

Design Efficacy Evaluation of a Landscape Information Modeling–Stable Diffusion (LIM–SD)-based Approach for Ecological Engineered Landscaping Design: A Case Study of an Urban River Wetland

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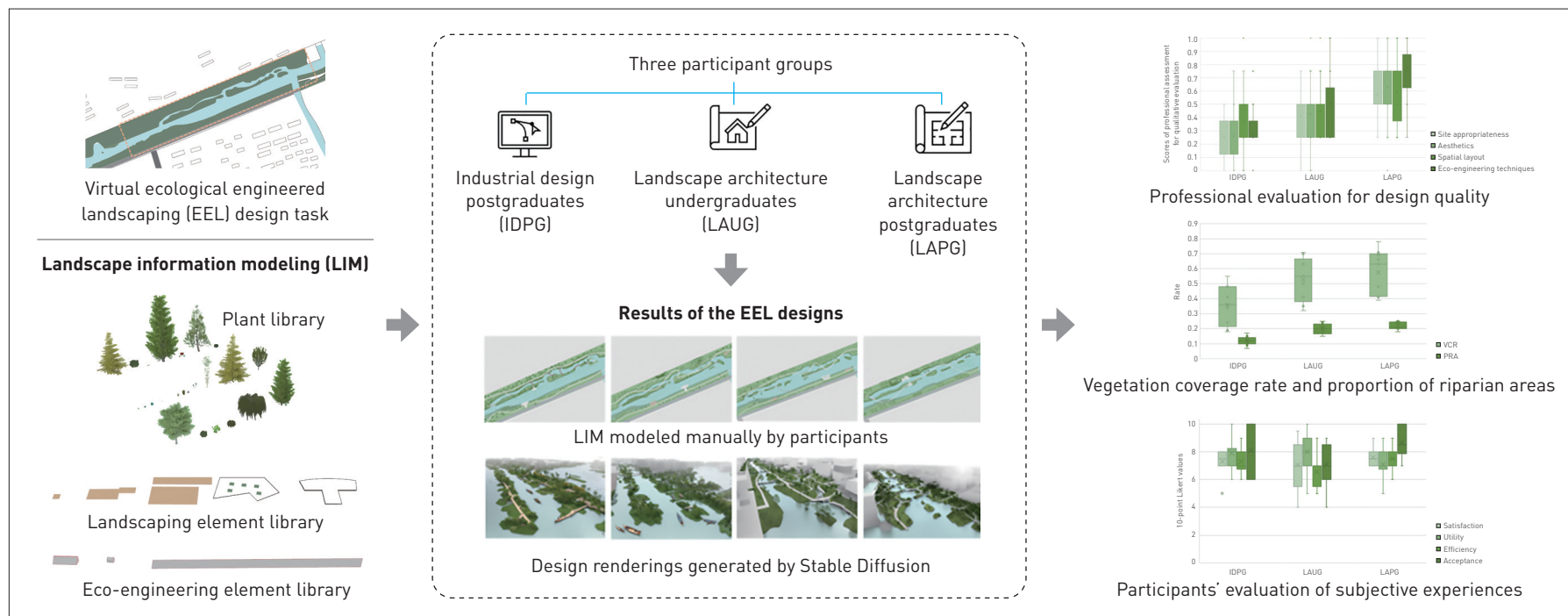
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GRAPHICAL ABSTRACT



ABSTRACT

This study introduces a Landscape Information Modeling–Stable Diffusion (LIM–SD)-based digital workflow for ecological engineered landscaping (EEL) design, focusing on urban river wetlands. It explores how students from diverse academic backgrounds perform EEL tasks using the LIM–SD approach. A total of 30 participants, including industrial design postgraduates and landscape architecture undergraduates and postgraduates, completed the design tasks. The efficacy of their designs was assessed through expert evaluations on site appropriateness, aesthetics, spatial layout, and eco-engineering techniques of the

design proposals, as well as the parametric simulation which calculated the vegetation coverage rate and proportion of riparian areas for each design. Moreover, evaluation of participants' subjective design experiences was conducted via questionnaires. Results indicated that landscape architecture postgraduates outperformed others applying ecological engineering principles. The study also elucidated discrepancies between LIM models and SD-generated renderings, as well as the uncertainty of SD-generated renderings, suggesting improvements are needed to align digital outputs with ecological design criteria.

KEYWORDS

Landscape Information Modeling; Stable Diffusion; Ecological Engineered Landscaping; Parametric Design; Digital Landscape; Design Efficacy Evaluation

HIGHLIGHTS

- Validates the design efficacy of using Landscape Information Modeling–Stable Diffusion (LIM–SD)-based workflow for urban river wetland ecological engineered landscaping projects
- Reveals that landscape architecture postgraduates produced higher-quality designs using the LIM–SD-based approach, compared with industrial design postgraduates and landscape architecture undergraduates
- Identifies discrepancies between LIM models and SD-generated renderings, requiring further refinement

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1 Introduction

Ecological Engineered Landscaping (EEL) is a specialized category of landscape design that synergistically integrates ecological principles to create semi-natural landscapes with both aesthetic appeal and ecological functionality^[1]. At the implementation level, the effectiveness of EEL design depends on various factors, including site compatibility, aesthetic-spatial planning, and

ecological engineering strategies^[2]. Recent trends illustrate that EEL projects are increasingly managed by interdisciplinary teams, reflecting the complexity and diversity of the field^[1].

While digital landscape methodologies, such as geodesign^[3] and microclimate simulation^[4], have become integral to eco-landscape design, there has also been significant progress in developing comprehensive digital landscape tools and techniques. These tools have evolved and matured to effectively meet the multifaceted requirements of EEL design, offering a systematic approach to creating ecologically resilient landscapes that harmonize aesthetics with environmental sustainability.

1.1 Applicable Landscape Information Modeling and Stable Diffusion Technologies in Landscape Design

Over the past decade, landscape-design-related disciplines have undergone a profound transformation along the growing integration of digital technologies in multiple areas such as green architecture, biodiversity-enhancing urban planning, and other environmentally conscious design practices^{[5]–[7]}. A significant advancement is the emergence of a wavelet-transform-based 3D ecological landscaping design methodology, which ingeniously combines a neural-network-driven information fusion model^[8]. This approach significantly enhances the precision, efficiency, and versatility of the digital design process, allowing designers to incorporate complex ecological dynamics into their work while ensuring a harmonious interplay between built environments and natural ecosystems.

Of these technologies, Landscape Information Modeling (LIM) encompasses a suite of digital workflows and techniques that utilizes geodesign tools and architecture, engineering, and construction applications to analyze, plan, design, and manage landscape engineering projects^[9]. LIM-based workflows are particularly effective for projects characterized by complex and dynamic eco-landscapes^[10]. Some LIM tools, such as Lands Design (a practical 3D visualization LIM plug-in for Rhinoceros developed by the Asuni Group) and Rhino Terrain (available for Rhinoceros software), offer parametric-aided design capabilities, facilitating collaboration between landscape architecture, urban design, environmental engineering, and environmental geography. Most LIM software has information processing capabilities for displaying and modifying ecological, morphological, and structural data. For instance, Lands Design has been developed within the GIS environment for small-scale terrain eco-engineering and EEL design. Additionally, several toolkits, including unmanned aerial vehicle (UAV) scanning and 3D digital LIM system, and image recognition, are integrated into a LIM-based workflow for environmental engineering and regional planning^[11].

Furthermore, the advent of Stable Diffusion (SD), a cutting-edge text-to-image synthesis model based on Latent Diffusion Models (LDMs), underscores the transformative potential of digital technologies in EEL design. SD is trained on a curated subset of the LAION-5B dataset, refining its performance by iteratively improving latent representations of data to progressively remove noise until generating coherent, high-quality images. The application of SD in practical engineering design contexts streamlines the ideation process and facilitates the visualization of complex concepts, bridging the gap between abstract ideas and tangible, ecologically sensitive designs^[12].

In terms of design visualization, SD models differ from traditional rendering software in several aspects, though sharing the common fundamental goal of transforming design concepts into photorealistic depictions across diverse disciplines, including architecture, landscape architecture, and interior design. Both models allow for customization through adjustable parameters, such as lighting, materials, and camera perspectives, thereby enhancing workflow efficiency. However, while traditional methods automate processes to reduce manual intervention, SD models leverage machine learning and artificial intelligence (AI) to expedite the generation of novel design alternatives^[6]. Regarding the generative process, the traditional rendering software relies on physical laws and computer graphics algorithms to simulate light interactions, but SD models use deep learning diffusion mechanisms, drawing from extensive datasets to generate visual content in a non-deterministic manner. This enables SD models superior creative breadth and variability, yielding innovative and diverse image renditions. It surpasses the limitations of traditional software which typically generates outcomes confined to predefined configurations and parameter ranges^[12]. Unlike the static computation pipeline of traditional rendering software, SD models facilitate interactive design exploration by continuously learning and adjusting outputs based on user feedback, allowing iterative refinement of prompts to discover a wide range of design possibilities^[12]. In contrast, changes in traditional design software generally require manual adjustments of model and material parameters.

1.2 Digital Landscape Approaches in EEL Design of Urban River Wetlands

Urban river wetlands, characterized by their linear morphology and dynamic aquatic environments, are typically defined as semi-natural urban wetland ecosystems with distinctive spatial configurations that play a pivotal role in providing ecosystem water quality treatment (WQT) services^[13]. Integrating EEL strategies into the development and management of these riverine wetlands

offers numerous advantages, effectively bolstering the resilience and functionality of urban green infrastructure systems^{[14][15]}. However, the conventional landscape design workflow, which relies primarily on 2D plans and physical models to investigate the morphological intricacies of landscape components, often falls short in achieving accurate 3D visualizations of micro-topographies and realistic representations of plant species. As a result, important micro-scale details and planting designs are frequently overlooked.

Many urban constructed wetlands and river wetlands with suboptimal riparian habitat conditions often fail to deliver intended WQT benefits. This deficiency can be attributed to the insufficient incorporation of wetland ecological principles during the design stage^[1]. Integrating the complexities of hydrological cycles, biodiversity conservation, and habitat connectivity in design and planning is essential for ensuring the long-term ecological health and WQT functionality of these systems. Therefore, there is a pressing need to reevaluate and modernize design methodologies to better align with the ecological imperatives required for successful urban river wetland EEL projects.

Despite the growing significance of urban river wetland EEL projects^{[1][16]}, a discernible gap persists in contemporary landscape architectural practice, where tailored strategies and tools to address the complexities of these projects remain largely unexplored. Although there is a burgeoning array of digital landscape methodologies and technologies applicable to river wetland EEL projects, few have been explicitly proposed and adopted^{[3][7][17]}. Notably, advanced design tools like LIM-based workflows, geodesign platforms, and SD-based rendering techniques have yet to be fully embraced and systematically integrated into foundational undergraduate curricula, despite their potential for enhancing project outcomes^[18].

Moreover, this gap extends to the evaluation of digital landscape workflows within the context of urban river wetland EEL projects. The absence of a standardized methodology to assess the effectiveness in terms of ecological resilience, design innovation, and overall project feasibility exacerbates the challenges faced by practitioners^[7]. Developing a validated assessment framework that measures the success of digital design methods against these critical criteria would enable the delivery of high-quality, sustainable urban river wetland EEL projects and promote more holistic and effective design solutions.

1.3 Digital Technologies Empowering Current Landscape Architectural Education

In current landscape architectural education and practice, a clear disparity exists between students specializing in Landscape Architecture and those from other disciplines when employing digital

tools to generate design proposals. Landscape architecture students, fortified by their comprehensive knowledge of design principles and disciplinary foundations, often adapt digital design tools to facilitate their creative processes^[19]. These students critically evaluate digital-generated proposals, thoughtfully incorporating human-centric considerations to ensure that the designs meet functional requirements and harmonize with the natural environment^[3].

In contrast, students from other disciplines may encounter additional challenges in utilizing digital tools for design tasks. Although the accessibility of these tools reduces technical barriers, allowing for rapid prototyping of visually appealing designs, the lack of specialized training can result in difficulties in articulating design intent, mastering spatial proportions, and comprehending ecological underpinnings^[17]. These students often rely heavily on the tools' suggestions, occasionally neglecting the depth of humanistic concerns, site-specific conditions, and ecological logic integral to a well-rounded design, which can impact the overall coherence and practicality of proposals^[6].

These disparities emphasize the indispensable role of professional landscape architecture expertise in guiding technological tools towards achieving higher levels of educational innovation. Future educational strategies should focus on fostering interdisciplinary collaboration skills and intensifying training for landscape architecture students on the critical and creative use of digital tools. Such an approach aims to leverage technology to promote a more holistic and profound design thinking process, thereby enhancing the potential of digital-tool-augmented design across various disciplines^[18].

Moreover, while certain landscape architectural educational research efforts have introduced "technology-driven process models" to revitalize landscape architecture and related engineering design education^[20], a notable gap remains in the availability of teaching frameworks that cultivate "multi-objective thinking" among landscape designers working on comprehensive design projects^[21]. This shortfall undermines professionals' capacity to holistically reconcile ecological, functional, and aesthetic imperatives within their design propositions.

1.4 Research Questions

In response to the identified gaps, this research proposes the following research questions regarding the work efficiency of designers when applying LIM and SD tools ("LIM-SD-based approach" hereafter) to urban river wetland EEL design projects. 1) Can this approach improve designers' productivity compared with traditional landscape design workflows? 2) Can this approach

help designers produce high-quality designs? 3) What differences emerge in design outcomes between students with various levels of professional education when using this approach? 4) Can students from other design disciplines (e.g., industrial design) use this approach to create EEL designs that meet the basic requirements of practical tasks?

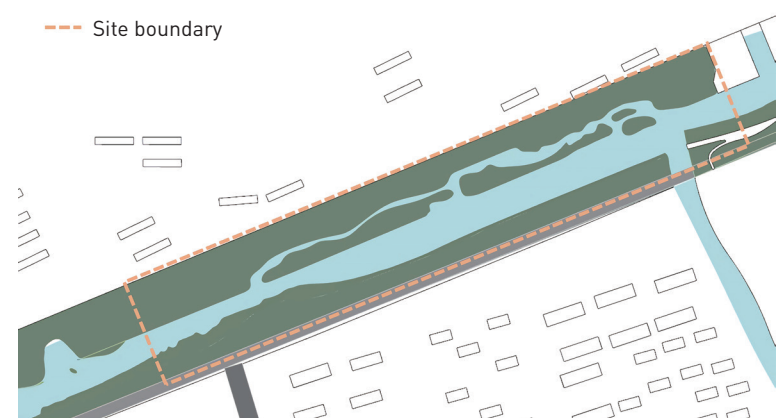
2 Materials and Research Methods

2.1 Design Task Criteria and Framework

This research illustrated with a virtual design task which required participants using LIM and SD tools to develop the EEL design for a small-scale ecological urban constructed river wetland in Hangzhou City, China, using LIM and SD tools. The detailed 2D plan of the site is shown in Fig. 1. The original digital 3D model used for the experiment was manually created by the authors, containing only the basic information, such as the locations of the waterbody and land. No vegetation, pathways, facilities or other elements were included in the model.

Participants were instructed to conduct the design according to following requirements. 1) The design should suit the physical geographic characteristics of the suburban environment of Hangzhou City. 2) It must integrate the site's hydrological and topographical characteristics. To ensure ecological functionality, the proportion of riparian areas (PRA) that might be inundated must be configured, such that most of the site could be dynamically flooded during a 30-year high-water-level event (assumed to be +1.9 m above the standard water level for this scenario). This aligns with the adaptive EEL principles that the designated riparian zones should respond to semi-natural hydrological fluctuations over time^{[1][7]}. 3) The design

1. The site plan of the virtual EEL design task.



should meet the needs of public recreation and nature education. 4) The designed wetland should be abundantly covered by appropriate vegetation structure or species. 5) Effective EEL elements, suitable for typical urban river wetlands, must be incorporated. 6) The design statement requires participants to modify four criteria of micro-topography, planting design, eco-engineering elements, and landscaping elements.

To examine the influence of different design criteria and variables input into LIM and SD tools on the efficacy of the overall landscape design in the EEL project, the research framework employed both quantitative and qualitative methods (Table 1, Fig. 2). These methods assessed the design efficacy of students from different professional education backgrounds.

2.2 Preparation of the LIM-SD Model

Several preparations were necessary for the experiment. Rhino 7 was used as the modeling platform, where an idealized model of a typical urban river wetland was constructed. A custom LIM component library was developed to run on Rhinoceros and Lands Design. This LIM component library consisted of three parts for typical wetland EEL design: a plant library, a landscaping element library, and an eco-engineering element library.

For the plant library, 23 common native wetland plant species were modeled. Each plant's LIM data included the scientific name, common name, and the projected crown diameter after 10 years of growth. Both conceptual and realistic 3D textured models of these plants were provided, allowing users to adjust their position, quantity, and species (Fig. 3).

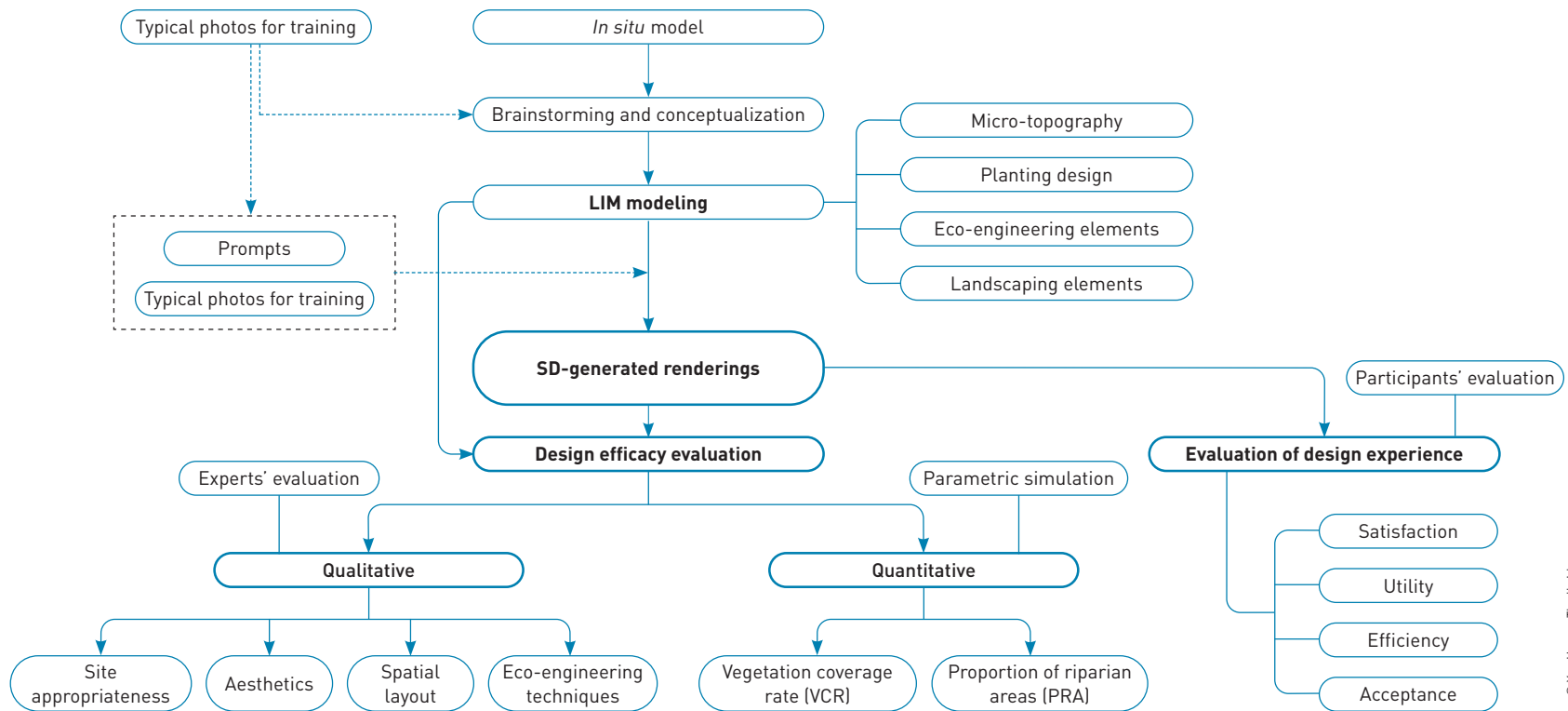
The landscaping element library contained five components: a wooden viewing platform, a wooden fishing platform, a wooden plank, a stone-paved square, and a stone-paved harbor (Fig. 4). These elements, based on materials and designs commonly used in Hangzhou's urban river wetland EEL projects^[1], were purposefully limited to ensure the ease of use during the experiment and to minimize potential distractions from having an extensive array of options for participants. This process followed similar settings in previous parametric design performance evaluations^{[22][23]}.

The eco-engineering element library included three key components: aeration weirs, small sluices, and rigid barge. All were modeled at real-world scale and selected due to their frequent use in urban wetland EEL projects^[1] (Fig. 4). Users can freely add, move or delete these components within the LIM environment as needed.

The SD model was adopted to generate realistic renderings of the scene from a fixed viewport within the LIM model, using

Table 1: Detailed phases of the experiments

Phase	Step	Actor	Method	Outcome
1	Basic modeling	Research team	Prepare a 3D model source file	An original test model for the experiment
	LIM object preparation	Research team	Input data for the LIM objects within Rhinoceros software	3D parametric LIM objects, including plants, eco-engineering elements, and landscaping elements
	SD model preparation	Research team	Input typical photos of other EEL design projects to train the SD model	SD model with EEL characteristics for rendering the outputs of LIM documents
2	LIM modeling	Participants	LIM modeling based on participants' conceptualization	Detailed LIM documents for participants' EEL design schemes, including modified micro-topography, planting design, eco-engineering elements, and landscaping elements
	SD-generated rendering	Participants	Render captures from LIM documents using the constructed SD model, with the aid of prompts	Renderings of design works
3	Evaluation of design efficacy	Experts	Conduct qualitative evaluations of participants' design works	Qualitative evaluations of design works
4	Evaluation of design experience	Participants	Evaluate their design experience during the design project	Students' feedback

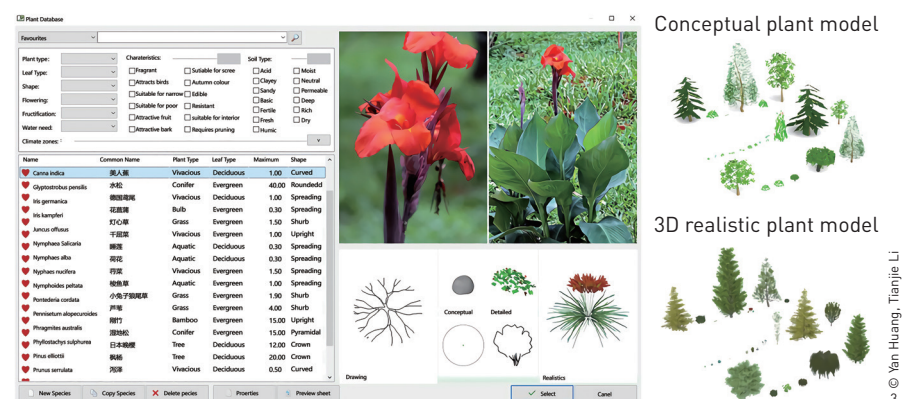


2. The research framework.

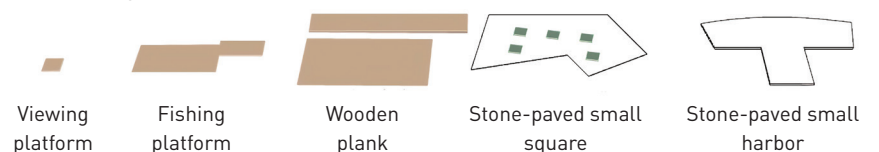
text prompts to modify the rendered images. The SD operated by utilizing text encoders that link text to corresponding images. In a hybrid text-image space, for each image-caption pair, the text encoders can convert tokens of the caption into a proxy of the vector of the image^[12]. The model in this study was trained on the basis of the “runwayml/stable-diffusion-v1-5” model within a Python 3 environment, which process included 1,000 training steps, with the U-Net learning rate set at 0.00050 and the text encoder learning rate at 0.000100. To ensure that the SD model produces renderings aligned with the characteristics of urban river wetland EEL projects, it was trained using 150 real-world images (photographs taken in situ by researchers) from successful wetland eco-parks and river wetland EEL projects in Hangzhou. Detailed descriptive texts for each image were manually input by the researchers. When generating renderings, the SD model’s sampling steps were set to 25 and the CFG (classifier-free guidance) scale was set to 8.

2.3 Participants and Session Procedure of the Experiments

The study was approved by the institutional administration committee and was conducted in May 2023. A total of 30 voluntary participants from a large public university in Zhejiang Province took part in the experiment, consisting of 10 industrial design



Landscaping element library



Eco-engineering element library



3. The graphical user interface of the plant library within the LIM environment.
4. Components in the landscaping element library and eco-engineering element library within the LIM environment.

postgraduates (IDPG), 10 landscape architecture undergraduates (LAUG), and 10 landscape architecture postgraduates (LAPG). All participants had previously acquired skills in spatial scale design related to urban environments and had at least one year of experience with 3D modeling software such as Rhino 7. However, the IDPG group had no formal training in landscape design, the LAUG group had basic knowledge in landscape design, and the LAPG group had advanced expertise in eco-landscape design with more EEL and basic hydraulic engineering knowledge.

The experimental sessions, lasting approximately 60 minutes each, were conducted in a controlled environment (separate rooms and seats) where participants worked independently. The procedure was as follows.

1) 15-min introduction familiarized participants with the design task and the tools; all participants were provided with the same test model file and design criteria.

2) After a 5-min warm-up period allowing participants to get acquainted with the software, they had 10 minutes to conceptualize their designs and 30 ~ 40 minutes to complete modeling and rendering using Rhino 7 and the integrated LIM-SD environment; participants had full access to Rhino 7's features and the entire LIM component library to complete tasks such as modifying microtopography, planning vegetation, incorporating ecological elements, and adding landscape features.

3) Upon completion of the LIM models, participants exported a standardized 2D plan and a fixed-view image of the scene as inputs for the SD model renderings; participants could adjust the prompts if necessary, with the number of prompt modifications recorded automatically; each participant then selected their preferred rendering.

4) Participants saved and submitted their design outputs, including the LIM model file, the 2D plan, and the SD-generated rendering.

2.4 Design Efficacy Evaluation Methods

After completing the design task, three experts—each with professional master's degrees in Environmental Geography, Ecology, and Landscape Architecture/Eco-engineering—were invited to assess the participants' design quality. Using the Consensual Assessment Technique (CAT) method^[22], the experts evaluated the designs in four aspects, i.e., site appropriateness, aesthetics, spatial layout, and eco-engineering techniques (Table 2), comparing with successful urban wetland EEL projects in Hangzhou^[1].

Experts used a 5-point Likert scale, i.e., “poor (0),” “acceptable (0.25),” “moderate (0.5),” “good (0.75),” “excellent (1),” to evaluate

participants' performance. They assessed each design independently, blinded to the group of participants.

To quantitatively assess the designs, a set of custom visual programming components (VPCs), including vegetation cover and riparian areas for rainstorm inundation, were developed and implemented within Grasshopper V1.0, a parametric platform integrated with Rhino 7. These VPCs were specifically tailored to automatically compute two key performance metrics: vegetation coverage rate (VCR) and PRA. The effectiveness of these VPCs was demonstrated in the context of a virtual urban river wetland EEL project, where they served as critical tools for evaluating the feasibility and resilience of the design proposals. Notably, all valid LIM models generated by the participants were successfully input into the VPC system for precise calculations of VCR and PRA values. This quantitative assessment approach not only ensured the consistency of design evaluation but also provided valuable insights into the ecological responsiveness and functional viability of the various EEL schemes developed during the experiment.

Finally, participants were asked four questions to gauge their experiences with the LIM-SD approach in terms of satisfaction, utility, efficiency, and acceptance^[19] in a 10-point Likert scale going from 1 to 10. These questions are as follows. 1) Satisfaction: do you believe LIM and SD techniques can enhance innovation in landscape

Table 2: Detailed evaluation standards for the design outputs

Aspect	Explanation
Site appropriateness	The design adheres to the site-specific attributes of the prototypical urban river wetland in Hangzhou, ensuring that the volume, scale, and intensity of development are harmoniously integrated with the site's inherent characteristics
Aesthetics	The design presents a diverse plant selection and a structural arrangement, creating a visually appealing and natural riparian zone with strategically placed viewing points
Spatial layout	The design reveals the coherence and functionality of the spatial layout, including the integration of roads, squares, and piers, vegetation, water bodies, landscape elements, and ecological engineering components
Eco-engineering techniques	The design incorporates appropriate eco-engineering elements, such as aeration weirs, eco-sluice gates, eco-barges, appropriate slopes, and abundant vegetation coverage in the riparian areas to enhance ecosystem services and promote hydrological resilience (source: Ref. [7])

design? 2) Utility: how would you evaluate these technologies in relation to your work as a design practitioner? 3) Efficiency: does the LIM-SD-based approach help you conceptualize and present intuitive design ideas more effectively? 4) Acceptance: would you adopt this digital approach in current and future EEL design workflows for urban river wetlands?

3 Results

3.1 Obtaining LIM Models and SD-aided Renderings

In this experiment, a total of 27 valid EEL designs were generated, with 9 from each group (Fig. 5). The others (one from each group) were deemed invalid because the participants did not complete the full task. The performance of participants when modifying prompts in the SD environment varied slightly between groups. Noticeably, the LAUG and LAPG groups modified their prompts an average of 3.5 times, with a maximum of 5 modifications, while the IDPG group averaged 2.6 modifications, with a maximum of 4 (Fig. 6). During the SD rendering process of the LIM files, the elements presented in the SD renderings were generated based on prompts manually set by the participants, reflecting their conceptualizations.

3.2 Evaluation of Design Qualities Based on Experts' Voting

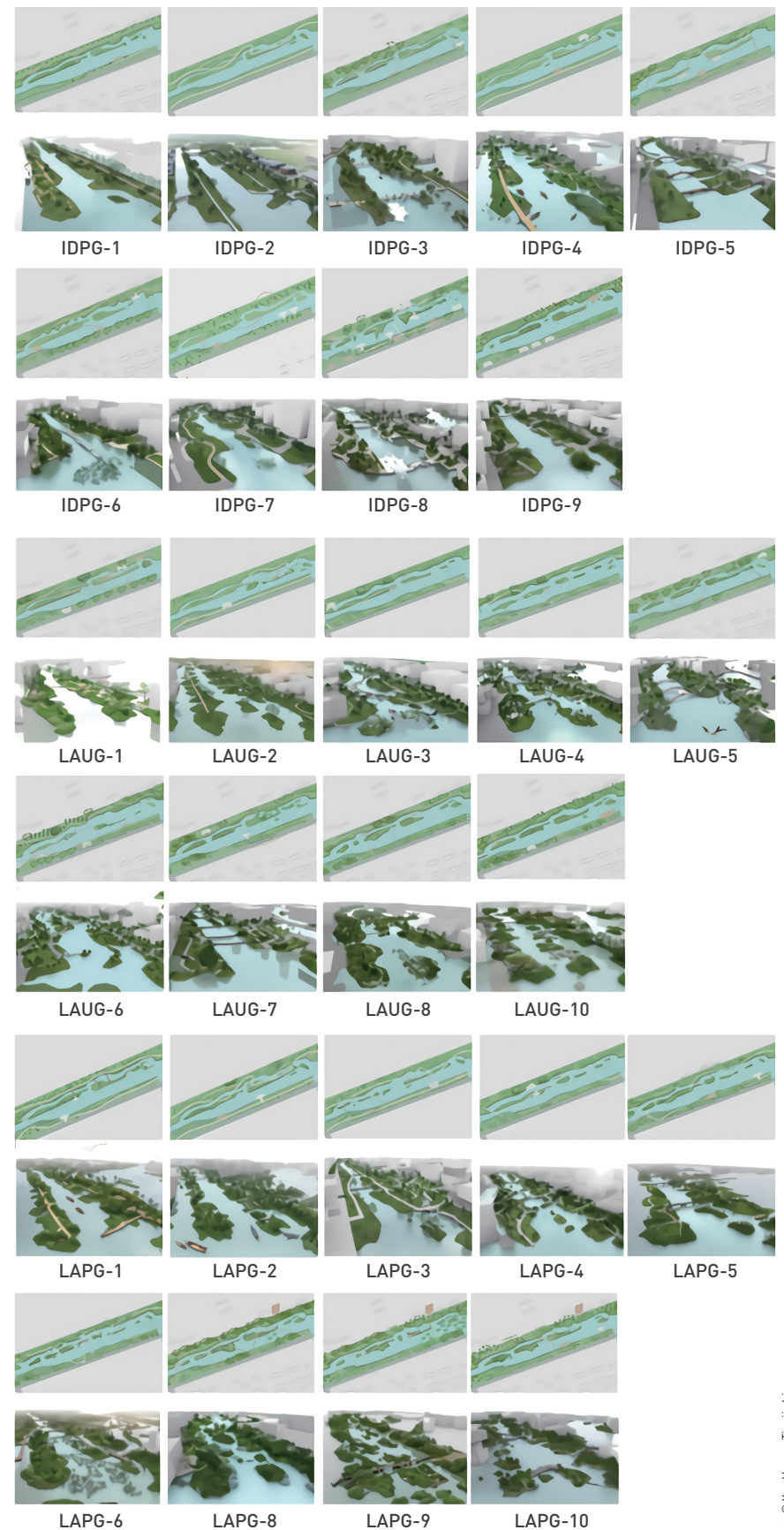
Renderings generated by the SD models, based on the LIM scenes are not always identical, as they are not fully controlled by the participants. Therefore, experts' evaluation primarily focused on SD-aided renderings, with partial reference to the 2D plans (Fig. 7).

An intraclass correlation coefficient (ICC) test was conducted to estimate inter-rater agreement, determining whether the experts shared a similar level of expertise^[24]. Since three experts participated, the ICC test was set to assess the mean of k raters ($k = 3$). Furthermore, to ensure the reliability of the results across a broader range of raters with similar characteristics, a two-way random effects model was selected^[25]. A Python program utilizing the Matplotlib package was also developed to calculate the ICC for the "two-way random effects" model.

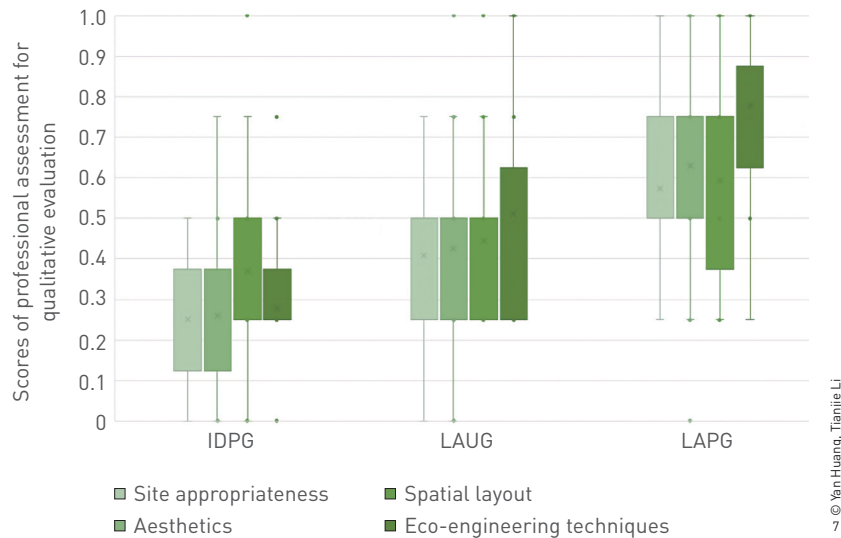
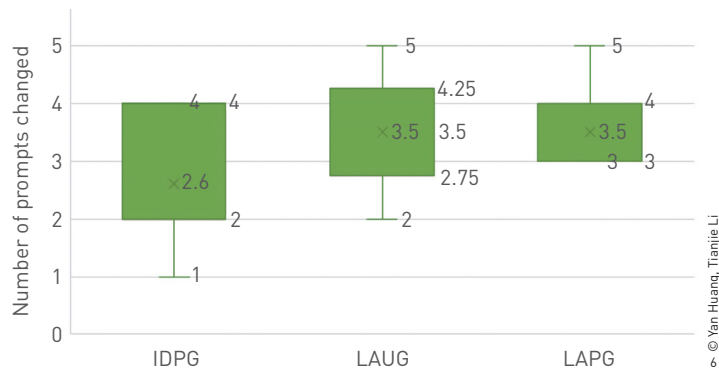
Although the experts had different areas of expertise, the study achieved a high level of consistency, with an average ICC measure of 0.887 (> 0.75). This result indicates a strong agreement among the three experts' ratings, meeting the reliability criteria for data in design efficacy evaluations^[26].

3.3 Evaluation of Design Qualities Based on Parametric Simulation

The VCR and PRA values of each design were automatically



5. Samples of 27 valid EEL designs.



6. Number of prompts modified by students.
7. The professional evaluation for design quality of each criterion across four aspects.
8. Results of VCR and PRA values among the three participant groups.
9. Evaluation results of students' subjective experiences.

calculated from LIM files (Fig. 8), using the aforementioned VPC programs. Among the three participant groups, designs from the LAPG group performed the best. The VCR for this group (mean = 0.630) was slightly higher than the LAUG group (mean = 0.548). Additionally, the LAPG group exhibited higher PRA (mean = 0.210) compared with the LAUG group (mean = 0.203). In contrast, the designs from the IDPG group had the lowest mean VCR and PRA.

3.4 Evaluation of Participants' Subjective Experiences

Regarding the evaluation of participants' experiences, all students completed a face-to-face questionnaire. Results showed that most students believed that the LIM-SD-based approach enhanced their innovation processes, compared with their traditional workflows (Fig. 9). Their satisfaction scores averaged 7.31 (IDPG), 7.22 (LAUG), and 7.66 (LAPG), indicating that the

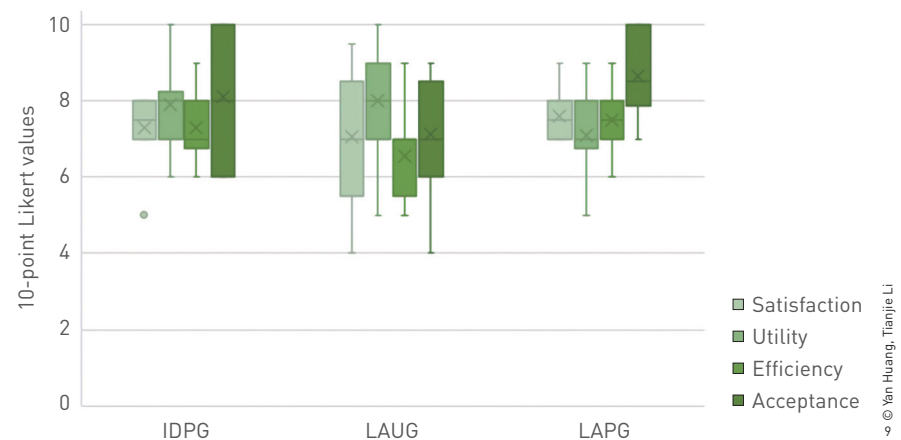
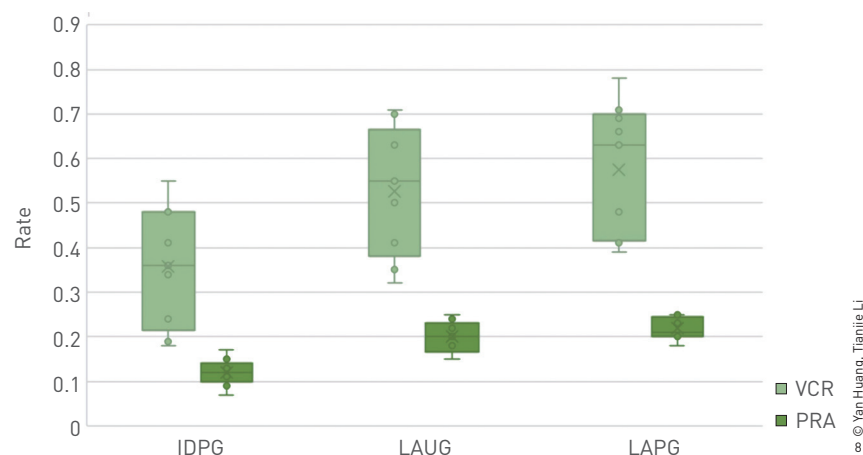
students generally agreed that the LIM-SD-based workflow provided useful tools and methods to conceptualize and visualize their EEL designs.

When asked to evaluate the practical assistance offered by LIM and SD technologies in their EEL design works, the average utility scores were 7.90 (IDPG), 8.10 (LAUG), and 7.10 (LAPG). For the question regarding how the LIM-SD-based method facilitated their conceptualization and intuitive presentation of design ideas, the efficiency scores averaged 7.30 (IDPG), 6.55 (LAUG), and 7.50 (LAPG). A clear inclination to adopt and further integrate digital approaches into their EEL design processes was observed, with the LAPG group showing the strongest willingness.

4 Discussion

4.1 Discussion of Primary Findings

Overall, the results suggested that the LIM-SD-based approach had a moderate effect on the EEL design efficacy. The following section summarized the insights gained regarding each research question.



Firstly, the LIM-SD approach was shown to improve productivity across all participant groups in practical EEL design tasks. The integration of real-time design performance feedback has the potential to enhance the link between digital design tools and conceptual design efficacy, providing more informed options for both designers and environmental engineers^{[27][28]}.

Secondly, with the support of the LIM-SD approach, participants from non-landscape architecture background were able to generate acceptable designs. However, students from the IDPG group performed relatively the weakest in most aspects. The ranking of both quantitative indicators, VCR and PRA, was LAPG, LAUG, and IDPG. Mean scores of the four expert evaluation aspects were higher for the LAPG group compared with the LAUG group, while the IDPG group had lower mean scores in each aspect. The LAPG group outperformed the other two groups in terms of eco-engineering techniques, VCR, and PRA. It was also noticed that the LAPG group focused more on vegetation diversity and riparian resilience in the EEL designs.

Thirdly, a clear pattern was observed in the frequency of prompt utilization, with the LAUG and LAPG groups making more frequent attempts than the IDPG group. The LAUG group achieved superior overall design outcomes compared with both the LAPG and IDPG groups, particularly in terms of VCR and PRA. Similar trends have been reported in studies on parametric architectural design efficacy^[26]. The incorporation of interactive design optimization methods encouraged abstract thinking, allowing students to explore a broader range of design possibilities. This highlights the importance of the LIM-SD-based approach in fostering innovative EEL solutions among design students and may account for the observed discrepancies in performance based on academic background^[21].

Fourthly, while some spatial design students, particularly those from the IDPG group, were able to complete the most basic landscape designs (setting up basic circulations, placing some landscape elements, etc.), their designs were more focused on hardscapes and lacked a thorough application of EEL principles. Their designs did not adequately reflect the representative landscape features and aesthetic values of urban river wetlands. One possible reason is that the LIM-SD-based approach can help designers from various backgrounds explore EEL design, where comprehensive understanding of EEL-related factors is necessary for creating well-rounded solutions^[17].

Furthermore, it was found that using LIM and SD input prompts requires a solid understanding of environmental geography, ecological landscape attributes, and ecological landscaping

components^[23]. The LIM-SD-based approach received overall positive feedback from the participants. However, the LAUG group rated the method lower in terms of both efficiency and acceptance. Their unfamiliarity with the intricate ecological techniques and eco-engineering elements in EEL projects often led them to input inappropriate prompts into the SD model, resulting in less suitable renderings. In contrast, the LAPG group consistently rated the approach higher in terms of “satisfaction,” “efficiency,” and “acceptance.” This disparity can be attributed to their deeper comprehension of wetland ecology, foundational ecological landscaping principles and their ability to apply relevant planning strategies within the LIM-SD workflow.

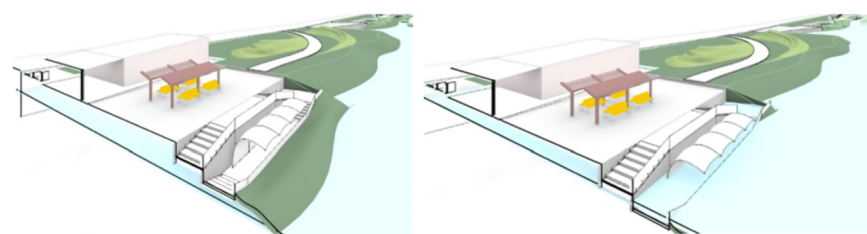
4.2 Performance of LIM-SD-based Approach on Addressing Ecological Principles

In the context of urban river wetland EEL project, careful vulnerability assessment of riparian zones to pluvial flood inundation is crucial for sustainable design. Thus, it is vital to define and consider the flood protection level, ensuring that these ecosystems can maintain their natural hydrological processes and support diverse aquatic habitats^{[1][7]}.

This virtual design task required scientifically informed and strategic configuration of PRA to ensure that the designed landscape can dynamically adapt to potential flood events, particularly during a 30-year high-water-level event. The LIM model generated showed the flooding conditions of the riverbank under different water levels (Fig. 10). Such dynamic accommodation of inundation not only enhances ecosystem resilience but also aligns with contemporary design practices that advocate for adaptive and responsive landscapes.

The proposals from the LAPG group demonstrated a commendable depth of understanding and sensitivity towards this critical design criterion. Their submissions reflected a strong awareness of the role PRA play in mitigating flood risks

10. Rendering examples of the river wetland landscape under the normal water level (left) and during a 30-year high-water-level event (right).



and preserving the ecological integrity of urban river wetlands. Conversely, the LAUG and IDPG groups' proposals lacked the same level of consideration for this fundamental aspect. This underscores the importance of incorporating advanced flood management strategies and ecological principles into the educational curriculum to foster a more holistic approach to riverine landscape design across all professional education levels.

4.3 Explanation of the Mismatch Between LIM-SD-generated Renderings

The composition, spatial distribution of landscapes, and the presence of ecological engineering elements significantly influence the dynamics and functionality of EEL projects. Additionally, the specific methods used to implement spatial patterns in landscape composition can impact the feasibility of the EEL design^[29].

The LIM-SD-based EEL design process requires interdisciplinary expertise, especially in eco-engineering, where complexity increases with specialized design variables, as evidenced in related research^[30]. This specialized knowledge influences key stages such as the development of the LIM model and the setting of prompts within the SD environment, thereby heavily affecting the final EEL design outcomes.

Findings of this research revealed that SD-generated renderings often deviate unpredictably from their input LIMs, unlike manually generated content that is fully controlled within LIMs. This discrepancy might stem from inadequate or imprecise prompt inputs and the limited ability of the SD tool. Even when the LIM layouts are similar and identical prompts are used in the SD environment, the generated renderings may show high levels of dissimilarity. Occasionally, the outputs produced by the SD model diverge from the training process, likely due to the inherent mechanisms in the SD model's training process^{[12][26]}. The specific interaction between prompts and the generation mechanics of the SD model requires further exploration.

4.4 Possibility and Uncertainty of LIM-SD-generated Renderings

The SD-based model generation process within the LIM-SD workflow involves inherent uncertainties. While to some extent participants can control and manage the object and scene information within the LIM model and its 2D plan representation, they cannot fully control the final outcomes generated by the SD model. As a result, renderings may include extraneous elements not specified in the LIM model, such as small teahouses, recreational facilities, or bridges, limiting designers' control over these features.

Certain renderings sometimes depict design anomalies, such as dead-end roads, oddly positioned bridges extending into water bodies, or oversized dams (as demonstrated by IDPG-6, IDPG-8, and LAPG-6 in Fig. 5), which defy design logic. In other instances (e.g., IDPG-8, LAUG-5, LAUG-10, LAPG-5, LAPG-10 in Fig. 5), the urban context of the river wetlands was diminished in the backgrounds, compromising the visual authenticity of the scenes.

In summary, while integrating SD for generating realistic environmental renderings from LIM-based designs shows promise, this study underscores the need for further improvements in the accuracy and consistency of the results to ensure alignment with both ecological principles and design conceptions.

4.5 Innovations and Limitations

The LIM-SD-based approach introduces significant innovations to the workflow of urban river wetland EEL projects, improving the efficiency of the preliminary design process. Landscape designers can quickly develop initial models within the LIM environment, import them into the SD platform with predefined viewpoints, and then input appropriate prompts to generate multiple renderings in a short time. This approach facilitates intuitive communication between landscape designers and environmental engineers. In addition, environmental engineers can make rapid adjustments to the schematic model and produce preliminary visualizations, thereby improving collaboration in practical EEL design tasks. However, several limitations need to be addressed in further studies.

1) Currently, participants can only influence the SD model's output by adjusting the prompts. Further research is necessary to identify effective methods for training the SD model to better capture the relationship between specific texts and design elements.

2) The current workflow only generates renderings from fixed perspectives with relatively low accuracy, and the tools available cannot produce high-precision engineering drawings. More research is needed to automate the creation of detailed LIMs based on more refined renderings.

3) The LIM-SD approach employed in this study is limited in visualizing EEL designs under specific conditions. However, it is equally important to develop digital tools that can simulate more complex inundation scenarios, as these can demonstrate the "resilience" of riparian zones during extreme rainstorm events. Expanding this capability would provide a comprehensive understanding of the ecological robustness and functionality of designs across a broader range of environmental conditions.

4) There is potential for further integration of LIM tools with parametric programs and rendering software. Combining geodesign

platforms like Civil 3D^[31] with LIM–SD tools could provide a more cohesive workflow, allowing for a more thorough evaluation on the design rationality and visual impact in river wetland EEL projects and supporting interdisciplinary collaboration^{[7][32]}.

5) The development of mixed reality, virtual reality, and augmented reality technologies for the Metaverse will transform the workflow of landscape designers and environmental engineers in the future^[33]. The effectiveness of using these virtual environments for landscape design tasks should be explored further^[19].

5 Conclusions

This study presents a novel LIM–SD-based methodology for EEL design in urban wetlands, focusing on its application to riverine environments. It empirically demonstrates the effectiveness of this digital workflow for EEL projects among design students from different professional backgrounds. The experimental framework was proposed to unravel the relationship between the use of LIM and SD technologies and the quality of design outcomes, as well as to analyze variations in design efficacy across three student groups.

Quantitative assessments of participants' design efficiency were conducted through expert evaluation and parametric program simulation. The findings indicate that with the help of digital tools, the LAPG group consistently outperformed the LAUG and IDPG groups in nearly every measure of design performance.

The study also revealed discrepancies between renderings generated by LIM and SD technologies and highlighted differing subjective experiences reported by participants. These observations suggest a possible correlation between the feedback mechanisms inherent in digital design tools and user performance on the LIM–SD platform. Future research could further explore the impact of alternative digital landscape design environments on the performance of designers and engineers in the realm of EEL design practices.

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Competing interests | The authors declare that they have no competing interests.

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基于景观信息模型—稳定扩散模型（LIM—SD）方法的生态工程景观设计效能评估：以城市滨河湿地为例

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摘要

本研究介绍了一种基于景观信息模型（LIM）和稳定扩散模型（SD）的数字方法在生态工程景观（EEL）——尤其是城市滨河湿地设计项目中的应用。研究探讨了拥有不同学科和教育背景的学生在使用基于LIM—SD的方法开展EEL设计任务时的表现。包括工业设计研究生、景观设计本科生和研究生在内的30名学生参与了本研究的设计任务。研究邀请专家对设计方案的场地适宜性、美学、空间布局和生态工程技术进行评估, 并对每个设计的植被覆盖率和河岸区比例进行参数模拟, 以评估设计的有效性。此外, 研究还通过问卷调查对参与者的客观设计体验进行了评价。结果表明, 景观设计研究生在应用生态工程原理方面表现更优异。研究还揭示了LIM模型与SD生成渲染图之间的差异, 以及SD生成渲染图的不确定性, 提出应就促进数字输出与生态设计标准保持一致进行改进。

关键词

景观信息模型; 稳定扩散模型; 生态工程景观; 参数化设计; 数字景观; 设计效能评估

文章亮点

- 证实了景观信息模型—稳定扩散模型（LIM—SD）方法在城市滨河湿地生态工程景观项目中具有良好的设计效能
- 相较于工业设计研究生和景观设计本科生, 景观设计研究生在使用LIM—SD方法时的设计质量更高
- 指出LIM模型与SD模型生成的渲染图之间存在差异, 需进一步优化

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