design (ARD)

Artful rainwater design (ARD) is an innovative approach to stormwater management that blends environmental sustainability and creative expression, improving both ecological health and aesthetic value in landscapes. It includes a variety of elements such as ponds, creeks, bioswales, and scuppers, each of which serves a specific purpose in water management while also contributing to the visual and educational experience. Ponds are aquatic bodies meant to collect and store rainfall, whereas streams and bioswales manage stormwater flow and filter pollutants through moving water. Scuppers, basins, and cisterns, depending on the design, direct the flow of stormwater, which can be stationary or moving, while rain chains provide a stylish manner to channel water from roofs to the ground.

Plunge pools and features such as runnels and flumes make stormwater movement audible and visible, incorporating it into the environment as a dynamic, eye-catching element. ARD emphasizes the role of water in education, wetland protection, and ecological health, advocating for creative, sustainable solutions that promote community engagement and environmental responsibility (ECHOLS & PENNYPACKER 2006, ECHOLS & PENNYPACKER 2008). ARD enables effective water management by implementing Best Management Practices (BMPs), improving the operation of urban spaces while encouraging biodiversity and public participation in sustainable practices (DREISEITL 2013).

2 Problem Statement

Landscape architects and environmental designers often lack efficient and accessible computational tools to address the complexities of small-scale hydrology in ARD. CFD techniques offer the potential for precise simulation and visualization of water flow in constrained spaces. However, further research is needed to evaluate CFD's applicability to ARD projects, as challenges related to accuracy, forecast reliability, and tool performance at this scale remain unresolved.

Many designers have attempted to use CFD in their studies to address this problem, but more work is needed to streamline processes, develop software at this scale, and improve calibration methods to align simulations with real-world scenarios. Additionally, there is a lack of comprehensive reviews comparing different software options, which could guide designers in selecting the most suitable tools for ARD applications.

2.1 Research Precedents

HE et al. (2008) used CFD to optimize a stormwater clarifier, significantly reducing maintenance costs associated with lamella plates. New intake designs were evaluated using Fluent software, enhancing cost-effectiveness while maintaining pollutant removal efficiency (HE et al. 2008)

KHAN et al. (2013) used CFD to study stormwater retention pond flow patterns. They used ANSYS CFX to develop a 3D CFD model, including particle tracking velocimetry and physical modeling. Their study, which focused on mesh density, advection schemes, and turbulence models, demonstrated the dependability of CFD for pond hydraulic design (KHAN et al. 2013).

LEE et al. (2013) reviewed CFD applications in agro-environmental sectors, focusing on water, land, and atmospheric management. Despite its widespread use in engineering, CFD application in agriculture remains in its early stages. The review highlighted several challenges, including validation techniques, and recommended further research in pollution prediction and the design of agricultural structures (LEE et al. 2013).

TSAVDARIS et al. (2015) used CFD to assess stormwater detention pond configurations, focusing on vegetated vs. non-vegetated designs. Their study identified optimal designs for sustainable flow and sedimentation, emphasizing the role of vegetation in turbulence and hydraulic performance. The elliptical pond with a central island showed the best performance (TSAVDARIS et al. 2015).

MUKHOPADHYAY's keynote (2017) emphasized the growing influence of real-world data and cross-disciplinary algorithms in CFD, enabling faster insights compared to traditional methods. He highlighted the need to advance algorithms, analytics, and simulations to efficiently address industry needs, leveraging abundant data for scalable insights (MUKHOPADHYAY 2017).

SHEVADE et al. (2020) developed and validated a CFD model for curb-cut inlets in green infrastructure. They addressed the challenges of real-world conditions versus lab settings and highlighted the importance of flow rates, slope, and clogging for optimizing inlet designs (SHEVADE et al. 2020).

2.2 Research Objectives and Questions

This research aims to review software related to water simulation and visualization in small-scale designs, specifically for Artful Rainwater Design (ARD) projects. Using the Flow Box test, it will evaluate the application, strengths, and weaknesses of selected CFD tools, including Flow3D Hydro, Auto-desk CFD, and Blender, and assess their reliability, accuracy, and usability. Given that the research is in its early stages, we will initially rely solely on the software outputs, as the self-sufficient nature of the Flow Box test negates the need for physical experiments at this point (real-world validation is planned for future work). Additionally, we are developing protocols and workflows to support both experts and non-experts in future research, and our evaluation incorporates both commercial software and accessible open-source options like Blender

2.2.1 Research Questions

1. What are the applications, strengths, and weaknesses of related software in computer-simulating water flow for small-scale hydrology with a focus on ARD?
2. How reliable, accurate, and user-friendly are selected software such as Flow3D Hydro, Blender, and Autodesk CFD in evaluating water behavior through Flow Box tests?

3 Methodology

This study uses modeling and simulation as key approaches for analyzing stormwater, with a focus on the quantitative features of rainwater at the Artful Rainwater Design (ARD) scale.

Modeling entails building simplified representations of systems in order to predict changes, whereas simulation uses these models to analyze system behavior, particularly when direct experimentation is impractical, expensive, or time-consuming (BISHOP 1974, MARIA 1997). These methods, which incorporate mathematical and digital tools, allow for extensive studies and experiments.

While large-scale hydrological models are effective at addressing challenges such as flood forecasting (Xiangyang and Tianyi) and rainfall-runoff prediction utilizing advanced technologies such as artificial neural networks (GHOLAMI & SAHOUR 2022), smaller-scale water flows pertinent to ARD are poorly understood. Current stormwater management models frequently assess Green Infrastructure (GI) efficacy, ecological feasibility, and integrated functionalities. However, few address localized hydrological flows or the specific requirements of ARD systems.

3.1 Preliminary Software Evaluation

After reviewing over 40 software products, we identified 21 that can produce animations during or after use. We next evaluated them to better understand their applications. We specifically looked at whether they were CFD or non-CFD, ideal for visual effects or scientific investigations, commercial or open source, and had a Graphical User Interface (GUI) or required inputting commands or coding. The results are displayed in the table below, with plus (+) indicating that the software supports a specific factor and minus (-) indicating that it does not.

Table 1: Associated software and outcomes of the initial evaluation

Software Name		Type		Purpose		Accessibility		Skill Level		
		Non-Cfd	Cfd	Visual Effects	Scientific	Commercial	Open Source	Gui	Command Driven	Coding
1	Altair CFD	+	+	-	+	+	-	+	-	-
2	Ansys Fluent / Fluent / Ansys CFX	+	+	-	+	+	-	+	-	-
3	Autodesk CFD	+	+	-	+	+	+	+	-	-
4	Bifröst (Maya)	+	-	+	-	+	-	+	-	-
5	Blender	+	-	+	+	-	+	+	-	-
6	DualSPHysics	-	+	-	+	-	+	-	+	+
7	Elmer	+	+	-	+	-	+	+	+	+
8	eVe	+	-	+	+	+	+	+	-	-
9	Flow 3d Hydro	-	+	-	+	+	-	+	-	-
10	Houdini	+	-	+	-	+	-	+	-	-
11	M-STAR	-	+	-	+	+	-	+	-	-
12	Open FOAM	-	+	-	+	-	+	-	+	+
13	ParaView CFD	-	+	+	+	-	+	+	-	-
14	Phoenix FD / Chaos Phoenix	+	-	+	-	-	-	+	-	-

15	SMS	+	-	-	+	+	-	+	-	-
16	Real flow	+	-	+	-	+	-	+	-	-
17	SimScale	+	+	-	+	-	+	+	-	-
18	SOBEK (Deltares)	-	+	-	+	+	+	+	+	+
19	TUFLOW	+	+	-	+	+	-	+	-	-
20	TurbulenceFD	-	+	+	-	+	-	+	-	-
21	Unreal Engine	+	-	+	-	+	-	+	-	+

From these 21 software, we chose Flow3D Hydro, Autodesk CFD, and Blender for further evaluation. We chose these three because they do not require coding and may be installed either because we have access to them or because they provide student or educational licenses. We also explored Ansys Fluent and OpenFOAM, but because they were more difficult to learn and use, we decided not to continue with them. To undertake a more exact evaluation, we created a model based on ARD (Artful Rainwater Design) fundamental needs that simulate all aspects of water behavior in a real-world project.

3.2 Evaluation Criteria and Factors for Software Performance

We used the Flow Box Test, together with a set of water-related evaluation criteria, to assess each software's strengths and limitations. These criteria include hydrodynamics, splash dynamics, and environmental variables, which provide a thorough foundation for evaluating each software's performance. This method ensures a thorough understanding of their capabilities in emulating ARD systems. For more information, see the table below.

Table 2: Evaluation criteria for flow rate box test in simulations

	Evaluation Factors	**Factor Description**
Hydrodynamics	Flow Rate Control	Adjusting water flow over time and volume.
	Viscosity	Resistance to flow, affecting water movement.
	Velocity	Speed of water particles.
	Gravity	Force influencing water movement and flow.
	Jump Behavior	Sudden flow height and speed changes.
Splash and Aesthetic Dynamics	Water Splash Dynamics	Simulation of splashing for interactive effects.
	Spray Angle and Reach	Spread and distance of water sprays.
	Foam Formation	Creation and persistence of foam.
	Visual Clarity of Flow Patterns	Visibility of water movement.
	Reflectivity and Refraction	Light interaction with water surfaces.
	Interaction with Surroundings	Water's interaction with design elements.
	Evaporation Visibility	The appearance of water vapor or mist.
Complex Conditions	Mixed-Phase Behaviour	Behavior of mixed-phase water (e. g., mist).
	Defining Initial Conditions	Setting parameters like flow rate and temperature.
	Temperature	Impact of temperature on water properties.

3.3 Evaluation Model

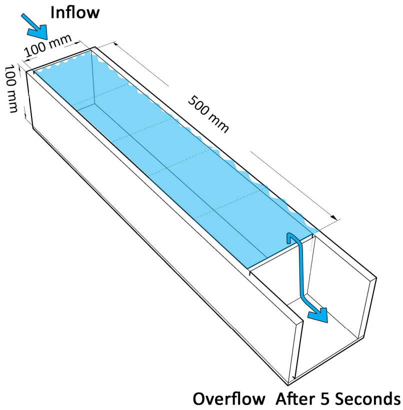
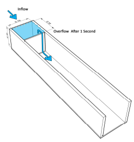
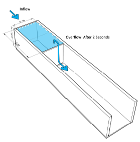
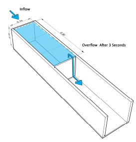
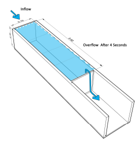
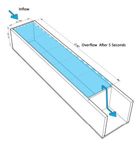


Fig. 1:
Flow box model, Version 5

Table 3: Variations of the water flow box

Versions	1	2	3	4	5
Model					
Expectation	It should fill within 1 second	It should fill within 2 second	It should fill within 3 second	It should fill within 4 second	It should fill within 5 second
Flow rate	$0.001 m^3/s$	$0.001 m^3/s$	$0.001 m^3/s$	$0.001 m^3/s$	$0.001 m^3/s$
Capacity	$0.001 m^3$	$0.002 m^3$	$0.003 m^3$	$0.004 m^3$	$0.005 m^3$
Duration	10 seconds	10 seconds	10 seconds	10 seconds	10 seconds

Computer simulations were developed to assess whether the software meets flow control requirements by analyzing time and volume flow rate. Five flow boxes (0.001–0.005 m^3) were tested at 0.001 m^3/s, projecting fill times of 1–5 seconds (see Table 3). The test eliminates the need for a physical model by measuring accuracy directly: if a 0.001 m^3 container fills in 1 second, or a 0.002 m^3 container in 2 seconds, the simulation is deemed accurate. Accuracy is defined by the correlation between flow rate and fill time. This straightforward approach, reflecting the niche nature of the research and its new lexicon, will be refined and expanded in future studies. Table 3 summarizes the projected outcomes for each flow rate box.

4 Findings

We ran three computer simulations for each version of the models, and the results were consistently identical. To ensure comparability, boundary conditions, and evaluation metrics were established throughout the procedure.

We examined the results of computer simulations qualitatively using animation outcomes. We also evaluated the software while using it to check if there was a clear way to control and change the variable we prepared in Table 2.

The photos below illustrate the outcomes of each computer simulation and demonstrate the software's post-processing capabilities. Additionally, the links provide animation samples for Flow Box Tests 1 and 5, selected as representative examples from the 15 total samples.

Flow Box Type 1

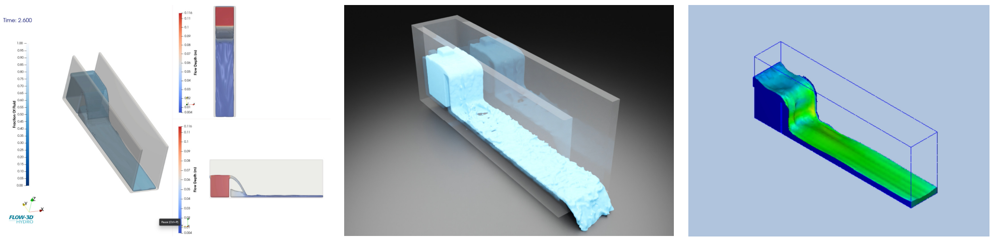


Fig. 2: Flow Box Test 1: Flow3D Hydro (left), Blender (middle), Autodesk CFD (right)

1. Flow3D Hydro: https://youtu.be/zaX7SSUP0m0
2. Blender: https://youtu.be/S5vUmeFw_DE
3. Autodesk CFD: https://youtu.be/fws6JgOmwr0

Flow Box Type 5

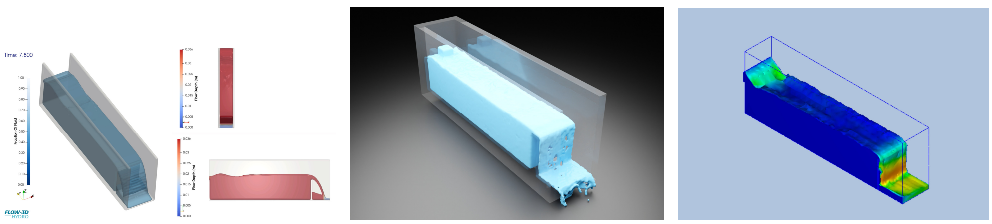


Fig. 3: Flow Box Test 5: Flow3D Hydro (left), Blender (middle), Autodesk CFD (right)

1. Flow3D Hydro: https://youtu.be/bO_VF5_scg8
2. Blender: https://youtu.be/g77cehljMPk
3. Autodesk CFD: https://youtu.be/l0OhcV8KSaM

Furthermore, the figures below show how good each software is in controlling the criteria we established in Table 2. The more effective a software is at handling a factor, the closer its point is to 10; the less effective it is, the lower its point.

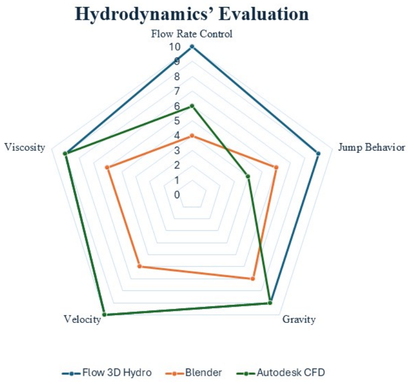


Fig. 4: Hydrodynamics' evaluation

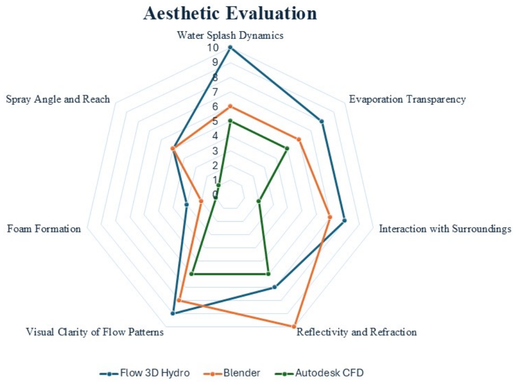


Fig. 5: Aesthetic evaluation

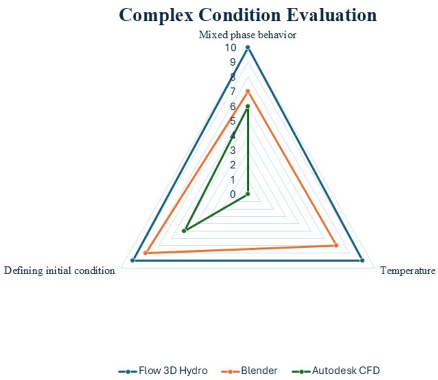


Fig. 6: Complex condition

5 Discussion

Choosing the right software for ARD water behavior computer simulations requires balancing several variables, including accuracy, convenience of use, and functionality. Flow3D Hydro excels at making accurate and dependable forecasts, making it excellent for comprehensive ARD designs. Blender, however, provides user-friendly graphics but falls short of accurately predicting water action. Autodesk CFD is appropriate for early-stage designs with basic conditions, but it lacks the detail required for more sophisticated ARD applications. The Flow Box study demonstrates that the choice of software should be determined by the project's requirements, with Flow3D Hydro suggested for designs that require both high functionality and visual quality, as seen in projects like Chambers Creek, WA, by Bruce Dees & Associates. The study emphasizes the necessity to broaden the evaluation to more advanced software for dynamic and complex ARD applications such as pollutant tracking and sediment transport.

6 Conclusion and Outlook

This study found that Flow3D Hydro is the most effective software for simulating water flow in ARD designs, delivering superior accuracy and visual fidelity. While Blender and Autodesk CFD are valuable for initial designs and less complex simulations, they lack the precision required for advanced ARD applications. Our analysis offers essential insights into selecting the right simulation tools for specific project requirements and provides methodologies that could be adapted for educational purposes in landscape architecture and hydrology.

The current phase of research relies primarily on software-based evaluations using the self-sufficient Flow Box test, where simulation accuracy is determined by the relationship between flow rate and fill time. Although physical models have not yet been employed, work on constructing such models to assess water behavior more precisely is in progress and will be published in the future. This forthcoming validation will complement our existing software-based approach, providing a more comprehensive understanding of flow dynamics in ARD systems.

Looking ahead, future research will expand the evaluation to additional software alternatives – including OpenFOAM, Ansys, Houdini, and Unreal Engine – to better model dynamic water features, real-time water dynamics, pollution interactions, and sediment transfer. These advanced platforms, which combine coding capabilities with high-level visualization, promise to support more sophisticated simulation scenarios and real-time modifications, broadening the scope of ARD applications. Additionally, the integration of digital twin technology will be explored to create a real-time, data-driven representation of ARD systems, enabling continuous monitoring, optimization, and predictive analysis. Future efforts will also focus on developing standardized workflows for experts and non-experts alike. Given the cost constraints of commercial software, open-source, code-based platforms that integrate with form-finding tools like Grasshopper will be prioritized, ensuring a more cost-effective and adaptable approach to ARD simulations. This study establishes a foundation for future advancements in accuracy, usability, and real-world applicability of ARD simulation tools.

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