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Landscape elements affect public perception of nature-based solutions managed by smart systems

Jiayang Li [a,*], Joan Iverson Nassauer [a], Noah J. Webster [b]

[a] School for Environment and Sustainability, University of Michigan, 440 Church Street, Ann Arbor, MI 48109-1041, USA
[b] Institute for Social Research, University of Michigan, 426 Thompson Street, Ann Arbor, MI 48104, USA

HIGHLIGHTS

- Water level manipulation by smart systems may undermine residents' perceptions of stormwater ponds.
- Land use contexts, basin slopes, and surrounding plants moderate the effects of water level on perceptions.
- High water is perceived more positively in greenspace ponds and low water is perceived more positively in residential ponds.
- Both high and low water are perceived more positively in ponds with steep slopes.
- Low water is perceived less positively in ponds surrounded by mown turf.

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ABSTRACT

Smart technologies promise innovative approaches to manage nature-based solutions (NBS) for more effective regulating functions under climate change. However, smart systems may also affect people's experiences of NBS by introducing noticeable changes in urban landscapes. This study investigated public perception of "smart" retention ponds that had changing water level as controlled by smart systems and varied in the following microscale landscape elements determined by planning and design choices: land use context, basin slope, and surrounding plants. Using visualizations that showed pond landscape design alternatives at typical, low (draining water), and high (retaining water) water levels, we surveyed residents in three American cities for their perceptions of smart ponds (n = 974). Our results suggest that water level manipulation by smart systems negatively affects perceptions of stormwater ponds; both low and high water were perceived as significantly less attractive, neat, and safe than the typical water level condition. Furthermore, these effects of water level were moderated by other design elements. Perceptions of high water level were more positive for ponds in greenspace than in residential or commercial contexts. Perceptions of low water level were more positive for ponds in residential contexts than in greenspace or commercial contexts, as well as for ponds surrounded by woody or unmaintained plants than those surrounded by mown turf edge. In both high and low water conditions, ponds with steep slopes were perceived more positively than those with shallow slopes. These findings can support successful planning, design, and management of smart NBS.

1. Introduction

The concept of "smart cites" and related technological innovations present novel approaches for managing urban ecosystems and the services they provide (Arts, van der Wal, & Adams, 2015; Goddard et al., 2021; Gulsrud et al., 2018; Nitoslawski, Galle, Van Den Bosch, & Steenberg, 2019). A widely considered application is smart stormwater systems that integrate technologies such as information and communication technology, sensors, and autonomous systems into nature-based solutions (NBS) for urban stormwater management (Bartos, Wong, & Kerkez, 2018; Lund et al., 2019; Meng & Hsu, 2019; Shishegar, Duchesne, Pelletier, & Ghorbani, 2021). Smart systems can monitor multiple NBS sites in real time and evaluate their systematic performances, providing new insights for management decisions (Kerkez et al., 2016; Meng & Hsu, 2019). Moreover, smart systems can actively control detention and retention processes to better respond to

* Corresponding author at: 440 Church Street, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109-1041, USA.
E-mail address: jiayang@umich.edu (J. Li).

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stressors from climate change, aging infrastructure, and land use change (Kerkez et al., 2016; Lund et al., 2019).

However, despite rapidly advancing technological capacity, how the public may respond to the visible effects of implementing smart stormwater systems has not been adequately considered. Smart systems can noticeably change the appearance of NBS by intentionally storing water in neighborhood streets or draining retention ponds. Such unfamiliar landscape appearances may degrade people's everyday experiences of urban nature, a cultural ecosystem service with implications for both urban residents' well-being and public support for smart system adoption (Li & Nassauer, 2021). Landscape experiences are a product of human perception and cognition, and may not align with environmental processes and functions (Andersson, Tengö, McPhearson, & Kremer, 2015; Daniel et al., 2012; Dronova, 2019; Gobster, Nassauer, Daniel, & Fry, 2007). Smart stormwater systems manage processes that occur at various spatial scales, some of which are not perceivable. In contrast, people immediately notice microscale landscape elements – the fine-grained characteristics of water, plants, landforms, and structural elements that are immediately perceptible – at the scale of streets and sites (Nassauer, Webster, Sampson, & Li, 2021; Raymond et al., 2017a).

This paper reports on our investigation of urban residents' perceptions of microscale landscape elements of NBS managed by smart systems. Specifically, we focused on "smart ponds", i.e., stormwater retention ponds in which sensors, actuators, and wireless communication devices are deployed to monitor weather and stormwater quantity and quality metrics and dynamically control flows across multiple sites in real time (Kerkez et al., 2016; Mullapudi, Bartos, Wong, & Kerkez, 2018). For many decades, stormwater retention ponds have been widely implemented in the US and many other countries in residential neighborhoods, greenspace, and commercial developments to collect and treat stormwater runoff (Eckart, McPhee, & Bolisetti, 2017; Fletcher et al., 2014; Hassall, 2014). Studies on public perceptions of stormwater ponds consistently highlight their amenity values, reporting that nearby residents often see safe and neatly kept pond landscapes as offering aesthetic experiences, including viewing birds and other wildlife (Bastien, Arthur, & McLoughlin, 2012; Eckart et al., 2017; Lamond & Everett, 2019; Moore & Hunt, 2012; Rooney et al., 2015; Williams et al., 2019).

The adaptation of stormwater ponds by smart systems, through both retrofitting and new construction, could enhance stormwater regulating functions and allow more flexible and responsive management regimes in response to climate change (Bartos et al., 2018; Goddard et al., 2021; Lund et al., 2019). Smart systems can drain ponds before an intense storm to free up storage space and retain more water during and after the storm to more effectively mitigate flooding risk and water quality impairment (Mullapudi et al., 2018; Shishegar et al., 2021). However, such manipulations of pond water level can result in visible landscape changes. Draining water can result in unusually low water levels, sometimes exposing sediments. Retaining water after storms at a higher than usual level can resemble flooding conditions. To our knowledge, no study has investigated how water level may affect people's perceptions of stormwater ponds, especially under the novel regime of smart systems where water level is managed through a highly engineered process and can change rapidly.

Given the different decision-making mechanisms that shape microscale landscape elements of smart ponds, we conceptualized these elements into two categories: pond water, which is inherently related to stormwater management functions and controlled by smart systems; and other "design elements" such as plants, landform, and adjacent buildings and structures, which depend on planning and design choices and maintenance regimes and will appear as more stable than pond water level. While these design elements are not directly controlled by smart systems, they constitute the overall smart pond landscape that people immediately perceive and experience. Based on our conceptualization of microscale elements, we draw from existing knowledge to consider pond water level as related to perception and to identify design elements that might affect perception.

Open water is critical for everyday aesthetic experiences offered by stormwater ponds. It is often associated with high landscape preference, aesthetic pleasure, and relaxation and restoration (Herzog, 1985; Kaplan & Kaplan, 1989; Völker, Matros, & Claßen, 2016; White et al., 2010). But the visual qualities of water such as transparency and color may also profoundly affect how people perceive it (Flotemersch & Aho, 2021). Studies of natural wetlands noted that absence of visible water (Dobbie, 2013) or presence of sediments (Cottet, Piégay, & Bornette, 2013) may significantly undermine aesthetic experiences. Aesthetic preferences for rivers have been reported to be greatest at medium water flow, with both high and low flows less preferred – possibly due to suspended debris and exposed channel beds (Brown & Daniel, 1991; Pflüger, Rackham, & Larned, 2010; Yamashita, 2002). For stormwater detention areas, temporary flooding in neighborhoods may raise safety concerns when residents are not aware of the intention and mechanism of stormwater management (Williams et al., 2019).

As design elements, characteristics of plants growing in and around ponds have been reported to affect both aesthetic appeal and neatness. Orderly-looking plants and regular mowing can signal ongoing maintenance, care, and conform to social norms, especially in residential areas (Li & Nassauer, 2020; Nassauer, 2004; O'Donnell, Maskrey, Everett, & Lamond, 2020; Taguchi et al., 2020). Mature canopy trees may also contribute to greater landscape preferences in some contexts (Dobbie, 2013; Lund et al., 2019; Suppakittpaisarn, Larsen, & Sullivan, 2019). In contrast, submergent plants and densely growing tall grasses are often noted as view-blocking, messy, and unpleasant (Flotemersch & Aho, 2021; Jarvie, Arthur, & Beevers, 2017; Taguchi et al., 2020). Messy-looking plants can also prompt concerns about safety; residents may associate these plants with dangerous and dirty breeding grounds for mosquitos and rats, especially when the extent of water is small (Jarvie et al., 2017; Monaghan et al., 2016; Taguchi et al., 2020; Williams et al., 2019). Moreover, low gradient basin slope is often mandated in stormwater pond construction to minimize drowning hazard, a safety concern people commonly raise (Bastien et al., 2012; Jones, Guo, Urbonas, & Pittinger, 2016). Besides, the basin slope of a pond affects the extent and shape of visible water, which may affect landscape perception (Dobbie & Green, 2013).

Further, land use context can prompt people to have certain expectations for landscape appearance, influencing how people perceive a landscape (Flotemersch, Shattuck, Aho, Cox, & Cairns, 2019; Gobster et al., 2007). For the purposes of this study, we operationalize land use context as a microscale design element because it affects what built structures and landcovers may exist adjacent to ponds. Previous studies on public perceptions of retention ponds that surveyed multiple sites in different land uses commented on substantial variations among sites, but did not explicitly examine the effects of land use context (Jarvie et al., 2017; Williams et al., 2019). Studies of other aquatic systems have noted that, for example, people may have greater preferences for restored wetlands that are located in a natural context (e.g., nature reserve) (Nassauer, 2004).

Building on this literature, we investigated how water level manipulations by smart systems affect the perceived attractiveness, neatness, and safety of pond landscapes. We also considered if and how the effects of water level on perceptions are moderated by design elements. We specifically addressed the following three research questions:

1. How does water level relate to perceived safety, attractiveness, and neatness of smart ponds?
2. How do design elements (i.e., land use context, basin slope, and surrounding plants) relate to perceived safety, attractiveness, and neatness of smart pond landscapes?
3. Are the effects of water level on perceptions of smart ponds moderated by these design elements?

2. Method

2.1. Study location and smart pond design alternatives

2.1.1. Study cities

In this study, we focused on three US cities, each of which were in a different stage of adopting smart systems that entail manipulation of stormwater pond water levels. Smart stormwater systems have been adopted pervasively in South Bend, Indiana; have been partially adopted in Ann Arbor, Michigan; and have not yet been adopted in Knoxville, Tennessee (Fig. 1).

2.1.2. Development of pond landscape design alternatives

To answer our research questions, we employed a factorial design to test each water level with all relevant combinations of design elements of land use context, basin slope, and surrounding plants (Fig. 2). We eliminated some combinations that were implausible in landscape applications. For example, in a commercial context, a steep-sloped basin is typically used to limit the spatial extent of ponds given high land costs, and in a residential context, maintenance typically controls tall weedy plants, like volunteer woody shrubs, at the edge of a pond.

2.1.3. Visualization generation

Based on these pond landscape design alternatives, we then created high verisimilitude visualizations as stimuli to elicit respondents' perceptions of smart ponds. Digitally generated realistic visualizations have been widely used in landscape perception research as validate surrogates to real landscapes (Daniel & Meitner, 2001; Deng et al., 2020; Jorgensen, Hitchmough, & Calvert, 2002; Sevenant & Antrop, 2011). Although such an approach does not account for multi-sensory and embodied landscape experiences, it offers the advantages of both high visual verisimilitude and controlled testing of design elements. Using Adobe Photoshop CC, landscape architects on our team created visualizations by manipulating photos of actual stormwater pond sites selected from the three study cities. In addition, other visible aspects of the pond landscape, such as light or weather conditions, were controlled across all visualizations. Fig. 3 shows 9 of the 90 visualizations employed in our survey.

2.2. Survey

2.2.1. Sampling frame

We employed a stratified random sampling method to obtain a more representative sample, increase generalizability, and to reduce sampling and non-sampling related error (Etikan & Bala, 2017). Using a factorial sampling design, we organized block groups as designated by the U.S. Census Bureau (U.S. Census Bureau, 1994) into four strata in each city according to income and flood risk. Low versus high income was determined by comparing the median household income of a census block group with that for each city. Low vs. high flood risk was determined by whether any part of a census block group fell within the Special Flood Hazard Areas or moderate flood hazard areas in US Federal Emergency Management Agency (FEMA) flood maps (FEMA https://msc.fema.gov/portal/home). Given our goal to survey full-time residents, we excluded census block groups with a median age less than 25, which were more likely to comprise temporary resident student clusters near large universities in the three cities.

Next, a random sample of household addresses from each of the 12 strata was obtained from the Marketing Systems Group, a vendor that supplies addressed-based random samples to research institutions. Structural equation modeling for the larger study suggested that a sample size of at least $n = 200$ per city (total $n = 600$) was needed (Kline, 2015). Informed by previous studies on green infrastructure that employed addressed-based mail surveys (Ambrey et al., 2017; Williams et al., 2019), we anticipated a 15% response rate to our survey. As a result, we obtained 336 household addresses within each of our 12 strata for a total of 1344 per city and an overall total of 4032 households in our mail sample.

2.2.2. Questionnaire design

Our questionnaire included two sections. The first section displayed visualizations of pond landscapes at three water levels. Respondents were asked to rate each pond landscape at typical, low, and high water level for its perceived attractiveness, safety, and neatness. Each was

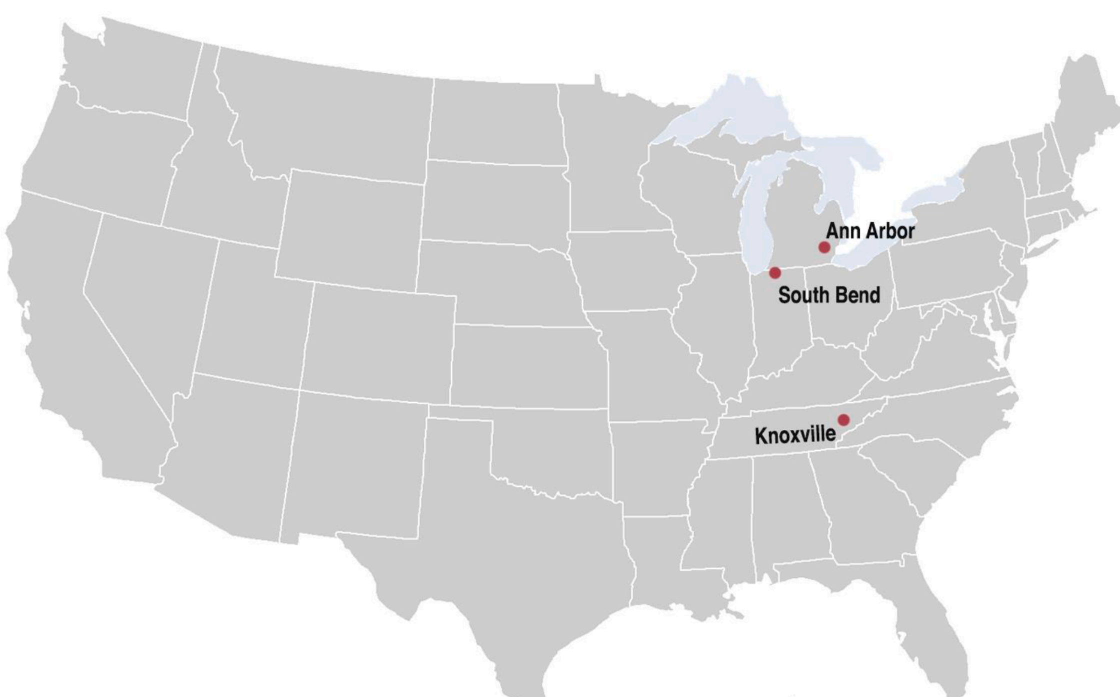

Fig. 1. Three US cities were sample areas for this study.

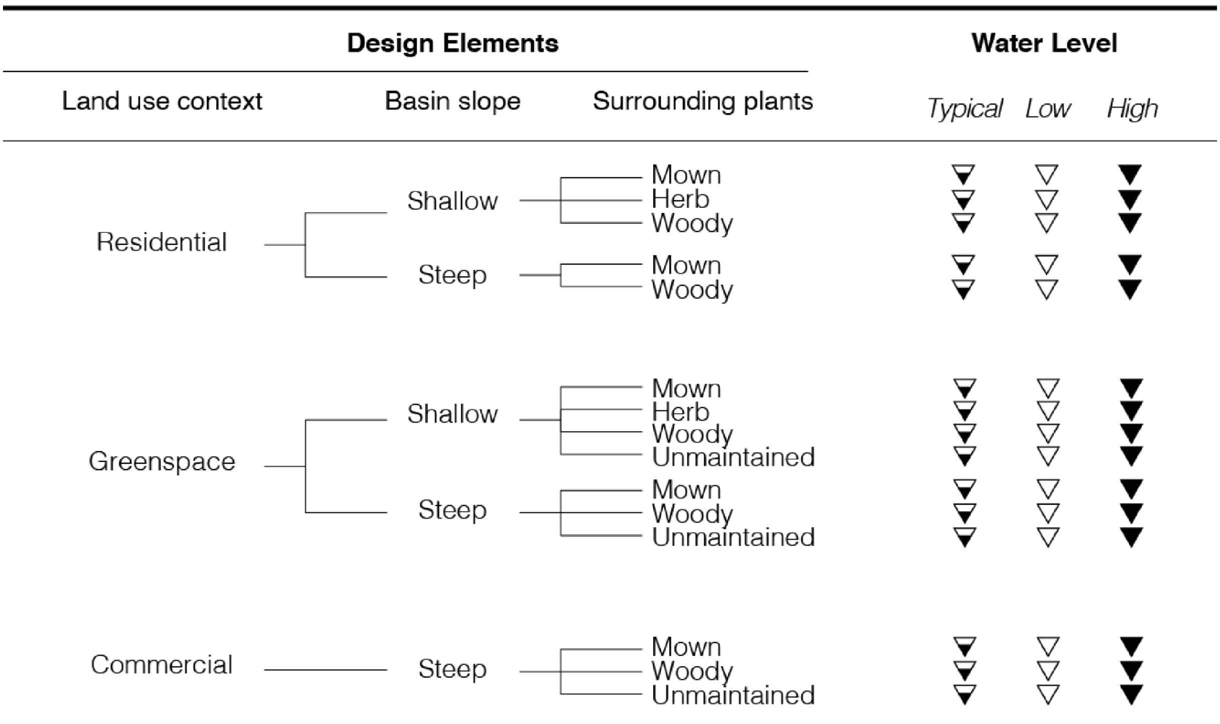

Fig. 2. Smart pond landscape design alternatives were created by a factorial combination of design elements to make 15 landscape design alternatives. Each was applied to two different pond sites, resulting in 30 different pond landscape design alternatives. Each pond landscape design alternative was depicted at three different water levels, in a total of 90 visualizations.

rated on a 5-point Likert scale (e.g., Attractive = 5, Somewhat attractive = 4, Neither = 3, Somewhat unattractive = 2, Unattractive = 1). The second section of the survey included questions about respondents' characteristics and their experiences related to flooding and stormwater management.

We randomly assigned each of the 336 household addresses within each of our 12 strata to be sent one of eight questionnaire versions. To avoid potential attention fatigue, each version of the questionnaire contained only five of the 30 pond landscape design alternatives, with each shown at all three water levels. We purposively selected these five alternatives to include varied design elements in each questionnaire version: all three land use contexts, both steep and shallow basin slopes, and at least three of the four types of surrounding plants. Further, to facilitate comparison across all respondents, we included one design alternative (a residential pond with shallow slope and herbaceous edge from Ann Arbor) in all versions, holding its order constant (the third). All other design alternatives were included in at least one but no more than two questionnaire versions, and randomly ordered in each version of the questionnaire.

Visualizations for typical, low, and high water level appeared in order on a single page for each pond landscape. Moreover, to facilitate respondents' understanding of water manipulations and land use context, we included text descriptions to accompany all visualizations (e.g., "The water level is drawn down before a storm and is temporarily higher after a storm." and "This is a pond in a commercial development."). The questionnaire was color-printed in high resolution as a letter-size booklet. There was a brief introduction explaining the concept of stormwater and stormwater management practices in non-technical language. Examples of questionnaire pages, including the explanatory text, are in Supplementary Materials.

2.2.3. Mail survey procedure

The survey was administered via the US postal mail in the fall of 2019. A postcard was first sent to each of the randomly selected households, notifying residents about the project and that a survey would be sent to their home soon. Next, the survey was sent, accompanied by a letter, an informed consent document, a pre-paid return envelope, and a $1 pre-incentive. The letter provided information about the project and survey, notified residents their household had been randomly selected, and invited a 'head of household (someone who is age 18 or older)' to participate. Respondents who completed and returned the survey with a mailing address were mailed a US $10 token of appreciation. The survey was reviewed and approved by the University of Michigan Institutional Review Board.

2.3. Data analysis

All analyses of survey data were conducted with R 4.0.2 (R Core Team, 2020). The original survey data were encoded at the respondent level, i.e., one row of data per respondent. The data were re-structured for analysis so that respondents' perceptions of each pond landscape design alternative at each water level were the unit of analysis, i.e., three rows of data for each of the five ponds that respondents were asked to rate (a total of 15 data lines per respondent). Data lines for a pond landscape design alternative were removed if a respondent did not provide any perception rating for one or more water level condition, resulting in a final analytic sample of n = 14,430.

To account for the non-independent data structure (i.e., that respondents reported on multiple pond landscapes at varying water levels and respondents did not see the same design alternatives but 5 out of all 30), we employed linear mixed effect models, considering both respondent and visualization as "crossed" random effects (Baayen, Davidson, & Bates, 2008; Spielhofer, Hunziker, Kienast, Wissen Hayek, & Grêt-Regamey, 2021; West, Welch, & Galecki, 2014). Mixed models also have the advantage of accounting for variation in data that is not explicitly modelled to specific variables, thus improving the generalizability of results to both residents and pond landscapes.

To address our research questions, we conducted mixed effects modeling predicting perceived attractiveness, perceived neatness, and perceived safety respectively with the R package 'lme4' (Bates,

Fig. 3. Examples of survey visualizations of three pond landscape design alternatives at the typical, low, and high water level. These alternatives varied basin slopes and surrounding plants and were located in different land use contexts. Respondents viewed each alternative at three different water levels, as manipulated by smart systems.

Maechler, Bolker, & Walker, 2015). Models with random intercepts for both respondents and pond deign alternatives were confirmed by likelihood-ratio tests to have significantly better fit compared to models without the random effects. Modeling was executed in two steps to examine main and interaction effects. In the main effects models, independent variables included: water level (typical level as the reference group), land use context (residential as the reference group), basin slope (steep as the reference group), and surrounding plants (mown turf as the reference group). Then we tested interactions between water level and the three design elements: water level × land use, water level × basin slope, and water level × surrounding plants. Based on the interaction effects models, interactions were further examined for estimated marginal means for perceptions of typical, low, and high water levels among different design elements, as well as contrasts between estimated marginal means. R package 'emmeans' (Lenth et al., 2021) was employed to calculate and graph estimated marginal means and contrast.

3. Results

3.1. Demographic profile of respondents

The response rate for this survey was 24.2% (n = 974/4032), which was much higher than our pre-survey estimate. Table 1 shows the demographic and socioeconomic profile of the sample.

3.2. Descriptive statistics: perceptions of smart ponds

For all three perceptions, mean scores were lower for low and high water levels than the typical water level (Fig. 4). Low and high water levels were associated with different perceptions: the low water level was perceived as less attractive and less neat than the high water level, but safer. Further, there were profound variations in mean scores by pond landscape design alternatives, especially for low and high water levels. This provides descriptive evidence that perceptions of pond landscapes at low and high water are moderated by microscale design elements.

Table 1
Demographic characteristics of respondents to our mail survey.

Respondents' characteristics	Survey Respondents (n = 974)	
	%[a]	*Mean (SD)*
Age (18–103 yrs)		52.1 (18.7)
Gender (% female)	57.3%	
Race (% non-white)	19.4%	
More than high school education	82.3%	
House tenure (% homeowner)	60.5%	
Household income (% above $35,000, before tax)	63.2%	

[a] Valid percentages are given, which exclude missing values.

3.3. Analysis for microscale landscape elements' effects on perceptions

3.3.1. Main effects of water level

Our main effects model showed that both high and low water levels of smart ponds were perceived as significantly less attractive, safe, and neat than the typical water level (Table 2). This confirms the differences in mean perception scores shown in Fig. 4 between the typical water level and water level manipulations.

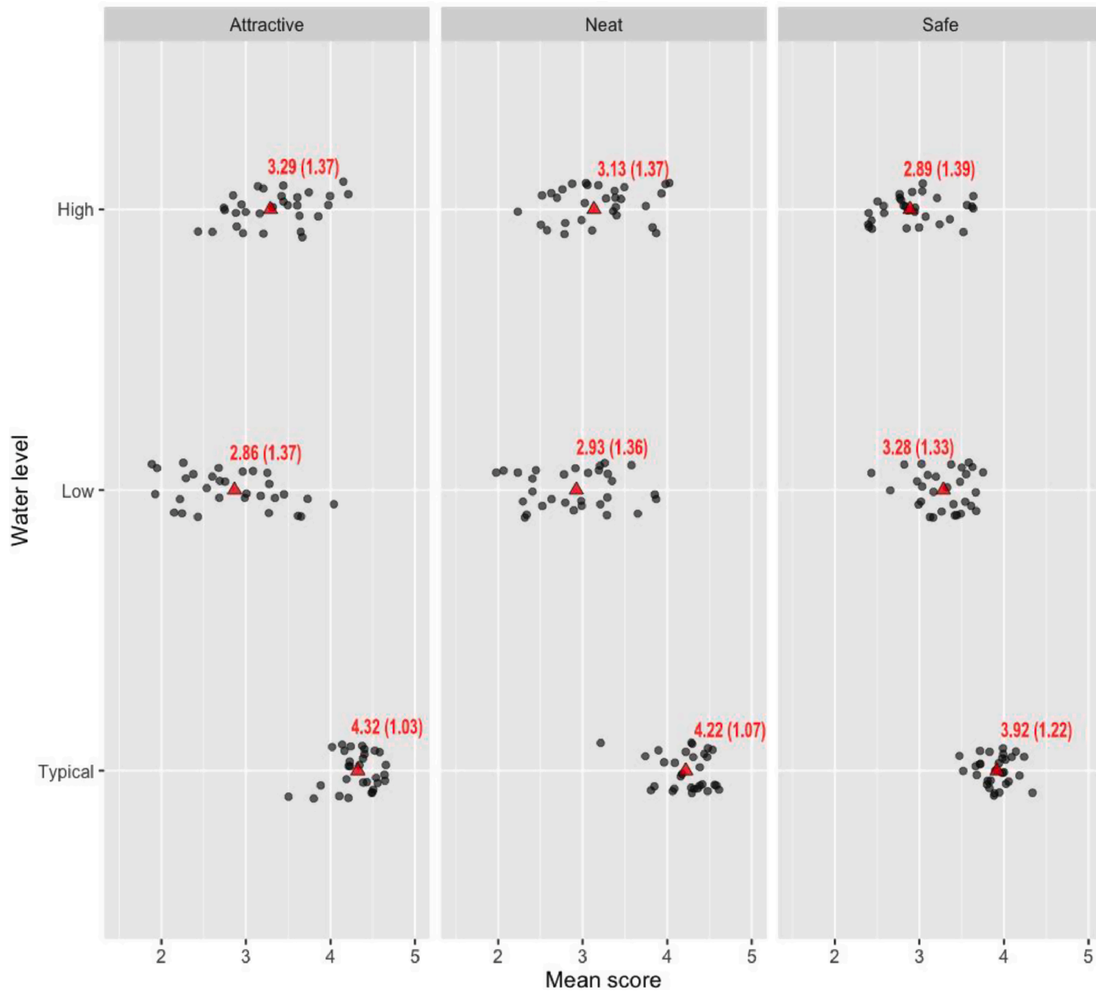

Fig. 4. Grand means and group means for perceptions by water level. Grand means (represented by red triangles, labelled with Mean (SD)) were calculated over all observations; and group means (represented by black dots) were calculated for each pond landscape design alternative. Note that the grand means are not an average of the groups means because slightly different numbers of respondents rated each pond landscape design alternative. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3.2. Main effects of design elements

The main effects models (Table 2) showed that ponds in a commercial context were perceived as significantly less attractive, safe, and neat than those in a residential context, and ponds in greenspace were perceived as significantly safer than those in a residential context. Considering basin slope and surrounding plants, ponds with a shallow slope were associated with significantly lower ratings across all three perceptions than those with a steep slope, and ponds with a woody edge were associated with significantly higher ratings for perceived attractiveness than those with a mown turf edge. However, given the presence of significant interactions between water level and microscale elements, these main effects are most usefully examined and interpreted with attention to different water levels.

3.3.3. Interactions between water level and design elements

Our interaction effects models showed many statistically significant interactions between water level (low or high versus typical) and design elements (Table 2). This suggests that the negative effects of low and high water levels on perceptions are moderated by design elements. In other words, respondents may perceive low and high water levels differently for smart ponds of varying designs.

Water level × land use. Land use context of smart ponds differentially affects the association between water level and perceptions (Fig. 5a). For all three perceptions, the negative effects of both low and high water levels (compared to typical) were significantly stronger for ponds in a commercial context than those in a residential context. Comparing greenspace and residential context, the negative effects of low water level on all three perceptions were statistically stronger for ponds in a greenspace context than those in a residential context. In contrast, the negative effects of high water on perceived neatness and safety were statistically stronger for residential ponds than greenspace ponds. For perceived attractiveness, the interaction was not significant.

Further examination of differences in the estimated marginal means reveals that low water level is perceived as significantly more attractive in a residential context compared to a greenspace context (contrast = 0.298, se = 0.104, $p < .05$), while high water level is perceived as significantly less safe (contrast = −0.322, se = 0.072, $p < .001$). There were no significant differences in perceptions of the typical water level when comparing ponds in commercial and residential contexts. However, both high and low water levels were perceived as significantly less attractive, neat, and safe for ponds in a commercial context, especially for low water level. Ponds in a commercial context were perceived as significantly less attractive and safe than those in a greenspace context for the typical water level ($contrast_{attractive}$ = -0.358, se = 0.129, p = $p < .05$; $contrast_{safe}$ = −0.344, se = 0.089, p = $p < .05$).

Water level × basin slope. Basin slope of smart ponds differentially

Table 2
Main and interactive effects of water level and design elements (i.e., land use context, basin slope, and surrounding plants) on perceived attractiveness, safety, and neatness. The unstandardized regression coefficients (b) for each independent variable are presented, accompanied by the standard error (SE). Significance levels are set as: *p < .05 **p < .01 ***p < .001. For random effects, σ^2 denotes the residual variance and τ^{00} denotes the random effects of respondent and visualizations allowing for random intercepts, with standard deviations (SD). The marginal R-squared considers only the variance of the fixed effects, and the conditional R-squared accounts for both the fixed and random effects (Lüdecke, 2021; Nakagawa, Johnson, & Schielzeth, 2017).

	Perceived Attractiveness		Perceived Neatness		Perceived Safety	
Independent Variables	Main effects model	Interaction effects model	Main effects model	Interaction effects model	Main effects model	Interaction effects model
	b (SE)	b (SE)	b (SE)	b (SE)	b (SE)	b (SE)
Water level						
Typical water (reference group)	–	–	–	–	–	–
Low water	**−1.46 (0.02)***	**−1.30 (0.05)***	**−1.30 (0.02)***	**−1.26 (0.05)***	**−0.63 (0.02)***	**−0.60 (0.05)***
High water	**−1.03 (0.02)***	**−0.83 (0.05)***	**−1.08 (0.02)***	**−0.94 (0.05)***	**−1.03 (0.02)***	**−0.94 (0.05)***
Land use context						
Residential (reference group)	–	–	–	–	–	–
Commercial	**−0.63 (0.14)***	−0.22 (0.14)	**−0.56 (0.14)***	−0.20 (0.14)	**−0.37 (0.09)***	−0.13 (0.10)
Greenspace	0.01 (0.10)	0.14 (0.10)	0.04 (0.10)	0.11 (0.10)	**0.18 (0.07)***	**0.21 (0.07)****
Basin slope						
Steep slope (reference group)	–	–	–	–	–	–
Shallow slope	**−0.31 (0.10)****	−0.07 (0.11)	**−0.34 (0.10)****	−0.14 (0.11)	**−0.23 (0.07)****	−0.14 (0.07)
Surrounding plants						
Mown turf (reference group)	–	–	–	–	–	–
Woody	**0.22 (0.10)***	0.13 (0.11)	0.11 (0.10)	−0.01 (0.11)	0.14 (0.07)	0.10 (0.07)
Herbaceous	0.18 (0.15)	0.07 (0.15)	0.11 (0.15)	0.01 (0.15)	0.15 (0.10)	0.10 (0.10)
Unmaintained	0.13 (0.12)	−0.25 (0.13)	0.01 (0.12)	**−0.44 (0.13)****	0.02 (0.08)	**−0.19 (0.09)***
Interactions						
Low water × Commercial		**−1.06 (0.07)***		**−0.90 (0.07)***		**−0.47 (0.07)***
High water × Commercial		**−0.17 (0.07)***		**−0.20 (0.07)****		**−0.23 (0.07)***
Low water × Greenspace		**−0.44 (0.05)***		**−0.33 (0.5)***		**−0.21(0.05)***
High water × Greenspace		0.05 (0.05)		**0.13 (0.05)****		**0.11 (0.05)***
Low water × Shallow slope		**−0.22 (0.06)***		**−0.14 (0.05)***		0.01 (0.05)
High water × Shallow slope		**−0.47 (0.06)***		**−0.45 (0.05)***		**−0.31 (0.05)***
Low water × Woody		**0.37 (0.06)***		**0.42 (0.05)***		**0.17 (0.05)****
High water × Woody		**−0.12 (0.06)***		−0.07 (0.05)		−0.04 (0.05)
Low water × Herbaceous		**0.28 (0.06)***		**0.25 (0.06)***		0.06 (0.06)
High water × Herbaceous		0.05 (0.06)		0.04 (0.06)		0.11 (0.06)
Low water × Unmaintained		**0.77 (0.06)***		**0.80 (0.06)***		**0.34 (0.06)***
High water × Unmaintained		**0.37 (0.06)***		**0.47 (0.06)***		**0.29 (0.06)***
Random effects						
σ^2	1.00 (1.0)	0.95 (0.98)	0.98 (0.99)	0.94 (0.97)	0.87 (0.93)	0.86 (0.93)
τ_{00}	0.52 (0.72) $_{respondent}$	0.52 (0.72) $_{respondent}$	0.57 (0.75) $_{respondent}$	0.58 (0.76) $_{respondent}$	0.80 (0.90) $_{respondent}$	0.80 (0.90) $_{respondent}$
	0.05 (0.22) $_{visualization}$	0.05 (0.22) $_{visualization}$	0.05 (0.22) $_{visualization}$	0.05 (0.22) $_{visualization}$	0.02 (0.14) $_{visualization}$	0.02 (0.14) $_{visualization}$
Observations	14,375	14,375	14,300	14,300	14,383	14,383
Marginal R^2/Conditional R^2	0.214/0.500	0.235/0.523	0.185/0.501	0.205/0.523	0.112/0.543	0.118/0.550
Deviance	42936.254	42306.716	42609.132	42011.777	41514.684	41303.760
log-Likelihood	−21484.271	−21194.834	−21320.690	−21047.385	−20776.288	−20696.760

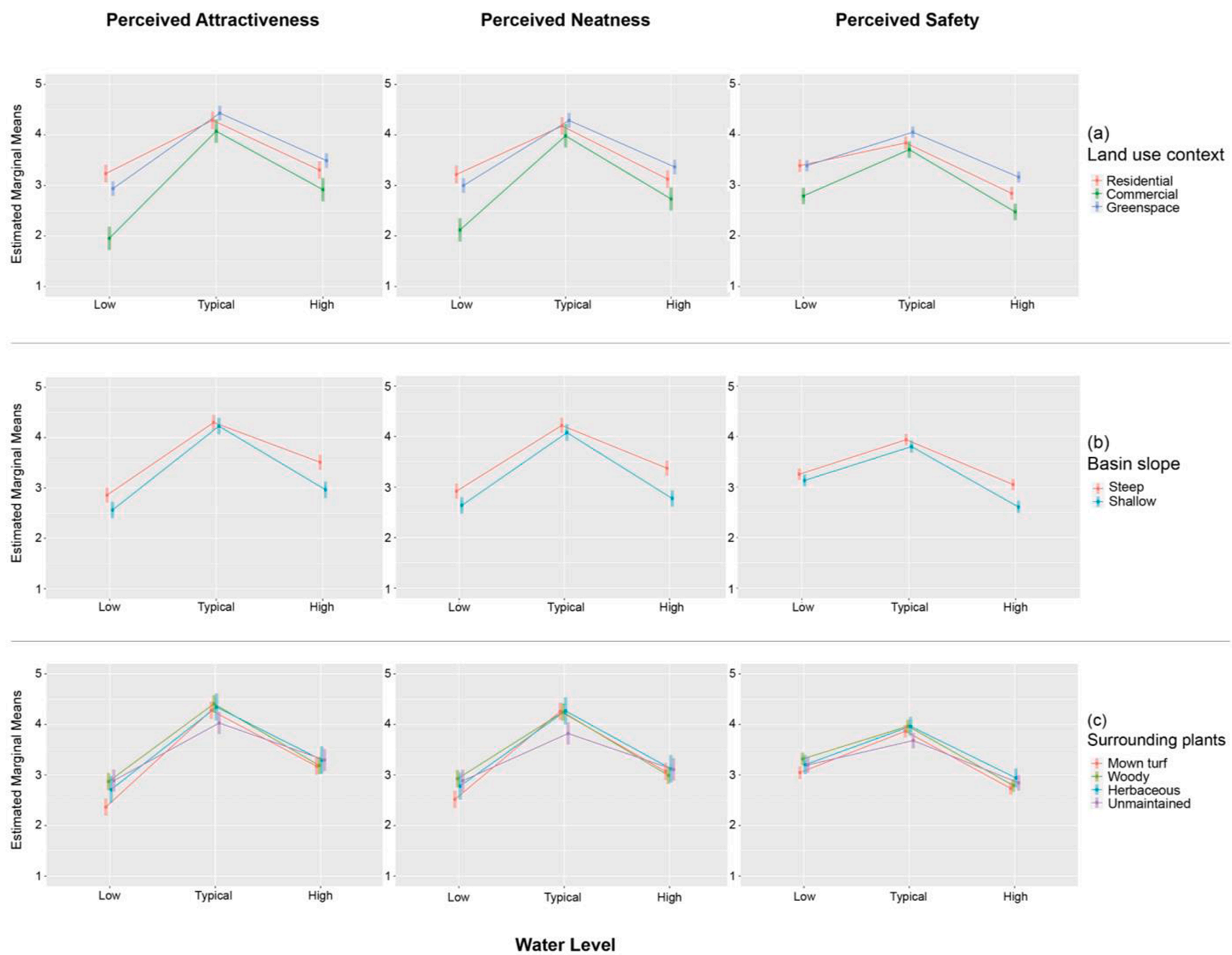

Fig. 5. Interaction effects of (a) land use context, (b) basin slope, (c) surrounding plants on the association between water level and perceptions. Estimated marginal means were graphed with 95% CI (confidence interval).

affects the association between water level and perceptions (Fig. 5b). For all three perceptions, the negative effects of both low and high (compared to typical) water levels were significantly stronger for ponds with shallow slopes than those with steep slopes, except for perceived safety under low water level.

Perceptions of typical water level were not significantly different when comparing ponds with steep versus shallow basin slopes. In contrast, for both high and low water levels, ponds with steep slopes were perceived as significantly more attractive, neat, and safe than those with shallow slopes. The only exception is that low water level was perceived as similarly safe among steep and shallow-sloped ponds.

Water level × surrounding plants. Surrounding plants of smart ponds differentially affect the association between water level and perceptions (Fig. 5c). Negative effects of low (versus typical) water level on all three perceptions were significantly stronger for ponds surrounded by mown turf than those surrounded by woody or unmaintained plants. Negative effects of low water level on perceived attractiveness and perceived safety were also significantly stronger for ponds surrounded by mown turf than those surrounded by herbaceous plants. Herbaceous plants and mown turf similarly affect the association between low water level and perceived safety. Negative effects of high (versus typical) water level were significantly different only when comparing mown turf with woody or unmaintained plants. Ponds surrounded by mown turf had significantly stronger negative associations between high water level and all three perceptions than ponds surrounded by unmaintained plants, and significantly stronger negative associations between high water level and perceived attractiveness than ponds surrounded by woody plants.

Further examination of differences in estimated marginal means reveals that, at low water level, ponds surrounded by mown turf were perceived as significantly less attractive, neat, and safe than those surrounded by woody plants ($contrast_{attractive} = -0.51$, $se = 0.11$, $p < .001$; $contrast_{neat} = -0.41$, $se = 0.11$, $p < .01$; $contrast_{safe} = -0.27$, $se = 0.07$, $p < .01$). They were also perceived as significantly less attractive and neat than ponds surrounded by unmaintained plants ($contrast_{attractive} = -0.52$, $se = 0.13$, $p < .01$; $contrast_{neat} = -0.37$, $se = 0.13$, $p < .05$). In contrast, at high water level, perceptions of smart ponds with different surrounding plants were not statistically different.

Perceptions of the typical water level were not significantly different when comparing ponds surrounded by different plants – except for when the plants are not regularly maintained. Ponds surrounded by unmaintained plants were perceived as significantly less neat than those surrounded by mown turf ($contrast = -0.44$, $se = 0.13$, $p < .05$), and as significantly less attractive, neat, and safe than ponds surrounded by woody plants ($contrast_{attractive} = -0.38$, $se = 0.13$, $p < .05$; $contrast_{neat} = -0.42$, $se = 0.13$, $p < .05$; $contrast_{safe} = -0.28$, $se = 0.09$, $p < .05$).

4. Discussion

This study investigated public perceptions of stormwater retention ponds managed by smart systems. We found evidence that microscale landscape elements may dramatically affect residents' perceptions. Smart ponds in which water level is intentionally manipulated to enhance stormwater regulating capacity risk degrading landscape experiences. However, how residents perceive water level changes also depends on the overall pond landscape. This suggests that design elements may help temper the negative effects of manipulated water levels on perceptions. Below, we discuss our specific findings as related to previous studies on public perception of stormwater ponds and illuminate the implications for planning, design, and management of smart ponds and broader smart NBS practices.

4.1. Effects of water level and design elements on perceptions of smart ponds

People may be familiar with the typical water condition of stormwater retention ponds and their experiences can be degraded when pond water levels are manipulated in visible ways. In our study, respondents perceived both low and high water levels as significantly less attractive, neat, and safe than the typical water level of stormwater retention ponds. Moreover, low versus high water level may affect landscape experiences of smart ponds differently. In general, ponds are likely to be perceived as less attractive with low water level than with high water level, and less safe with high water level than with low water level. Differences in perceived neatness of low and high water levels were smaller.

These results are consistent with previous studies that suggest low aesthetic preferences for water bodies with visible sediments (Cottet et al., 2013; Flotemersch & Aho, 2021) and little surface water (Dobbie, 2013; Völker et al., 2016). They also support observations about safety concerns associated with stormwater ponds (Bastien et al., 2012; Jarvie et al., 2017) and residents' worries about flooding related to temporary detention (Williams et al., 2019). Our results enrich this literature by explicitly providing evidence on the relationship between perception and water level in ponds. Our study indicates that, visible, unfamiliar landscape changes introduced by smart stormwater systems may undermine pleasant everyday experiences valued by residents. While these changes support and benefit stormwater management, the pleasant experiences offered by more familiar, stable conditions of visible water might be a higher priority for nearby residents.

However, the potential degradation of residents' experiences by water level changes needs to be understood as part of the overall pond landscape. Notably, we found that the effects of water level changes on perceptions are affected by microscale design elements including land use contexts, surrounding plants, and pond basin slopes. Our results showed that water level manipulations can be perceived dramatically different across different pond designs. Although microscale design elements may not fully ameliorate the negative effect of water level changes, certain design choices promise to elicit more positive experiences than others.

That residents may perceive water level changes differently under different pond designs might be attributed to shared expectations for how stable a landscape should appear in a specific locale. For example, people may perceive water level changes in a commercial context as far more negative than that in a residential or greenspace context because they expect businesses to maintain an attractive, neat, welcoming landscape appearance. The interactions between water level and design elements could also be attributed to the visibility of water. For example, water level changes in a steep-sloped pond can be less visible and noticeable than those in a shallow, gradual sloped pond due to the blocking of the bank, and consequently, have more positive effects on perception.

Furthermore, our study suggests that a design element might affect residents' perceptions under water level manipulations in very different ways than under the typical water condition. For example, a large literature concludes that mown turf contributes to perceived attractiveness and neatness around stormwater ponds or wetlands (Hu, Yue, & Zhou, 2019; Li & Nassauer, 2020; Nassauer, 2004), while "messy-looking", unmaintained plants are often disliked (Bastien et al., 2012; Flotemersch & Aho, 2021; Suppakittpaisarn et al., 2019). Our study shows that, when at low water level, ponds surrounded by mown turf are likely to be perceived as significantly less attractive and neat than ponds surrounded by regularly maintained woody plants or by unmaintained volunteer plants. We note that, compared with taller plants, mown turf allows unimpeded sight lines to unattractive sediments at low water. Moreover, we speculate that manicured mown turf around ponds signals expectations for neatness, while pond appearance at the low water level may signal neglect or malfunction. These contradictory perceptions may not be compatible.

In contrast with low and high water levels, at typical water levels, perceptions of varied pond landscape designs were significantly different only when comparing a few design elements (e.g., unmaintained surrounding plants versus mown turf or woody plants, commercial versus greenspace context). Consistent with abundant literature that associates native plants around wetlands and ponds with messiness (Bastien et al., 2012; Flotemersch & Aho, 2021; Jarvie et al., 2017; Nassauer, 2004), our results showed that unmaintained surrounding plants were perceived as significantly less positive than other surrounding plants (Fig. 5c). However, respondents in our study did not show strong preferences for mown turf over woody plants as some studies have reported (Hu, Hansen, & Monaghan, 2017). We also found that ponds in greenspace contexts were perceived as significantly more attractive, neat, and safe than commercial contexts at typical water levels, but only more safe than residential contexts (Fig. 5a). These findings provide nuance to those reported in previous studies that indicate positive (Nassauer, 2004) or negative (Rooney et al., 2015) effects of "natural" contexts (e.g., nature reserve, protected area) on perceptions and landscape experiences. Considering basin slope, similar to what Bastien et al. (2012) have observed, we found no obvious differences in perceived safety when pond slopes are less steep.

Compared with perceived neatness and attractiveness, perceived safety of smart ponds might be more strongly shaped by past experiences of flooding or demographic and socioeconomic characteristics (Lechowska, 2018) than by microscale landscape elements. In our study, main effects and interaction effects models for perceived safety showed smaller marginal R-squared yet greater conditional R-squared than perceived attractiveness and neatness (Table 2). This suggests that variations in our respondents' ratings of safety were explained by microscale elements to a lesser degree than variations in their ratings for the other two perceptions. Further, respondent characteristics may have greater impacts on perceived safety, a topic that is in need of further research.

4.2. Implications for the design, planning, and management of smart stormwater systems

Overall, our study suggests that attention to public perception is necessary to the success of smart ponds and NBS broadly. Specifically, manipulation of pond water levels may undermine urban residents' experience of stormwater ponds, with implications for human well-being as well as public support for smart system adoption (Li & Nassauer, 2021). Moreover, though beyond the scope of this paper, ecological implications of water level manipulation must also be considered – for example, whether flashy manipulated water levels, coupled with steep slopes, threaten habitats and biodiversity and impact sedimentation and carbon accumulation (Moore & Hunt, 2012; Rooney et al., 2015). Such implications are also related to residents' perceptions given that wildlife is widely valued in everyday experiences that pond landscapes can offer (Bastien et al., 2012; Nassauer, 2004; Williams et al., 2019). If smart stormwater systems are to provide a more complete set of ecosystem services, their development should integrate measures informed by both public perception and ecological functions (Kabisch et al., 2016; Keeler et al., 2019; Raymond et al., 2017b).

Our results suggest that design, planning, and management choices can affect residents' perceptions of water level manipulations with implications for these potential impacts. Design approaches should be pursued to mitigate possible negative perceptions of smart ponds' attractiveness and safety in commercial settings. In residential settings, our results suggest that smart pond design may benefit from reshaping basin slopes to be steeper, and by planting trees or perennial flowers in the surroundings. In low-lying areas, adoption of smart systems may be prioritized in greenspace contexts, given that extra retention and resulting high water level are less likely to arouse safety concerns and fear in greenspace. Moreover, opportunities to provide other ecosystem services such as biodiversity support and carbon sequestration should be pursued – for example, introducing low-maintenance woody and herbaceous plants in some less accessible sections (Hassall, 2014; Moore & Hunt, 2012).

Knowing which microscale elements in pond landscapes are important for public perception of smart ponds, managers can also design public outreach more effectively to address residents' concerns (Derkzen, van Teeffelen, & Verburg, 2017). For example, communication strategies can be tailored to specific land use contexts. In residential contexts, they may target safety concerns related to high water levels and emphasize the intentional, controlled water level manipulations; in greenspace contexts, they can focus on articulating when to expect low water level conditions and how it prepares the community for extreme storms.

4.3. Limitations

Limitations of our study suggest grounds for carefully and critically drawing on the study results and related implications when considering smart systems adoption for specific ponds and other NBS for stormwater management. First, using visualizations to collect perception data addressed only visual qualities of smart ponds. Other sensory experiences such as smell and sound can influence residents' perceptions (Flotemersch & Aho, 2021). This could be a further concern for smart stormwater systems that may produce a foul odor from dampened or saturated soils and sediments. Moreover, the still visualizations employed in our study depicted discrete water level conditions, and the timeframe for water level change was described verbally. This can feel different from real-world experiences that take place over time. Therefore, future research may investigate in-situ experiences through, for example, on-site interviews, or explore how the dynamic process of water level manipulation may affect perception.

Second, although our data analyses have accounted for random effects associated with respondents, the study results may not be generalizable to communities that are distinctive from the three in our sample. This is particularly relevant for perceived safety, for which variation might be more attributable to past experiences of flooding and demographic characteristics. Future research may examine whether respondents' past experiences with flooding or their home location relative to flood zones affect safety perceptions of smart ponds. Further, while we recognize that perceptions can have important implications for support, we did not explicitly examine residents' support for smart systems adoption and how their support is related to perception.

Finally, visualizations for our study employed a uniform prototype of a rounded shape pond, with design elements shown only in a small area around the edge of ponds. Responses to smart ponds with varied shapes, more varied planting compositions, and more complex edge conditions could be different. Further, these more complex designs could prioritize different landscape experiences and other ecosystem services in different zones, especially when a large area of land is allocated for smart ponds.

5. Conclusion

Smart technologies are changing how cities function, including the management of everyday urban landscapes and their embedded ecosystems. Smart stormwater systems may better prepare cities to respond to climate change and aging infrastructure. However, enhancement of stormwater regulating services cannot automatically ensure pleasant everyday experiences, a critical cultural ecosystem service, or other ecosystem services such as habitat provision. Rather, noticeable yet unfamiliar changes that smart systems introduce into the urban landscape can degrade landscape experiences valued by nearby residents.

Focusing on the example of smart ponds, our study offers insights into residents' perceptions related to water level manipulations and other design elements of land use context, basin slopes, and surrounding plants, with implications for planning, design, and management. We found that high and low water levels are likely to degrade landscape experiences, but their negative effects may be moderated by planning and design choices. In general, adoption of smart ponds may be prioritized in residential neighborhoods and greenspace over commercial contexts. Moreover, avoiding shallow basin slopes and mown turf around ponds may help to alleviate negative effects of water level manipulation on perceptions. In contrast, steeper basin slopes and surrounding woody and herbaceous plants may contribute to more positive perceptions, as long as regular maintenance can keep pond landscapes looking attractive and neat at the typical water condition.

With promise for promoting collective stormwater regulating services at a catchment or watershed scale, smart NBS like smart ponds could serve as a ubiquitous measure of climate change resilience and adaptation in cities. We assert that considerations about how such practice could change residents' everyday landscape experiences must be integral to its implementation. Everyday landscape experiences can have far-reaching implications for urban residents' well-being as well as public support for smart NBS. To avoid degrading landscape experiences that residents value, adopting smart systems to manage urban landscapes requires considerations about microscale landscape elements – both those directly controlled by smart systems and those shaped by broader landscape planning, design, and management choices.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104355.

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