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Achieving Urban Stormwater Mitigation Goals on Different Land Parcels with a Capacity Trading Approach

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Abstract: Building Green Infrastructures (GIs) to reduce stormwater runoff has been recognized as an effective approach to mitigate the negative impact of urban sprawl. Due to the significant differences in urban land use, some Land Parcels (LPs) may have difficulty in building enough GIs to meet stormwater mitigation goals. In this paper, we proposed a Capacity Trading (CT) approach that allows some LPs to trade their extra runoff retention capacities with LPs that have building difficulties, so that they can jointly reach the overall mitigation goal together. The rationale behind CT is that, to avoid potential penalties, it may be more economical for some LPs to 'buy' credit rather than to 'build' GIs. A case study was used to demonstrate CT operations for two trading scales: (1) CT within neighboring LPs (i.e., CT-1), and (2) CT within 20 m-radius LPs (i.e., CT-2). A GI implementation baseline intensity was set up firstly by treating the whole study area as one entity to reach a specified stormwater runoff control target; individual LPs were then examined for their GI building capacities, which may be deficit or surplus against the target. Results showed that the number and area of deficit LPs were reduced significantly through either CT scales; the number of deficit LPs was reduced from 139 to 97 with CT-1 and 78 with CT-2, and the deficit area was reduced from 649 ha to 558 with CT-1 and 478 ha with CT-2, respectively. The proposed method assumes LPs as the basic planning unit and encourages some stakeholders to maximize their GI building potential to compensate for those with disadvantages. The economic incentives for conducting CT among different LPs in urban area can help achieve stormwater mitigation goals more economically and flexibly. Some coordination among LPs in GI implementation is necessary, which presents both opportunities and challenges for city management.

Keywords: green infrastructure; land parcels; capacity trading; trading scales

1. Introduction

To mitigate the negative impact of urbanization on regional hydrology and environment, different initiatives or plans have been made worldwide, such as Low Impact Development (LID) or Best Management Practices (BMP) in the US [1], Sponge City construction plan in China [2–4], and Sustainable Urban Drainage System (SUDS) and Green Infrastructure in UK [5,6]. These plans all include building 'Green Infrastructures', or GIs [7,8] to decentralize stormwater management. GIs built for retaining and infiltrating stormwater runoff have been found very effective in runoff reduction and pollutants removal across various spatial scales [9–13].

Existing studies mostly focused on physical performance of GIs, i.e., stormwater retention or pollutant removal efficiencies. The issue of financial responsibility in construction and operation of

GI facilities has not been investigated thoroughly; though a few studies mentioned that financial concerns can be a major barrier for GI implementation [5,11,14–18]. In order to reach full-scale GI implementation, we need to locate the responsible parties by examining the general pattern of urban development process. A city usually expands with addition of different Land Parcels (LPs), including industrial parks, transportation areas, cultural and educational facilities, business and residential areas. Owners or operators of different LPs need to understand that while they benefit from the land development, the change in land use will cause negative impacts on urban hydrology. They should take the mitigation responsibility and pay the additional cost for disposing the increased stormwater runoff, such as stormwater taxes [19,20]. Alternatively, they can install mitigation GIs to earn credits to avoid such cost or penalty [18,19]. Thus there is a great advantage to hold the LP owners as responsible for GI implementation [5,11,15,17]. However, city LPs vary considerably in land use, constructing GIs to reach the same storm runoff mitigation goal would result in different levels of difficulty in different LPs. Theoretically, it is possible to design GIs to make all LPs to meet the mitigation requirement [3,21–23], but this may not be economically feasible. The sponge city construction guideline of China set lower standards for some LPs with GI construction difficulty [4]; such compromises, however, will have a negative effect on the overall compliance of building mitigation GIs. To avoid this shortcoming, we may look beyond an individual LP's boundary, and look for suitable sites in neighboring LPs, in which GI construction may be easy so that extra stormwater retention capacity can be generated for credit trading [18]. This capacity trading (CT) approach may create links among LPs so that overall storm runoff mitigation goals can be achieved through uneven construction of GIs.

Few studies have been conducted to explore planning and management of urban stormwater based on LPs, but the idea has been raised for some years. For example, Thurston (2006) [17] and Thurston et al. (2003) [18] cited the work by Pigou (1962) [24] and argued that the optimal solution for combating pollution is to directly tax the parties that are responsible for. This has been materialized in several cases [19,20]. Meanwhile, the advances in monitoring technologies have made it possible to locate the responsible parties accurately [25], and the modern technologies in managing spatial and temporal information can plan GIs on different or newly developed LPs at reasonable cost and speed [5]. Unfortunately, few studies have been conducted on the effect of LPs, we postulate the following two reasons for the gap:

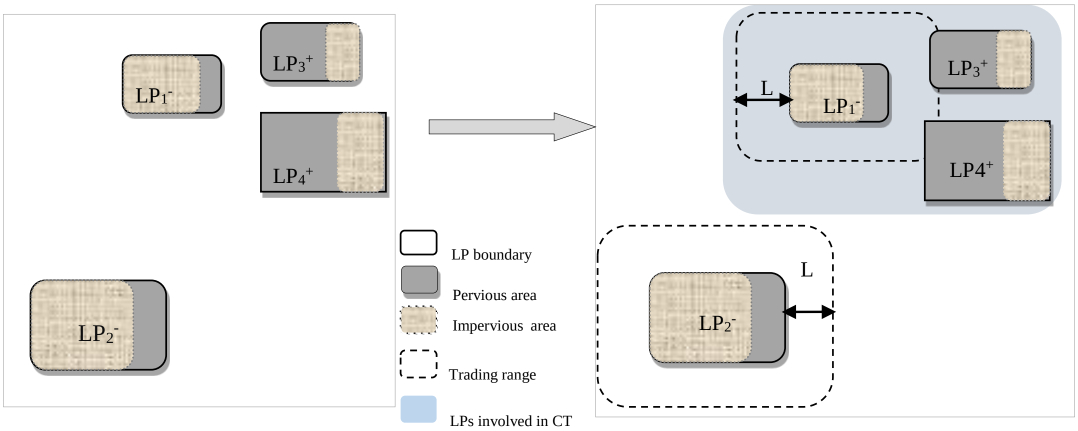
1. Existing GI projects are mainly supported by public funds on public domains, or on private properties with some government subsidies; many of these projects are research oriented, or for demonstration purposes. This to a great extent has made the economic concerns less pressing than it should be;
2. Many studies that were conducted at watershed scale or over large areas used mathematical models to evaluate hydrological and environmental impact of GIs; these modeling studies generally dealt with physical delineation lines, such as rivers, roads, and watershed boundaries, economical responsibilities were seldom considered [3,26].

Previous studies have investigated the economic advantages of building GIs over the conventional stormwater facilities [17,18], or the flexibility in implementation schemes [10]. While they have encouraged more GIs implementations, the economic responsibility of GIs has not been clearly addressed. Considering the high upfront cost of GI implementation and the long-term maintenance requirement, economic analyses and optimization should be studied considering the constraints imposed by urban LP distributions [5]. In this paper, we proposed a GI building capacity trading (CT) approach to optimize the construction cost in an urban development area; as a preliminary investigation on the feasibility and potential of CT, we demonstrated the procedures and effectiveness of CT under different trading conditions with a case study in the ancient city of Yangzhou, China.

2. Materials and Methods

2.1. Procedure for GI Capacity Trading (CT) and Significance of Trading Scales

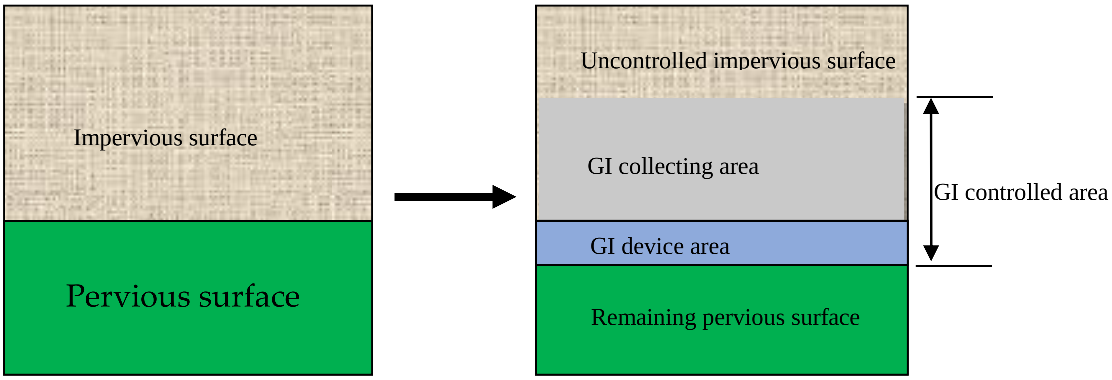
The proposed CT method is based on a premise that it is more economical for some LPs to 'buy' credit for building GI for storm runoff retention rather than to 'build' their own; CT bridges the gap in GI implementation among different LPs of a city area. Figure 1 illustrates the basic concept of CT, in which the '+' sign denotes LPs with extra GI capacity (i.e., surplus LPs), and '−' sign denotes LPs without enough GI capacity (i.e., deficit LPs). To carry out CT, deficit LPs will seek surplus LPs for trading. Apparently, whether a deficit LP can find appropriate trading parties depends on the trading scale. For example, when the trading scale was limited to 'L' (Figure 1), one deficit LP (LP1) was met with two trading parties (LP3 and LP4), while the other one (LP2) was left out. Apparently, a larger trading scale will yield better results, i.e., more deficit LPs can be met with surplus LPs. This, however, is limited by the nature of GIs. Unlike some tradable commodities or services, stormwaters possess great quantity (or mass) as they concentrate to downstream in confined waterways, it is difficult to transfer this water from one location to another, and the water problem needs to be dealt with locally [17,18]. This is why LIDs or GIs are proposed for 'decentralized' or 'source control' of storm runoff [5,7,16,27].



(**a**) Surplus and deficit LPs for baseline (**b**) CT for a spatial distance 'L'

Figure 1. A schematic diagram for capacity trading (CT), the superscript '+' is for Land Parcels (LPs) with surplus capacity, and '−' for LPs with deficit capacity, 'L' indicates the spatial trading scale. (**a**) Surplus and deficit LPs for baseline; (**b**) CT for a spatial distance 'L'.

Current studies that involved either hydrological or economic optimization mostly adopted an overall trading scheme; GIs settings did not consider constraints or requirements of individual LPs [2,27,28]. The proposed CT method is intended to compensate this potential pitfall. For the CT approach, to facilitate CT among different LPs, the potential surplus and deficit LPs were identified first referring to a baseline condition. The baseline condition was set based on a threshold intensity for GI implementation to meet the regional stormwater control target without considering any building constraints; it is an optimal or lowest regional GI implementation requirement that can be determined through the following two steps as illustrated in Figure 2:



(a) Before GI

(b) After GI implementation

Figure 2. A schematic diagram for LP/regional surface cover changes before (**a**) and after Green Infrastructure (GI) implementation (**b**).

2.1.1. Step 1: Determining Runoff Coefficient (*RC*) before and after GI Implementation

Figure 2 shows surface cover change before and after GI implementation in a LP or specific region. Before GI implementation, the surface cover of the region can be generally classified as pervious and impervious. The pervious surfaces normally include grass and trees covered land area; the impervious surfaces include building roofs, roads, and plazas, etc. Supposing Runoff Coefficient (*RC*) can be used to represent storm runoff generation conditions, we use capital Italian letters (*RC*) to denote runoff coefficient of the region, the lower-case letters (*rc*) to denote runoff coefficient of individual LPs, and a single letter (ψ) to denote runoff coefficient of a specific land use type. Before GI implementation (Figure 2a), the initial *RC* of the *i*th LP ($rc_{0,i}$) can be calculated as

$$rc_{0,i} = \psi_{per}\alpha_{per,i} + \psi_{imp}(1 - \alpha_{per,i}) \quad (1)$$

where $\alpha_{per,i}$ is the pervious surface area proportion, ψ_{imp} and ψ_{per} are runoff coefficients of the impervious and the pervious surfaces, respectively.

After GI implementation (Figure 2b), assume that a portion of pervious surfaces were used to build GIs to collect runoff from surrounding impervious surfaces. The *RC* of the LP after GI implementation becomes

$$rc_i{}' = \psi_{GI}a_{GI,i} + \psi_{per}a'_{per,i} + \psi_{imp}a'_{imp,i} \quad (2)$$

where ψ_{GI}, α_{GI} are the *RC* and areal proportion of GI controlled area, which includes GI device area itself and runoff contributing area,

$$a_{\mathrm{GI},i} = \zeta\alpha_{per,i} + \zeta s(1 - \alpha_{per,i}) \quad (3)$$

where ζ is GI implementation intensity expressed as the ratio of GI area ($A_{\mathrm{GI},i}$) over the initial pervious area ($A_{per,i}$):

$$\zeta = A_{\mathrm{GI},i}/A_{per,i} \quad (4)$$

The remaining pervious area proportion ($\alpha'_{per,i}$) becomes

$$a'_{per,i} = (1 - \zeta)\alpha_{per,i} \quad (5)$$

The uncontrolled impervious surface proportion ($\alpha'_{imp,i}$) becomes

$$a'_{imp,i} = 1 - \alpha_{per,i} - s\zeta\alpha_{per,i} \quad (6)$$

where *s* is the GI collection areal ratio.

2.1.2. Step 2: Determining the Baseline Condition and the Trading Capacity

The baseline condition treats the whole region as one entity, the overall runoff coefficient (RC') can be calculated from the three areas shown in Figure 2 by pooled values from all LPs:

$$RC' = \psi_{\text{GI}}\overline{a_{\text{GI}}} + \psi_{per}\overline{a'_{per}} + \psi_{imp}\overline{a'_{imp}} \quad (7)$$

When a uniform GI implementation intensity is applied for all LPs, the pooled areal proportions can be calculated as area-weighted values:

$$\overline{\alpha'_{imp}} = \sum_i \alpha'_{imp,i}A_i / \sum A_i,\ \overline{\alpha'_{per}} = \sum_i \alpha'_{per,i}A_i / \sum A_i,\ \overline{\alpha'_{\text{GI}}} = 1 - \overline{\alpha'_{per}} - \overline{\alpha'_{\text{imp}}} \quad (8)$$

The baseline intensity (ζ_{bl}) can be derived from Equation (7) by setting the RC' value to the target value, i.e., $RC' = RC_{targ}$.

Once the baseline intensity (rc_{bl}) is determined, we can compute RCs of individual LPs with Equation (2). The individual LPs may have different areal proportions from the average values, the LPs with higher impervious ratio will have higher RC than the target value, so they possess deficit capacities. Conversely, LPs with lower than average impervious ratios will have lower RC than the target value, and they generate surplus capacities. The magnitude of surplus or deficit capacity of the ith LP can be calculated as

$$\begin{gathered} W_i^- = (rc_{bl,i} - RC_{targ})A_i \\ \text{or} \\ W_i^+ = (RC_{targ} - rc_{bl,i})A_i \end{gathered} \quad (9)$$

where W^+ and W^- are the deficit or surplus capacity (expressed in area, ha) of ith LP, respectively.

As illustrated in Figure 1, the trading capacity available to a deficit LP can be calculated as the sum of surplus capacities within the trading range:

$$W = \sum_{i=1}^{N} W_i \quad (10)$$

where N is the number of surplus LPs within the trading range.

2.2. Study Area and Proposed CT Scenarios

Yangzhou is an ancient city in southeastern China (Figure 3); it is located at the lower reach of the Yangtze River (119°1′~119°54′ E, 32°15′~33°25′ N); it has mean annual temperature of 14.8 °C and mean annual rainfalls of 1063.2 mm. Yangzhou has been rapidly expanding in recent years; the urbanization rate has exceeded 66%. Following the national Sponge City construction guidelines of China for urban stormwater management, Yangzhou has outlined its goals reaching 80% mitigation in stormwater runoff by means of various GI constructions by year 2020. Based on this plan, this paper selected a study area in the downtown region as delineated by major city roads in Figure 3. The study area covers 1722.7 ha that is divided into 355 LPs; these LPs can be categorized into six types according to their major functions. Table 1 lists the number, area, impervious surface proportion, and runoff coefficients for different LP types. The six LP types include education organizations (colleges and schools), commercial plaza, residential areas, and industrial areas (large and small). Residential areas include 152 LPs that cover a total area of 815.9 ha; industrial areas are the second largest that include 81 LPs over 422.7 ha; it is followed by commercial plazas that include 100 LPs over 312.6 ha; and education organizations include 22 LPs over 171.5 ha. We sampled several LPs for each type and delineated their land use to compute typical RCs. Using the typical RC values recommended by the MORC (2014) [4], we computed RCs for six LP types as listed in Table 2. Commercial LPs had the highest RC (0.82), and education LPs had the lowest (0.54). The overall RC for the study area was 0.67.

The baseline condition can be viewed as the overall CT condition; we examined the effect of CT on number and area of deficit LPs for scenarios of (1) No CT, (2) CT with various scales, and (3) Overall CT.

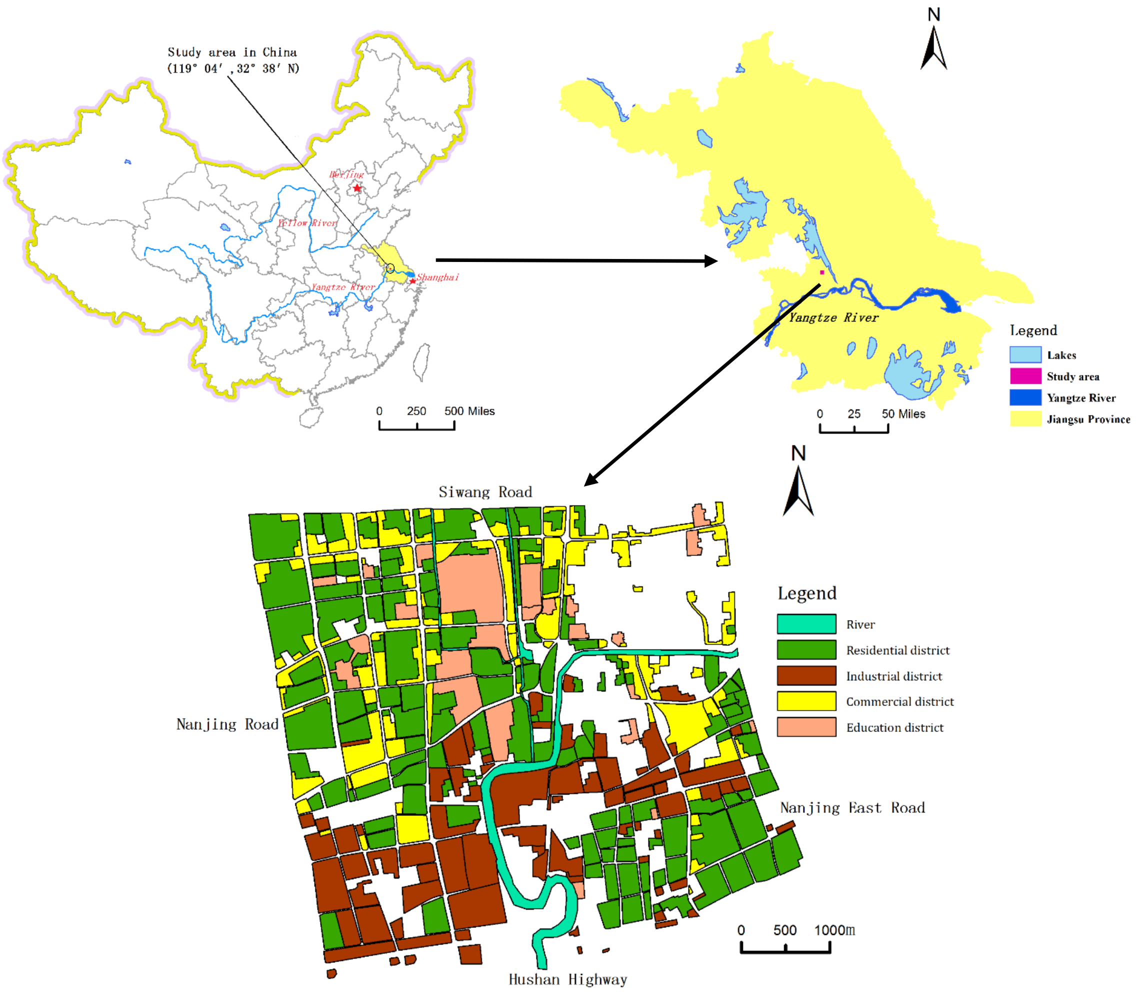


Figure 3. The location of study area and its LP distribution.

Table 1. Numbers, area and typical Runoff Coefficients (*RC*s) of different LP types in the study area.

LP types	Education Organizations		Commercial Plazas	Residential Area	Industrial Areas		Total
	Colleges	Schools			Large	Small	
No. of LPs	4	18	100	152	21	60	355
Area (ha)	107.0	64.5	312.6	815.9	272.1	150.6	1722.7
α_{imp} (/%)	24–42	24–52	75–86	54–61	71–80	66–76	49~68

3. Results

Under the baseline condition of GI implementation, the *RC* of the study area was proposed to be reduced to the predevelopment level (0.5). The suggested *RC* values for runoff retention facilities (ψ_{GI}) that possess catchment area ratio (s) of 10:1 was 0.2 (Ministry of Resident and Contruction (MORC), 2014). For the baseline condition of converting 10% pervious surface into flow retention GI space, the *RC*s for different LP types were computed as listed in Table 2. Comparing with the target value (0.5), deficit LP types include commercial plazas (*RC* = 0.70), large industrial areas (*RC* = 0.58), and lower education schools (*RC* = 0.59); surplus LP types include residential area (*RC* = 0.36), higher education organizations (*RC* = 0.22), and small industrial areas (*RC* = 0.48).

Table 2. Calculated RCs for different LP types under present and the baseline conditions of GI implementation in the study area [a].

LP types	Education Organizations		Commercial Plazas	Residential Area	Industrial Areas		Total
	Colleges	Schools			Large	Small	
Present (*RC*)	0.54	0.76	0.82	0.60	0.75	0.69	0.67
Baseline CT (*RC′*)	0.22 [b]	0.59 [c]	0.70 [c]	0.36 [b]	0.58 [c]	0.48 [b]	0.50 [d]

[a]. The target *RC* is 0.5.; [b]. Deficit LP; [c]. Surplus LP; [d]. The target.

As a preliminary experiment, we examined two CT scales: (1) neighboring trading, and (2) 20 m range trading scale, which is about the width of a medium size road. Following the procedures described in Section 2.1, the number and area of deficit LPs were identified for the two trading scales and the results are listed in Table 3. For better comparison, the overall CT was included as the fourth scenarios in Table 3, and the four scenarios under consideration are as follows:

1. No capacity trading (No-CT),
2. Trading with neighboring LPs (Neighboring CT),
3. Trading with surplus LPs within 20 m range (20 m radius CT), and
4. Baseline condition, which is equivalent to overall trading (Overall CT).

Table 3. The change of the number and area of deficit LPs for different trading scenarios.

Changes of the Deficit LPs	No. of LPs with Deficit	Area of LPs with Deficit (ha)	Left Deficit Area (ha)
No-CT	139	649.2	−90.1
Neighboring CT	97	558.4	−75.5
20 m radius CT	78	478.2	−59.9
Overall CT †	0	0	0

† The baseline condition has no deficit.

Without CT, there were 139 LPs with deficit that covered 649 ha, which accounted for 39% and 38% of the total number and area of LPs in total (355 LPs over area of 1723 ha). With Neighboring CT, the number and area of deficit LPs were reduced to 97 and 558.4 ha, or about 30% reduction in number and 14% reduction in area comparing with the No-CT condition. When the trading scale extended to 20 m, the number of deficit LPs was further reduced to 78, and the deficit area was reduced to 478 ha; these is 40% reduction in number and 26% reduction in area of the deficit LPs.

Table 4 lists composition of the deficit and surplus LPs. For the No-CT condition, 100 deficit LPs (72%) are commercial area, 21 (15%) are industrial, and the rest 18 (13%) are lower education organizations. These ratios changed little under the neighboring trading scenario. Under the 20 m range trading scenario, the percentage of deficit commercial area lowered to 62%, while the percentage of industrial LPs increased from 15% to 23%.

Table 4. Compositions of deficit LPs under different trading conditions.

LP Types	Commercial Area	Industrial Area	Education Area	Total
No-CT	100	21	18	139
Neighboring CT	66	18	13	97
20 m radius CT	48	18	12	78
Overall CT †	0	0	0	0

† The baseline condition has no deficit.

4. Discussion

4.1. The Impact of Trading Scales on CT Effectiveness

The effectiveness of CT depends highly on the trading scale. Thurston et al. (2003) [18] proposed a similar idea of tradable capacity, but they did not set the trading scale limits. The trading scale is critical to retain the virtue of GIs and keep the practice manageable. The compositions of deficit LPs (Table 3) indicate that CT leads to varying CT results in different types of LP; elimination of the deficits depends on whether enough surplus capacities are available within the trading range. Table 4 lists the number of LPs that are available for neighboring CT, and the total number of LPs involved was 86, accounting for 62% of the total deficit LPs, and 49% of these LPs can be eliminated (42) after trading. When the trading scale was extended to 20 m wide, the number of involved deficit LPs increased to 117, or about 84% of the total deficit LPs; 52% of these LPs can be eliminated after trading. Therefore, the number of LPs involved and eliminated was significantly increased by slightly enlarging the trading scale.

In addition to the number of deficit or surplus LPs involved, the effectiveness of CT is highly dependent on the LP distributions, i.e., the mixing pattern of land parcels that have deficit or surplus capacities. Table 5 lists the number of LPs involved in different land use types. It is obvious that commercial LPs may benefit most from the CT and the benefit increased with trading scales. Table 6 lists the number of different types' LPs involved and eliminated for different trading scenarios. Within the 100 commercial LPs, 68 could be traded in the neighboring range, and the number increased to 94 in the 20 m trading scale. The high (94%) trading proportion of the commercial LPs was due to their interleaving distributions with the surplus LPs. The latter is mainly occupied by residential areas as shown in Figure 4. The distribution pattern between commercial areas and residential areas offers a good opportunity for CT in GI construction in the study area. But for some large commercial centers in isolated locations, it is difficult to find enough surplus LPs for CT. Thus, large shopping centers may face very challenging task in stormwater mitigation. The numbers of deficit LPs in industrial and educational areas were reduced immediately after neighboring trading, but further expansion to 20 m trading range obtained little improvement in reducing the deficit number.

Figure 4 shows the distribution of deficit and surplus LPs under different trading scenarios. The deficit LPs eliminated through neighboring trading (Figure 4b) were mostly small commercial areas concentrated at the upper-left part of the study area; and 20 m CT further eliminated some deficit areas, including some big commercial areas (Figure 4c). The remaining deficit LPs (red circles in Figure 4c) contain mainly two LP types: old residential areas and concentrated industrial areas. The remaining deficit LPs shows some clustering pattern, which is somehow associated with concentrations of some land use types. For the identified deficit LP types, the modern residential LPs and education LPs are evenly distributed, but the industrial and commercial LPs are more or less concentrated; the industrial ones are getting more limited to industrial zones, while the commercial zones are mostly distributed in busy commercial districts.

Table 5. The number of LPs involved for different trading scenarios.

Trading Range	Involved	Eliminated
Neighboring	86	42
20 m radius	117	61

Table 6. The number of different types' LPs involved and eliminated for different trading scenarios.

LP types	Commercial	Industrial	Education
Neighboring CT	68 [a]/100 [b]	10/21	8/18
20 m radius CT	94/100	13/21	10/18

[a] The number of LPs involved. [b] Total LP number.

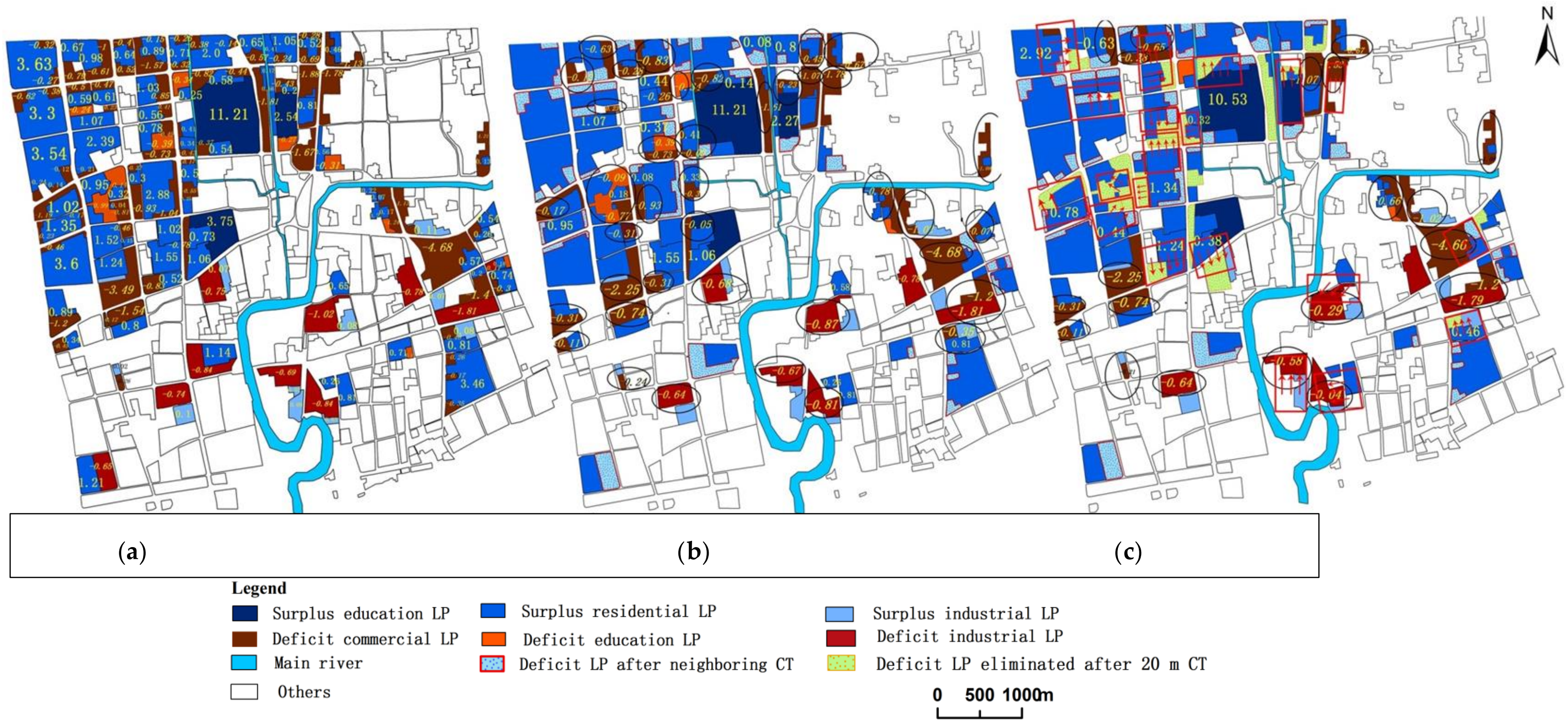


Figure 4. The distribution of deficit and surplus LPs for various scenarios: (**a**) No-CT, (**b**) Neighboring CT, and (**c**) 20 m CT. The black circles in (**b**) and (**c**) indicate the deficit LPs left after CT, and the red boxes and arrows indicate the path that deficit LPs eliminated by 20 m CT.

Above analyses clearly show that CT, even at very small scales, can connect many different LPs and achieve significant improvement in GI construction to reach stormwater mitigation goals in the study area. While larger trading scales may produce better results, the magnitude is highly dependent on the distribution of deficit and surplus LPs. Urban landscapes often present greater variations within a small spatial scale; as the scale increases to a critical value, LP compositions may reach a stable proportion. Several studies that investigated cities in China presented variable values of the critical range, varying from 500 m [29] to 7000 m [30].

4.2. *Economic Incentives for Capacity Trading and Limitations of the Current Study*

Although we have limited our discussions to minimum on the economics of GI implementations, it is inevitable that the economic incentive for conducting CT should be discussed. Either taxation on increased stormwater runoff or earned credit from GI installation [19,20] may provide economic incentive for the proposed CT approach. The underlying economics may be displayed with unit GI cost (C) calculated with the following equation:

$$C = C_0 \xi^r \tag{11}$$

where C_0 is a reference unit cost of GIs, and r is the exponential factor describing the effect of implementation intensity (ζ) on C.

In order to generate economic incentive, the value of the exponential factor (r) in Equation (11) should be greater than 0; when $r = 0$, it indicates no incentive. Thurston (2006) [17] presented an economic model that is similar to Equation (11), but the variable in his model was the total stormwater retention. Because finding suitable sites for new GIs will become increasingly difficult and costly when the GI implementation intensity increases, using a parameter (r) that indicates the GI implementation intensity as in Equation (11) is more appropriate. In order to focus on the CT approach, one important factor that is not mentioned in this research is the runoff concentration regime, which is often limited by topographic condition of adjacent land parcels. We carefully avoided this issue by restricting the CT to a limited scale. This, however, may present a big problem when there is great variation in stormwater runoff over large scale. CT may not be conducted solely based on spatial relationships of LPs as discussed in this study, the effect of flow collection along sewer pipelines may have to be included to determine proper trading zones or scales.

5. Conclusions

Current GI constructions are mostly implemented by academies, public agencies, or private sectors with public cooperation; this situation has somehow hidden or shadowed the financial responsibility of construction. Thus, explicitly linking responsible parties from different LPs in urban development can be functional for large-scale implementation of GIs. Considering different land use in variable LPs in the urban landscape, reaching a stormwater control target across-the-boundary will encounter some difficulties or resistance in some LPs. Not to compromise the overall goal, the proposed CT approach may be used to coordinate the efforts across different property lines. Considering the special features of stormwater management, CT may be spatially restricted to adhere to the onsite treatment principle normally associated with GIs. The CT mechanism is to ensure that LPs creating retention capacity surplus will be rewarded, and LPs with building difficulties can meet the target in a more cost effective way. Otherwise, there will be no incentives for some LPs to produce extra stormwater retention capacities. To some extent, introduction of CT overcomes the shortcoming and yet preserves the advantage of using LP as the basic counting units.

In this paper, we only discussed the CT approach associated with the physical or land use differences, there may exist other factors that interfere with the trading processes, such as urban pipe network layout, surface elevation difference, construction cost, and so on. Findings from this study may serve as a bottom-line for further investigation on how to coordinates the multilateral efforts.

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