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The Agrihood Design: Valuation of Ecosystem Services for NbS Visions in Peri-urban Housing Estate Development, Bangkok, Thailand

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Abstract

Nature-based Solution (NbS) designs increasingly are being implemented to reduce environmental impacts of urban development and enhance community resiliency to disruptions ranging from floods to climate change to Covid-19. But, the question remains, how do we assess the ecosystem service benefits provided by competing NbS designs in order to optimize such benefits? As such, the objective of this study was to develop and trial an assessment approach for the valuation of ecosystem services in a peri-urban area of Bangkok, Thailand. In our evaluations we considered the ecosystem service benefits of: i) water yield; ii) sediment yield; iii) nutrient yield; iv) carbon sequestration; v) urban heat island mitigation; vi) crop production; vii) habitat quality; and viii) aesthetics. Our ecosystem services valuation approach was tested using three case studies in peri-urban Bangkok, Khlong Luang, Pathum Thani: i) an existing new single detached housing development in the area; ii) an area in its currently undeveloped, open and scrub forest state; and iii) the same area as (ii), but theoretically developed using an Agrihood design concept. The valuation approach included a combination of mathematical modeling for the water, sediment, and nutrient yield ecosystem services and an empirical, data-driven approach for urban cooling, carbon sequestering, crop production, habitat quality, and aesthetics. While the existing housing development design was meant to be relatively green and nature-oriented, the Agrihood design outperformed it in every ecosystem service category, including habitat quality and aesthetics. The Agrihood design also had lower sediment and nutrient yields and mean concentrations as compared to current (natural) conditions at the site, which is attributed to the inclusion of constructed wetlands in the design for the main drainage canal. This work represents a good preliminary step in establishing a local scale ecosystem services valuation framework for urban areas in a tropical climate, but additional refinements to the indicator determinations are needed.

Keywords

Nature-based Solutions; Ecosystem services; peri-urban housing development; Water quality modeling; Urban heat island mitigation; Habitat quality

1. Introduction

Nature-based Solutions (NbS) design has been gaining traction globally as an approach that integrates elements of greenscape and bluescape to provide a more naturalized and resilient urban space (Song et al., 2019; Albert et al., 2021; Li et al., 2021; Moosavi et al., 2021; Wickenberg et al., 2021). Ruangpan et al. (2020) define NbS as *...participatory, holistic, integrated approaches, using nature to enhance adaptive capacity, reduce hydro-meteorological risk, increase resilience, improve water quality, increase the opportunities for recreation, improve human well-being and health, enhance vegetation growth, and connect habitat and biodiversity.* NbS has some relationship with the earlier design traditions of Frederick Law Olmsted, Ebenezer Howard, Ian McHarg, and Berkley's Urban Ecology group of the 1970's (McHarg & Mumford, 1969; Roseland, 1997; Howett, 1998; Clark, 2003), together with the more recent concepts of Water Sensitive Urban Design (WSUD), also known variously as Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), and Sponge Cities (Fletcher et al., 2015; Beza et al., 2019; Lashford et al., 2019; Irvine et al., 2021; Hamel & Tan, 2022). NbS takes a broader, more holistic approach to urban design than green urban water management approaches such as WSUD (Irvine et al., 2022a) in that it additionally considers habitat, biodiversity, aesthetics, community well-being and resiliency and appears to have taken shape particularly through support from the European Commission in 2015 and the International Union for Conservation of Nature, IUCN (Albert et al., 2021). Frantzeskaki (2019) concluded that successful NbS must be aesthetically appealing to citizens, creating a new green urban commons through social innovation and collaborative governance, thereby emphasizing the need for community consultation and involvement. The importance of community consultation or "familiarity" in developing NbS visions also has been well-noted by a number of other researchers (Martín et al., 2020; Ferreira et al., 2020; Irvine et al., 2022b).

While NbS is beginning to gain traction with the planning and design community, Wickenberg et al. (2021) noted that more research is needed to help move beyond conceptual NbS frameworks and towards an operational understanding of NbS principles. Cohen-Shacham et al. (2019) concluded that there is a need to provide greater clarity of NbS definitions, principles, and connections to related approaches in establishing evidence-based standards and design guidelines. Several modeling and assessment frameworks for NbS have been piloted, including different combinations of fieldwork, community surveys, Multi-Criteria Decision Analysis, indexes, geospatial mapping, conceptual mathematical modeling, and ecosystem services valuations (Raymond et al., 2017a; Ferreira et al., 2020; Croci et al., 2021; Croeser et al., 2021; Kumar et al., 2021; Sowińska-Świerkosz and García, 2021; Wu et al., 2021), although there is relatively little standardization of these approaches, which essentially is one of the barriers to NbS implementation noted by Cohen-Shacham et al. (2019). One assessment framework that has received attention recently is Stanford University's Nature Capital Project (https://naturalcapitalproject.stanford.edu/software/invest, accessed 25 April 2022) and the associated InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) suite of models (Salata et al., 2017; Lüke & Hack, 2018; Caro et al., 2020; Cong et al., 2020; Benra et al., 2021; Hamel et al., 2021). InVEST combines geospatial analysis and modeling of a variety of ecosystem services and seems particularly well-suited for planning level evaluations at a watershed scale. However, InVEST is overly simplified for more detailed systematic analysis at the neighborhood scale that requires design specifics. This more detailed analysis at a smaller spatial scale would be particularly helpful for developers in selecting between different neighborhood design options. As such, the objective of this paper is to outline the development of an assessment framework for the valuation of ecosystem services in a peri-urban area of Bangkok, Thailand, at the neighborhood scale. The utility of this assessment framework will be illustrated through a case study comparison of the ecosystem service values for an existing, single detached housing development, a currently undeveloped land parcel, and the same land parcel under an Agrihood design vision.

The concept, design typologies, and implementation of Agrihoods is emerging and has limited documentation in the peer-reviewed literature. Breger (2020) has suggested that "Agrihoods are a recent trend in real estate development that integrate agricultural amenities - such as working farms, orchards, or community gardens - into residential or mixed-use communities". While this definition captures the general idea of an Agrihood, Harrington (2018) further notes that:

> *A relatively uncommon phenomenon, but growing in application, is the creation of pastoral and farming efforts as a part of housing developments. In these cases, agricultural activities are not related to individual properties, but to the development as a whole. Sometimes referred to as agrihoods, it has been estimated that the United States now has about 200 of these developments... The production-focused areas are sometimes referred to as "communal" land (Donally 2015), but under variable models management of this part of the development is often contracted.*

Although Keely and Benton-Short (2019) suggested that Agrihoods also can be found in cities, citing an example of a repurposed warehouse space for lofts and 30 community garden plots in Oakland, California, we have retained the peri-urban focus of the Agrihoods concept in keeping with the philosophy that agriculture-focused development should conserve open space and agricultural lands while also providing residential development (Breger, 2020; Wulfkuhle, 2022).

A number of reasons have been suggested as to why buyers may be interested in an Agrihood development, including a strong sense of place and community, with the convenience of living near urban amenities, but also with the proximity of farms and access to fresh (and perhaps organic) food. In some ways, this concept is related to the local foods movement, preservation of agricultural land, food security, being able to maintain a backyard garden with lesser responsibility, and provision of green space for community wellbeing. Hauser (2019) has further suggested that Agrihoods capture the imagination of Millennials, a generation that might be characterized as one that enjoys unique experiences, while also appreciating sustainable environments, and having a strong sense of place and community.

In their reviews of selected existing Agrihoods throughout the United States, Breger (2020) and Wulfkuhle (2022) showed that there was considerable variability in design typology and project operation and management. For example, of the six Agrihoods examined by Wulfkuhle (2022), the range in total project area was 69-486 ha; the land use distribution ranged between 2-33%, 10-70%, and 23-70% for agriculture, residential, and open space, respectively; and operations included larger and smaller scale professional farms, Community Supported Agriculture (CSA) where farmers and consumers are directly connected through the food production and distribution systems; and small scale community plots.

The foregoing discussion on Agrihoods serves to provide context for the Agrihood design presented as a case study in this research. However, we emphasize that the focus of the paper is on development of an ecosystem service evaluation framework that can be applied to any peri-urban development, rather than establishing a design typology for Agrihoods. We also note, however, that most of the existing literature focuses on North America and considerable scope remains to explore the design and operations characteristics of Agrihoods for Thailand and Southeast Asia.

2. Methodology

2.1 Study Sites

The study area is located in peri-urban Pathum Thani province, approximately 55 km north of downtown Bangkok (Figure 1). Traditionally, this area was predominantly agriculture, although it is now transitioning rapidly to include residential developments, commercial and higher-education institution zones, and industrial estates (Klinmalai & Kanki, 2013; Tsuchiya et al., 2015; Loc et al., 2020; Irvine et al., 2022b; Likitswat & Sahavacharin, 2023). The land use map in Figure 1 clearly illustrates the urban development core of Pathum Thani, particularly east of the Chao Phraya River along a central north-south arterial for Thailand, Phahonyothin Road (Highway 1). The urban development has been expanding eastward from Phahonyothin Road, particularly along main east-west roadways, Khlong Luang Road (Highway 3214) and Rangsit-Nakhon Nayok Road (Highway 305), and the north-south khlongs (or canals), numbers 1-4. The rural character of the province remains evident, however, with Figure 1 showing the extensive paddy field and orchard areas.

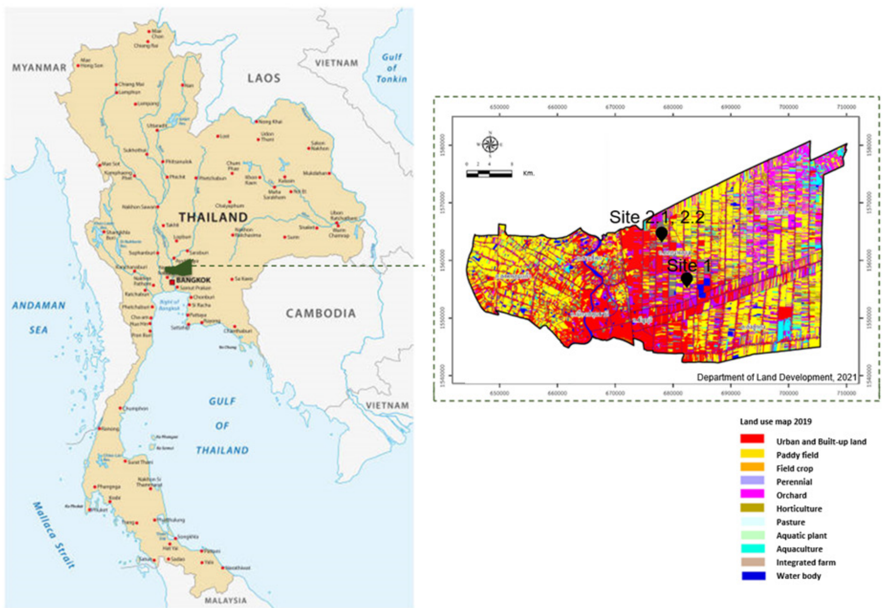

Figure 1 Study area and study site locations. Land use map represents the year 2019. Source: Department of Land Development.

The study sites (Site 1, Site 2.1, and Site 2.2) were located approximately 11 km apart. Study Site 1 is an existing 7.3 ha new, single detached housing development (Figure 2). The design philosophy for this development is “Let the outdoor in”, whereby the interior and exterior of the house are connected with open spaces and a large patio while innovative breezeway windows increase the efficiency of ventilation. Each house has a relatively large greenspace/lawn area (minimum of 54 m^2 as built) for such developments and small pocket parks and a swimming pool/gym complex also are located in the development.

Sites 2.1 and 2.2 are the same location, where “Site 2.1” is the current land use condition and “Site 2.2” is the Agrihood vision as a possible design for future development. This location is approximately 34.9 ha in area and currently consists of scrub forest and abandoned agricultural land open for development (Figure 3). An existing khlong, part of the Tung Rangsit project (1890-1900) runs north-south through the heart of the site and plays an important role in local drainage. The Tung Rangsit project was constructed to provide transportation, irrigation, and drainage opportunities for Pathum Thani. The Agrihood visioning for the site is summarized in Figures 4 and 5. This design features the integration of single family and cluster homes around a variety of gardens and orchards and includes a series of constructed wetlands as part of the main canal system.

Figure 2 Plan view of study site 1 (left), typical house architecture (top right) and park/swimming pool/gym area (bottom right).

Figure 3 Plan view of Site 2.1, current (left) and typical land conditions of the site (top right and bottom right).

Figure 4 Plan view of Site 2.2, Agrihood design.

Figure 5 Enlarged plan view of Site 2.2, Agrihood design (left) showing the relative proximities of the main drainage canal, constructed wetlands, community gardens, and cluster homes. Perspective visions of the Agrihood design (top right and bottom right).

2.2 Ecosystem Services Valuation

Following the general InVEST approach, 8 ecosystem services were identified for valuation in this study, as summarized in Table 1. We note, however, that the InVEST valuation approach was modified in four important ways. First, the InVEST hydrology, sediment, and nutrient yield estimation approaches are quite general, which is appropriate for a watershed scale, but not the neighborhood scale we are assessing in this work. Instead, we employed the conceptual, deterministic hydrologic/hydraulic model, PCSWMM (Personal Computer version of the Stormwater Management Model). PCSWMM is a robust physical/conceptual computational model that has been applied in urban water resource studies throughout the world (Shrestha et al., 2014; Irvine et al., 2015; Ho et al., 2015; Irvine & Chua, 2016; Marvin & Wilson, 2016; Akhter & Hewa,2016; Nasrin et al., 2017; Goncalves et al., 2018; Paule-Mercado et al., 2017; Akter & Alam, 2019; Beganskas et al., 2021; Piloti et al., 2020; Saurav et al., 2021; Sidek et al., 2021; Chitwatkulsiri et al., 2022).

Second, crop production values were empirically determined as a function of crop yield rate per ha and retail price of the crops that will be cultivated under the Agrihood scenario. This information was determined through surveys done in local fresh markets and with local farmers.

Third, habitat quality was simplified in this study to species richness for plant types, which is a common indicator of biodiversity (Gioia & Pigott, 2000; Gotelli & Colwell,2002; Brunbjerg et al., 2018). More sophisticated measures of biodiversity and habitat quality exist (Ferris & Humphrey, 1999; Simaika & Samways, 2009; Wu et al., 2013; Ali & Yan, 2017; Wright et al., 2021), and the issue should be explored further, but for this prototype valuation framework species richness of trees, shrubs, grasses, and groundcover was implemented as it is relatively easy to quantify and we believe it provides an acceptable overview of habitat quality. Species richness was determined using a combination of Google Street View and on-site survey.

Fourth, the aesthetics of each site were assessed by a year 4 Landscape Architecture class of 15 students at Thammasat University that was co-taught by two of the co-authors. Rapphorst et al. (2017) note that the visual representations of a design are the primary means of communication between stakeholders in the design process. Assessment of the visual representations therefore is an essential element of this process. A variety of tools and approaches have been developed to assess landscape design (e.g. Polat & Akay, 2015; Kalinauskas et al., 2021). Daniel (2001) concluded that assessment of landscape quality has become a balance between expert and perception-based approaches where the expert approach focuses on the biophysical features of the landscape as they relate to formal design parameters (e.g. form, line, variety, unity) based on human perception and aesthetic judgement. Conversely, the perception-based approach characterizes biophysical features of the landscape "as stimuli that evoke aesthetically relevant psychological responses through relatively direct sensory–perceptual processes and/or through intervening cognitive constructs (e.g. legibility, mystery, prospect-refuge)." In this study a hybrid approach between the expert and perception-based approach was applied in which the assessment tool criteria were developed through class discussion and consensus and contained 5 categories: i) green space proportion, naturalness, and shadiness; ii) open space availability, cleanliness, and general pleasing appearance; iii) biodiversity; iv) blends harmoniously with the surrounding landscape; and v) potential for provision of ecosystem services. Each category was scored by the individual students on a scale of 1-10. Each category was weighted equally and the maximum score for each scenario was 50.

Table 1 Ecosystem Services and Summary of Valuation Methods

Ecosystem Service	Valuation Methodology	Indicator Units
Water Yield	PCSWMM hydrologic modeling	Soil infiltration depth, mm
Sediment Yield	PCSWMM erosion modeling	TSS mass load, kg/ha; TSS concentration, mg/L
Nutrient Yield	PCSWMM nutrient runoff modeling	TN and TP mass load, kg/ha; TN and TP concentration, mg/L
Carbon Sequestration	InVESTand supporting data bases	Tons/ha
Urban Cooling	InVEST Cooling Capacity Index, CCi	Adjusted mm/day water loss through evapotranspiration
Crop Production	Empirical data collection	THB/ha/year
Habitat Quality	Species richness, empirical data collection	Number of trees, shrubs, grasses, and groundcover
Aesthetics	Landscape Architecture Year 4 students visual rating of key criteria	Rating score with a maximum value of 50

2.3 PCSWMM Configuration

PCSWMM was used to determine the indicator values for the water yield, sediment yield, and nutrient yield ecosystem services. PCSWMM explicitly models both the surface and drainage network water quantity and quality processes and the general representation of the three study scenarios within the model is shown in Figure 6. Attributes required for the surface subcatchments include subcatchment area, width of overland flow, slope, per cent imperviousness, Manning's roughness coefficients, depression storage, and soil infiltration characteristics. Attributes required for the drainage network include location, slope, geometry, and Manning's roughness coefficients. These attributes for each site were determined through a combination of the designs, on site investigations/measurements, the literature, and the professional urban hydrology modeling experience of the senior author (35+ years). The Agrihood design included 7 constructed wetlands as part of the main channel configuration (Figure 7). For this study, the wetland storage function was represented using a surface area-depth rating curve based on the design dimensions while the water quality treatment simulation was based on performance efficacy reported in the literature (Luederitz et al., 2001; Vymazal, 2007; Sim et al., 2008; Koottatep et al., 2005; 2021).

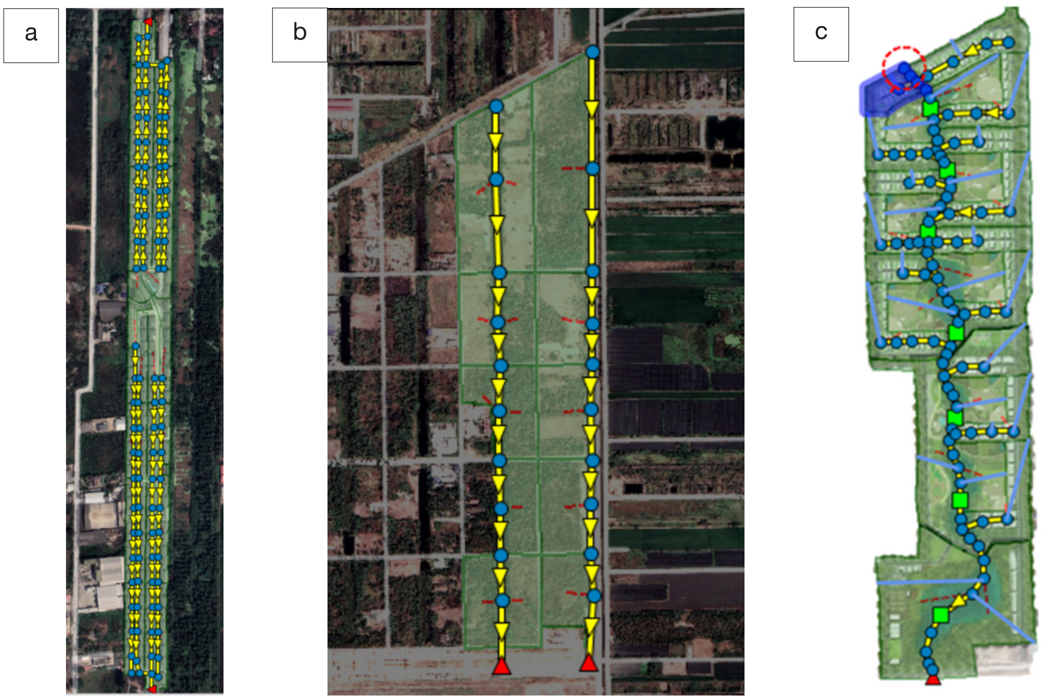

Figure 6 The study sites as represented in PCSWMM (a) Site 1; (b) Site 2.1, current conditions; (c) Site 2.2, Agrihood design. The green shaded polygons represent individual subcatchment areas; the yellow lines represent the drainage network; the blue circles represent nodes that are connected by the drainage lines, where surface flow enters the drainage network, or to allow a change in geometry/positioning of the drainage line; the green squares represent constructed wetlands; and the red triangles represent the outlets of the modeled systems.

To explore the water, sediment, and nutrient yields for each site, we employed 1D PCSWMM using: a) 24-hour, Type II SCS design storms of 30, 60, 90, 120, and 150 mm and; b) a continuous modeling approach with 5 minute rainfall data from the area for October, 2021. The Universal Soil Loss Equation (USLE) option was employed to consider erosion of pervious land and water quality while a buildup/washoff approach was used to model impervious land water quality with parameterization drawn from past studies in Thailand and Singapore (Chaosakul et al., 2010; Irvine & Chua, 2016; Htun et al., 2016; Le et al., 2017; Irvine et al., 2022c).

The USLE has a long history of being applied to estimate soil erosion rates throughout the world, including in urban areas (Wischmeier & Smith, 1978; Irvine et al., 1990; Benavidez et al., 2018). PCSWMM includes the USLE as an option, with the general form:

$$A = R\ K\ LS\ C\ P \qquad [1]$$

Where A is the average annual (or event) soil loss, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the field topography (slope-length) factor, C is the cropping and management factor, and P is the conservation practice factor.

The rainfall erosivity factor is an empirical function of the kinetic energy of rainfall and peak 30 minute rainfall intensity for each storm, which accounts for both the influence of total energy of rainfall and the extra erosivity related to high intensity rains. The soil erodibility factor is assessed empirically and is a function of soil texture, clay and organic content, and soil permeability. The slope-length factor is the ratio of erosion for the given condition to erosion for a standard 22.1 m plot length of 9% steepness. The cropping and management factor is the ratio of the erosion rate for the given condition to the erosion rate for a standard bare soil (C values excluding bare soil will be <1). The conservation practice factor is the ratio of soil loss under the given condition to soil loss from up-and-down-slope farming (defined as the standard condition). Therefore, the P values will range between 0 and 1, but will be <1 for all conditions other than the standard condition. The literature and field measurements (including the IoT rainfall data, discussed below) were combined to develop appropriate estimates for the different USLE factors.

Figure 7 Detailed view of PCSWMM representation, constructed wetland, for the Site 2.2, Agrihood design. The green square in the middle of the design represents the constructed wetland footprint that can be seen surrounding it.

2.3.1 Water Quality Sampling

Water samples were collected at three locations in Khlong 3 between Kanchanaphisek Road and Khlong Luang Road for analysis of Total Nitrogen (TN), Total Phosphorus (TP) and Total Suspended Solids (TSS). Sample results were used to validate the water quality estimates from PCSWMM. The samples were collected on 9 dates between September, 2021 and January, 2022, and represented both storm event and dry weather conditions. Samples were collected manually near the water surface at the middle of the khlong using a dipper deployed from bridges. Samples were stored on ice until delivered to the lab and analysis was conducted by the NATS (Naturally Acceptable and Technological Sustainable) ISO 17025-certified Lab on the Asian Institute of Technology (AIT) campus, Khlong Luang, Pathum Thani.

2.4 Urban Cooling

The urban cooling ecosystem service was evaluated following the InVEST model approach that calculates a Cooling Capacity Index:

$$CC_i = 0.6 \cdot shade + 0.2 \cdot albedo + 0.2 \cdot ETI \quad [2]$$

Where CC_i is the Cooling Capacity Index, shade is the proportion of tree canopy ≥2 m in height, albedo is the proportion of shortwave radiation reflected by different urban surfaces, and ETI is an evapotranspiration index calculated using the Blaney-Criddle approach. Shading was estimated using canopy measurements from each site based on the most recent Google Earth images (2022) or the Agrihood design. This was done through a combination of measuring canopy polygon areas in Google Earth for Sites 1 and 2.1, together with field verification that trees were >2m. The Agrihood design designated the type of trees to be planted and we assumed these would have a height of >2m at maturity. The albedo values were obtained from Sailor (1995), while the Blaney-Criddle estimate, as modified by Ponce (1989), is calculated as:

$$ET_c = k_c \cdot ET_o \quad [3]$$

Where ETc is the daily consumptive water requirement in mm for a particular crop, ETo is the reference evapotranspiration estimate, and kc is a crop use coefficient. In this study, the value for kc was taken as 0.7 which is representative of both turfgrass and deciduous trees (Ponce, 1989; Romero and Dukes, 2009).
The reference evapotranspiration (ETo) is calculated as:

$$ET_o = a + b_f \quad [4]$$

Where a and b are empirically-derived constants based on insolation time, relative humidity, and wind speed. The value for f (a consumptive use factor in mm/d) is calculated as:

$$f = p(0.46t + 8.13) \quad [5]$$

Where p is the ratio of daily mean daytime hours for a given month to the total daytime hours in a given year (as a percent), which is a function of latitude (Ponce, 1989) and t is the daily mean temperature for the month, °C.

2.5 Meteorologic Data for PCSWMM and the Cooling Capacity Index

Rainfall and meteorologic data for the month of October, 2021, were used in the PCSWMM modeling and the Cooling Capacity Index calculations as part of the ecosystem service valuations. The data were obtained for the Thai Meteorological Department sites at the Bangkok Airport, downtown Bangkok, and Pathum Thani, as well as from an IoT station close to the Agrihood site that is maintained by the study team.

3. Results

3.1 PCSWMM Validation

PCSWMM model results suggest no surface flooding would occur at Site 1 for the 90 mm, 24 hour design storm but minor flooding may be observed for the 120 mm, 24 hour design storm. No flooding was observed at Site 1 for a rainfall event on 16 October 2021 which had a return interval of approximately 3.5 years, a 63.8 mm depth in 24 hours, and a peak intensity of 89 mm/hr. In fact, flooding has not been observed at Site 1 for the 3 years in which observations have been made. Based on this admittedly limited data set, it can be concluded that PCSWMM accurately reflects hydrologic conditions at Site 1. PCSWMM results also indicate that Site 2.1, current conditions, and the Site 2.2, Agrihood, would experience no surface flooding under the 150 mm 24 hour design storm.

Figure 8 compares PCSWMM water quality model results for the 30 mm design storm (peak event concentrations) with the observed mean concentrations for Khlong 3 (all 3 sites averaged together). The 30 mm design storm is used for comparison purposes because it is of similar magnitude to events sampled for Khlong 3. Recognizing the simplifying assumptions made in this comparison, nonetheless, it can be concluded that for planning level purposes the model accurately reflects water quality processes.

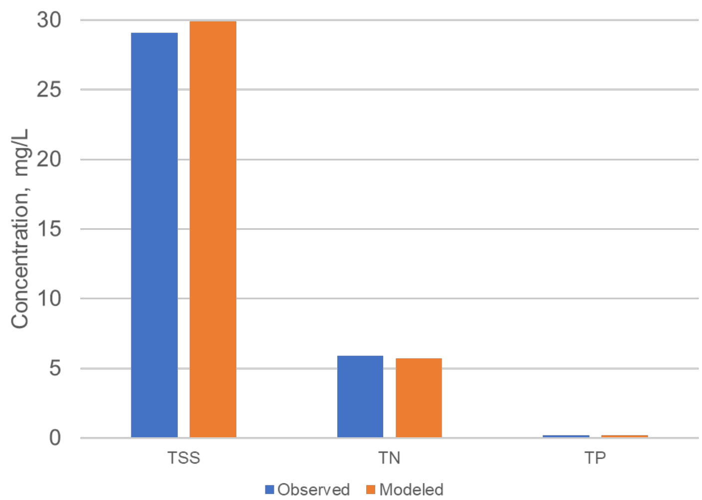

Figure 8 PCSWMM model results for peak concentrations associated with a 30 mm design storm at Site 1 (Modeled) and observed mean concentrations at Khlong 3 (Observed).

3.2 Valuation of Ecosystem Services

As noted, 8 ecosystem services were identified for valuation (Table 1): i) water yield; ii) sediment yield; iii) nutrient yield; iv) carbon sequestration; v) urban cooling; vi) crop production; vii) habitat quality; and viii) aesthetics.

Water Yield - as there is no pluvial flooding to speak of with the existing study sites, we can only note that current design is sufficient to manage stormwater runoff. Residential developments in this area frequently rely on groundwater as the potable water source and rather than avoided costs due to reduced flooding, for this specific case study infiltration depth (mm for the month of October, 2021) was selected as the water yield ecosystem service indicator since it would represent higher groundwater recharge potential and reduced risk to potable water access.

Sediment Yield and Nutrient Yield - sediment and nutrient loads, kg/ha, for the month of October, 2021 were used as one of the ecosystem service indicators for sediment yield and nutrient yield. A second indicator, event mean concentrations (30 mm, 24 hour design storm), also was included to reflect risk of eutrophication and negative impacts to fish habitat.

Carbon Sequestration - was calculated following the InVEST model approach that considers above ground, below ground, soil, and dead vegetation storage for different vegetation/land use types. Data for these calculations were based on information provided by the InVEST model as well as Arunyawat and Shrestha (2016). The ecosystem services indicator is represented as Tons of Carbon Sequestered/ha.

Urban Cooling - The Cooling Capacity Index (CCi), equation 2, was used as one ecosystem services indicator. Furthermore, the CCi was used to calculate the expected temperature differences for the each of the three study sites and based on average monthly electricity consumption for a single family home, this information was used to estimate monthly CO_2 emission rates.

Crop Production – was based on a survey of local market retail prices for the expected crops grown in the Agrihood scenario (Figure 9). In addition, some cattle foraging was observed for Site 2.1, current conditions, and foraging crop value also was estimated based on cassava prices in Thailand.

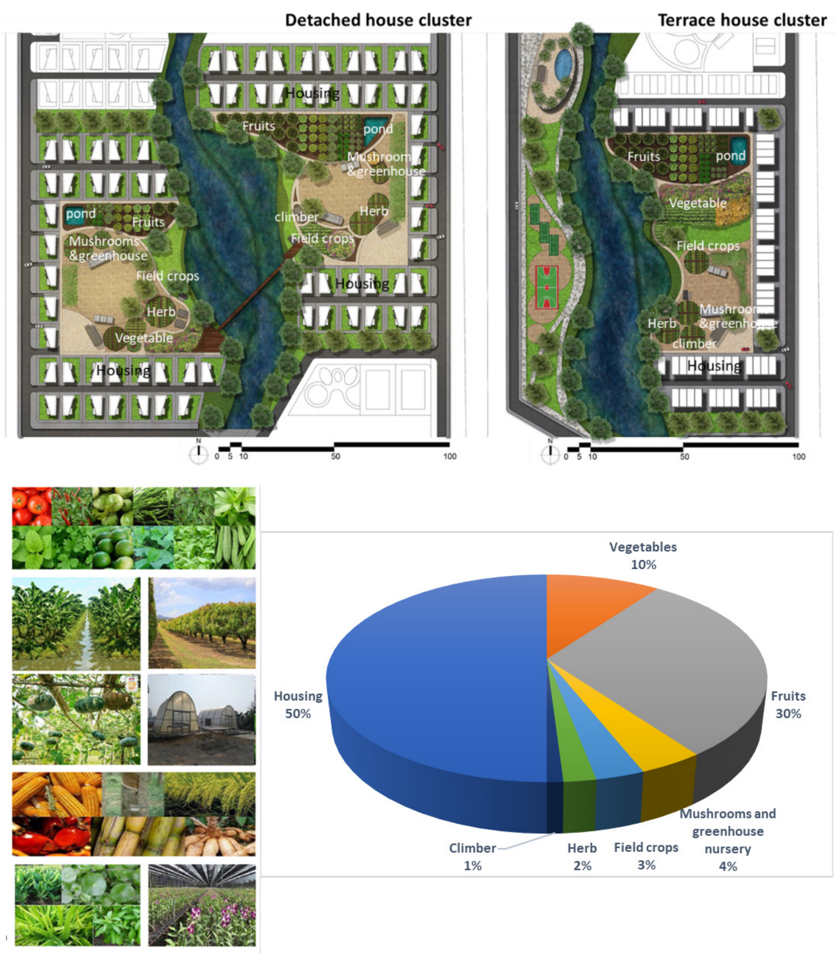

Figure 9 Agrihood design, focusing on the community gardens (top) and the crop types and land use crop proportions (below).

Habitat Quality – was assessed using total species richness of trees, shrubs, grasses, and groundcover for each site determined through a combination of Google Street View and on-site survey.

Aesthetics – was evaluated by the year 4 Landscape Architecture class based on the five categories noted in Section 2.2, with each category being scored on a scale of 1-10. The categories had equal weights such that the total maximum score for this indicator would be 50.

The results of the ecosystem service indicator valuations are summarized in Table 2. We also note that based on a standardized, comparative number of homes (n=180) for both Site 1 and Site 2.2, Agrihood using the CC_i, Site 1 would emit 2,172 kg of CO_2 per month more than Site 2.2, Agrihood.

As an alternative way to help visualize and compare results for the different scenarios, the ecosystem service indicator values from Table 1 were standardized to a scale of 0-5 using equation [6]:

$$\textit{Standardized value} = \frac{x_i - x_{min}}{x_{range}} \cdot 5 \qquad [6]$$

Where x_i is the calculated raw value for the variable, xmin is the expected minimum value for the variable, x_{range} is the expected range for the variable (maximum expected value – minimum expected value), and 5 is the scaling factor.

The results of the indicator standardization are summarized in Figure 10 and clearly show that while Site 1 was meant to be a relatively green and nature-oriented design, Site 2.2, Agrihood design outperforms it in every ecosystem service category, including habitat quality and aesthetics. This type of comparison can be helpful to community planners and private sector developers in deciding on relative benefits of different development pathways. The Agrihood design had lower TSS, TN, and TP yields and mean concentrations as compared to current conditions, which is attributed to the treatment capacity of the constructed wetlands that have been integrated into the main drainage canal (Figure 11). The Agrihood design also had a higher habitat quality compared to current site conditions, which is more of a transitioning scrubland (Figure 3). The intent of the Agrihood design is to produce a rich vegetated experience for the community and this objective generally appears to be met. However, the Agrihood habitat quality is not at the same level as a natural forest stand (e.g. Kamo et al., 2002; Asanok et al., 2017) and perhaps through further reflection the value could be increased, which indicates the benefit of this critical review approach, thereby facilitating optimization of ecosystem services. Not surprisingly, Site 2.1, current conditions, exhibits the largest infiltrated water depth since it has the greatest pervious land percentage of the three scenarios. Site 2.1 also has the highest carbon sequestration of the three scenarios, although because the vegetation at this site is still fairly sparse scrubland, the sequestration level (Figure 10) is not comparable to a mature forest (e.g. Arunyawat & Shrestha, 2016). The crop provisioning value for the Agrihood design is greater than for the other two scenarios, as is the aesthetics assessment.

Table 2 Ecosystem Service Valuation Comparisons for Site 1, Site 2.1 (Current Conditions) and Site 2.2 (Agrihood)

Ecosystem Service	Site 1, Existing Residential	Site 2.1, Current Conditions	Site 2.2, Agrihood Design	Comments
Water Yield, Infiltrated water depth, mm in Oct.	82.1	185.5	157.9	October 2021 rainfall
TSS Yield, kg/ha in Oct.	78.3	9.2	0.47	October 2021 runoff
TSS Mean concentration, mg/L in Oct.	4.8	13.8	0.5	30 mm, 24 hour design storm
TP Yield, kg/ha in Oct.	0.546	0.064	0.014	October 2021 runoff
TP Mean concentration, mg/L in Oct.	0.034	0.1	0.021	30 mm, 24 hour design storm
TN Yield, kg/ha in Oct.	15.0	1.76	0.42	October 2021 runoff
TN Mean concentration, mg/L in Oct.	0.92	2.65	0.58	30 mm, 24 hour design storm
Carbon Sequestration, Tons/ha	33	89	50.6	
Urban Cooling, Cooling Capacity Index, CCi	0.169	0.400	0.31	Based on the average meteorological conditions for August, 2021-January, 2022
Crop Production, THB/USD/ha/year	Negligible	Foraging crops for cows estimated at 3,926 THB ($120 USD)	116,982 THB ($3,859 USD)	
Habitat Quality (total species richness of trees, shrubs, grasses, and groundcover)	31	28	55	
Aesthetics (total rank score, with maximum value of 50)	32	34	40	

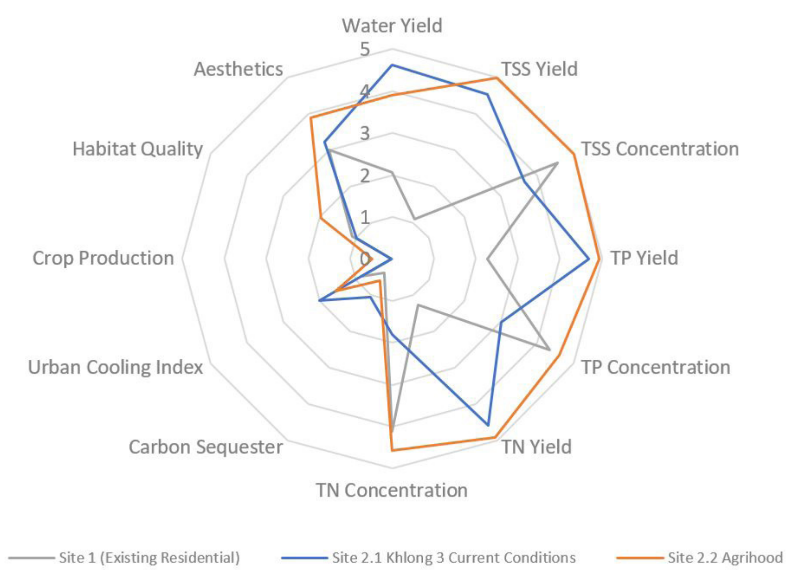

Figure 10 Standardized ecosystem indicator results.

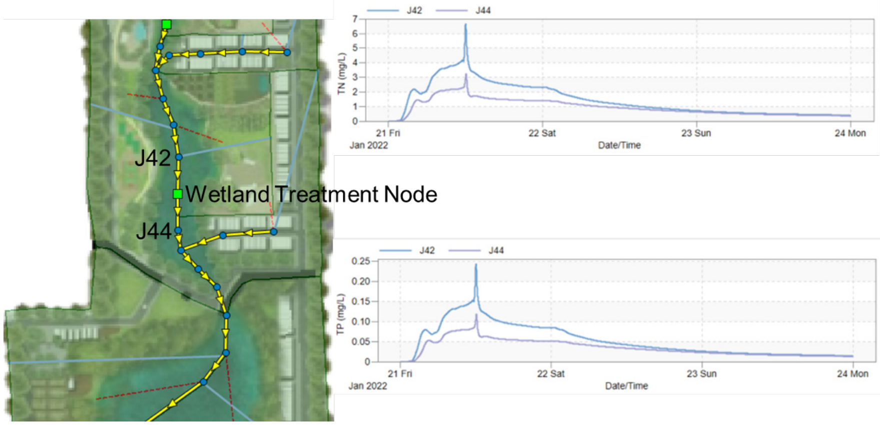

Figure 11 Example PCSWMM model results for 30 mm design storm where J42 is the node upstream of the constructed wetland and J44 is the node downstream of the constructed wetland.

4. Discussion

This research represents a first effort in developing a practical application framework that would facilitate assessment of NbS ecosystem services as part of integrated design visioning at the neighborhood scale for urban areas. The framework workflow is summarized in Figure 12. This framework represents a progression from the four broad categories of ecosystem services established some 17 years ago by the Millennium Ecosystem Assessment (MA, 2005): supporting (e.g. nutrient cycling, soil formation, primary production); provisioning (e.g. food, water, fiber); regulating (e.g. climate regulation, disease regulation, water purification); and cultural (e.g. spiritual, religious, aesthetic). The framework is sufficiently flexible to accommodate a variety of different possible models or empirically-driven approaches to quantify the ecosystem services indicators, depending on the environment and design at hand.

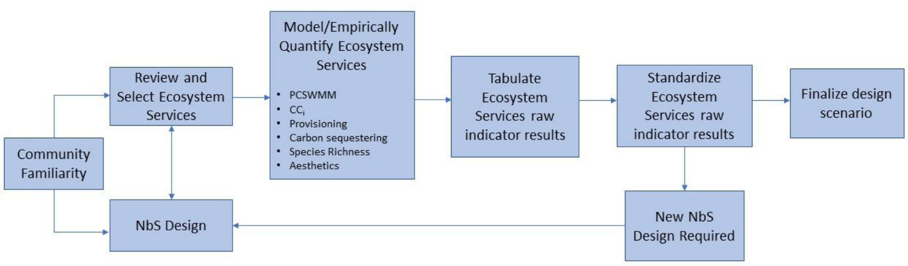

Figure 12 Framework workflow to integrate ecosystem services evaluations as part of the NbS design visioning process.

Figure 12 emphasizes that a necessary first step in the ecosystem services assessment is to become familiar with the community or study area. Familiarity should involve directed seeing through extensive site visits, passive observation, and photodocumentation (LeCompte et al., 1999; Büscher, 2006), as was done in this study. Familiarity also should include meaningful community participatory planning and consultation, particularly for established areas that are undertaking re-development to ensure a diversity of visions are considered (Cox et al., 2010; Lenzholzer et al., 2013; Cilliers & Timmermans, 2014; Heyes & Saniga, 2014; Swapan, 2016; Makhzoumi & Al-Sabbagh, 2018; Raaphorst et al., 2019; Irvine et al., 2022b). In both re-development and new development a design thinking approach should be undertaken that holistically and creatively considers market and site potentials and constraints (Tan, 2012; Murphy, 2016; Nijhuis & de Vries, 2019). For simplicity in Figure 12, we note that design thinking is represented by individual boxes and a linear process. In fact, design thinking would be more accurately represented as a non-linear, interactive process, as captured in the double diamond framework (Tantiyaswasdikul, 2019; Spruce, 2021), but a simplified visualization approach is adapted in Figure 12 to introduce the methodology.

Results of the ecosystem services assessment showed that the Agrihood design provided a positive alternative compared to a recent, relatively green suburban design, but also indicated where the design could be enhanced (e.g. Cooling Capacity Index). As captured by Figures 10 and 12, the assessment framework developed to characterize ecosystem services in this study is a good first step towards establishing standard valuation practices.

Community gardening in urban environments has long been conducted throughout the world and the associated ecosystem services potentially are diverse. In addition to the food provisioning and food security, enhanced biodiversity, carbon sequestration, and urban heat island mitigation noted here, cultural services can include community wellbeing through place-based connection, enhanced physical and mental health through activity and feelings of joy and fulfilment, and environmental education/literacy (WinklerPrins, 2002; Corrigan, 2011; Lovell et al., 2014; Thornbush, 2015; Clucas et al., 2018; Porter, 2018; Sonti & Svendsen, 2018; Caneva et al., 2020; Zasada et al., 2020; McGuire et al., 2022). These cultural services were not explicitly captured in this study, but should be given consideration as a future refinement of the valuation framework. Ebissa and Desta (2022) noted that in addition to flood management benefits, urban agriculture can help transition a community from a linear to a circular water economy by including greywater reuse for irrigation purposes. Greywater reuse was included as part of the Agrihood vision (Figure 13) and initial estimates of the water yield for a cluster of 32 households was 4,800-8,000 liters/day. While greywater reuse was not quantified as an ecosystem service indicator in this study, it should be considered in future work.

Figure 13 Visioning of greywater reuse for urban agriculture irrigation.

As noted in the Introduction, Agrihood designs, as practiced in North America, exhibit considerable variability, lacking a standardized typology. The total area of the Agrihood design presented in this study (34.9 ha) is smaller than many projects reported in the literature for North America, while the relative distribution of residential space (50%) in this study is within the range reported in the literature (10-70%). The dedicated agricultural space in the Agrihood design of this study (~50%) is greater than that reported in the literature for North America (2-33%), although we also note that North American studies often distinguish between open space and agricultural space, which was not done here. Probably the greatest difference in the Agrihood design reported herein and those reported for North America relates to plot management. All plots for the Agrihood design in this study would be community plots maintained by the residents, for their benefit, whereas the North

American approach tends towards larger, professionally-operated farms. These potential differences in design approach should be explored further.

PCSWMM is an excellent decision support tool for assessing water quantity and quality elements of NbS in the ecosystem services framework. PCSWMM is spatially scalable and therefore could be applied in a larger watershed context, much like InVEST, but importantly, it also can explicitly represent hydrologic/hydraulic processes at a smaller design scale from the neighbourhood level to individual NbS features. We believe that while design standards must be developed and applied to individual NbS features (e.g. raingardens, bioswales, cleansing biotopes, constructed wetlands), final neighborhood designs should represent an hydrologically inter-connected system. PCSWMM is capable of holistically quantifying the performance of such inter-connected system designs. Machine learning methods also have been considered as a viable approach to characterize urban runoff, but Mosavi et al. (2018) noted that such applications "...can numerically formulate the flood nonlinearity, solely based on historical data without requiring knowledge about the underlying physical processes". It is our opinion that this indeed is a considerable limitation compared to the PCSWMM approach, as without an understanding of underlying physical processes it will not be possible to properly evaluate the magnitude of change associated with different design scenarios.

This issue of scale and connectivity also needs to be considered in the context of cumulative effects, thereby addressing the larger question of whether ecosystem services of altered landscapes, even if they are managed through an NbS design, are sufficient to respond to a larger context of changing landscape/ecosystem. Raymond et al. (2017b) concluded that the spatial and temporal dimensions of NbS impacts remained poorly considered and were an important direction for future research, while Sowińska-Świerkosz and Garcia (2021) noted that it is necessary to consider NbS-oriented solutions in a local, regional or national context to select an appropriate intervention that matches the scale of the problem. In their review of modeling approaches for NbS Kumar et al. (2021) felt that the SWMM model can be an effective tool in evaluating the performance and efficacy of a range of NbS designs for flood mitigation, much as was done in our current study. As noted previously, the advantage of PCSWMM is that it is capable of scaling up or scaling down to consider the geographic dimensions discussed by Raymond et al. (2017b) and Sowińska-Świerkosz and Garcia (2022). Irvine et al. (2022b) emphasized the importance of connectivity in their development of Smart City designs for a peri-urban area of Pathum Thani, Thailand; connectivity of water movement, habitats for biodiversity, and community flow lines for smart mobility. Cumulative environmental effects have been considered since the late 1980's as an element of Environmental Impact Assessments (EIAs)(e.g. Cooper & Sheate, 2002). Seitz et al. (2011) observed that development within a watershed can produce both additive and synergistic hydrologic impacts over space and time whereby these cumulative effects might be characterized as relatively minor for an individual project, but may be significant when considered collectively over time and space. In other words, a system-wide assessment should be taken in addressing such cumulative effects (and including the potential cumulative benefits of NbS design). Unfortunately, cumulative effect evaluation has proven to be elusive in many EIA efforts. A modeling approach may be necessary to address cumulative, systematic, impacts. Hoghooghi et al. (2018) recently used such an approach to assess impacts of a combination of WSUD features (raingardens, pervious pavement, riparian buffer zones) in a small (0.94 km^2), mixed land use watershed, and concluded that while there were some positive hydrological changes with respect to runoff, infiltration, shallow groundwater flow, and evapotranspiration, these improvements were relatively limited. Teang et al. (2021) applied PCSWMM to the entire drainage system of a mixed land use industrial estate of Pathum Thani and for a 2 year (72 mm for 24 hours) design storm, showed a combination of raingardens and grassed swales could decrease surface runoff volume for the entire study area by up to 12.7 % (with a range from 6-78% for individual subcatchments) and reduce surface flooding volume by up to 3.6 % for the entire study area. It is important to conduct further research into these aspects of scale, connectivity, and cumulative effects related to NbS design.

5. Conclusion and the Way Forward

An urban ecosystem services valuation framework was established and tested using three case studies in peri-urban Pathum Thani, Thailand: a new, single detached housing development; a site that currently is open scrubland; and the same site, but developed under the Agrihood design vision. These sites represent a smaller spatial scale in more detail than has previously been done using the Nature Capital Project (InVEST), for example. The valuation approach included a combination of mathematical modeling for the water, sediment, and nutrient yield ecosystem services and an empirical, data-driven approach for urban cooling, carbon sequestering, crop production, habitat quality, and aesthetics. Valuation outputs were provided in raw data units, but to facilitate a comparison of the suite of ecosystem services for the different designs, the individual indicator results also were standardized to a scale of 0-5.

This work represents a good preliminary step in establishing a local scale ecosystem services valuation framework for urban areas in a tropical climate. However, some important future steps need to be considered. First, the valuation has been expressed in non-monetary terms. Assessing the ecosystem services in terms of economic value should be conducted to facilitate a deeper understanding of the values, particularly for private sector developers, general community stakeholders, and government agency decision makers. Second, the methodology to value the aesthetic ecosystem services provided by the sites or designs needs to be more fully explored and standardized. Third, the framework needs to be tested on a greater range of existing developments and future plans for both urban and peri-urban Bangkok (and beyond). Fourth, while the modeling with PCSWMM provided valuable insights to system performance, the available data for model calibration was limited. In particular, the methodology used to represent water quality treatment by the constructed wetlands was simplistic and it would be better to model the processes based on hydraulic residence time and first-order kinetics. Finally, the linked issues of scale, connectivity, and cumulative effects based on a systemic analysis of NbS features relative to the larger landscape changes should be resolved in greater detail using a combination of empirical evidence and modeling. This will require a scaling up of monitoring from the individual NbS feature level to a larger watershed level to resolve systematic response to the new designs.

Author Contributions

Conceptualization, F.L., A.S., A. Suwanarit, K.N.I., T.L.; methodology, F.L., A.S., A. Suwanarit, K.N.I., T.L., D.C.; software, K.N.I., D.C.; T.L.; formal analysis, F.L., A.S., A. Suwanarit, K.N.I., T.L., D.C.; writing-original draft preparation, K.N.I.; writing-review and editing, F.L., A.S., A. Suwanarit, K.N.I., T.L., D.C.; visualizaition, F.L., A.S., K.N.I., T.L.; Agrihood design through the Sustainable Landscape Studio 4 (LN 316), Thammasat University, T.L. All authors have read and agreed to the published version of the manuscript.

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