

A dynamic modeling of cap-and-trade mechanism to accelerate the application of Lid in stormwater systems.

Modélisation dynamique du mécanisme de plafonnement et d'échange visant à accélérer l'application du système Lid dans les réseaux d'évacuation des eaux pluviales.

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RÉSUMÉ

Dans les villes brésiliennes, la gestion des eaux pluviales urbaines est considérée comme le service lié à l'eau le moins réglementé et le moins financé par rapport à l'approvisionnement en eau et à la collecte et au traitement des eaux usées. L'absence de réglementation et de mécanisme de financement appropriés se traduit par des services de drainage médiocres, ce qui a un impact sur la qualité de l'eau et entraîne souvent des inondations, avec des conséquences négatives pour la société et l'environnement. Une alternative pour remédier à ces problèmes consiste à mettre en œuvre un développement à faible impact (LID). Toutefois, ces approches souffrent d'une efficacité incertaine, de coûts de mise en œuvre et d'exploitation élevés, d'un faible niveau d'implication de la communauté dans les décisions relatives aux projets, de normes techniques médiocres et d'incitations économiques insuffisantes. Dans ce travail, nous nous sommes attachés à comprendre comment la typologie urbaine influence le choix des systèmes de gestion des eaux pluviales intégrés au LID. Pour ce faire, nous explorons comment les outils économiques peuvent contribuer à la mise en œuvre de systèmes LID efficaces qui favorisent le bien-être et partagent les avantages sociaux et environnementaux entre les ménages et les communautés. Plus précisément, nous évaluons un système d'échange de licences environnementales. La diversité des caractéristiques locales des zones urbaines et des municipalités nécessite des solutions qui combinent les aspects environnementaux, sociaux et économiques. Nous soutenons que la mise en œuvre réussie du LID pour la gestion des eaux pluviales nécessite encore une législation solide et des outils économiques.

ABSTRACT

In Brazilian cities, urban stormwater management is considered the least regulated and funded water service in comparison to water supply and wastewater collection and treatment. The lack of proper regulation and funding mechanism results in poor drainage services, which impacts water quality and often results in flooding, with negative impacts to society and the environment. One alternative to address these issues is the implementation of low-impact development (LID). Such approaches, however, suffer from uncertain effectiveness, high implementation and operational costs, low level community involvement in project decisions, poor technical standards and economic incentives. In this work, we focused on understanding how urban typology influences the selection of stormwater systems integrated to LID. To do so, we explore how economic tools may contribute to the implementation of effective LID systems that favor the well-being and share social and environmental benefits among households and communities. In specific, we evaluate a trading of environmental licenses. The variety of local characteristics of urban areas and municipalities requires solutions that combine environmental, socio and economic aspects. We argue that successful implementation of LID for stormwater management still requires robust legislation and economic tools.

KEYWORDS

Cap-and-trade, stormwater management, financing, economic regulation

1 INTRODUCTION

This study develops a dynamic model to simulate a cap-and-trade system for stormwater management. From a hydrological perspective, a trading market establishes a feasible limit on the flow allowed within a watershed while simultaneously accommodating current and future development within its boundaries. This work was inspired by Wilkerson et al. (2022), who examined the effectiveness of subsidies in promoting the implementation of LID in Oslo, Norway. However, this approach developed differs substantially in both scope and structure. This study adopts a dynamic modeling framework based on a cap-and-trade mechanism. This research contributes to the literature that investigates how economic instruments can accelerate the adoption of LIDs and seeks to understand how this process can be effectively stimulated. A considerable body of work discusses the socioeconomic benefits of green infrastructure. Although these studies provide valuable insights into the technical potential of LIDs to enhance urban resilience, they focus primarily on technical aspects associated with a limited set of devices, without addressing the behavioral and institutional barriers that must be overcome to scale up the use of such technologies.

2 METHODS

A dynamic model was developed in Vensim 10.2.2 to simulate a cap-and-trade system for stormwater management, integrating three dimensions: (i) hydrological conditions; (ii) social dynamics of LID adoption; and (iii) the operation of a regulated storage credit market. The model adopts a system dynamics approach, enabling feedback representation, nonlinear behavior, and the continuous evolution of system states. It was applied to a hypothetical watershed in the Federal District (Brazil) with 1,000 potential users, to explore behavioral mechanisms influencing the adoption of green infrastructure when linked to a cap-and-trade mechanism. The first stage estimated the potential water storage provided by LID units. Precipitation, runoff, and LID efficiency were incorporated, and seasonal precipitation was represented through a monthly lookup table based on historical averages. The second stage formulated the model's regulatory and economic structure. Each agent receives a maximum storage limit (CAP). When storage provided by LIDs exceeds this threshold, surplus volume is converted into tradable credits. Credit pricing is endogenous and depends on the interaction between supply and demand, using equations that incorporate credit flow, the number of buyers and sellers, and the accumulated system deficit. Finally, the third stage incorporated social and behavioral dynamics. Two stock variables—acceptance and attractiveness—represent how users perceive the benefits of LIDs. Acceptance reflects the recognition of hydrological performance, while attractiveness varies between defined minimum and maximum values based on relative acceptance, reinforcing adoption through feedback. The number of LID units is modeled as a stock, increasing through installation (initial and replacement) and decreasing through scrapping, which is calculated as the ratio between installed units and their average useful life.

3 RESULTS AND DISCUSSION

The simulation of the hydrological, economic, and social subsystems revealed dynamic behavior aligned with the feedback structure of the model. The stock-and-flow diagram in Figure 1 highlights the role of Water Storage as the basis of the credit market. Interactions among precipitation, LID efficiency, and installed capacity determine the stored volume, which generates Created Credits when the CAP threshold is exceeded. Higher storage increases credit availability and reduces prices, whereas lower storage restricts supply and raises prices, illustrating the regulatory logic of a cap-and-trade system.

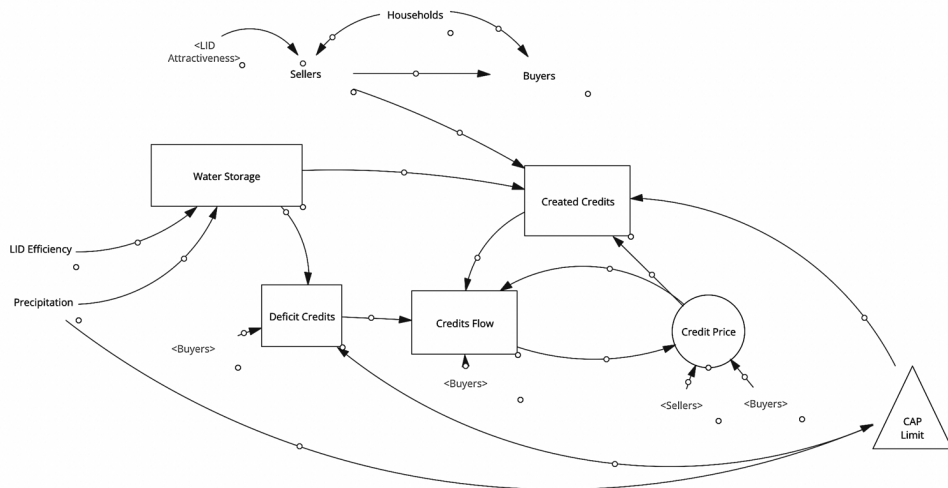


Figure 1 – Simplified scheme for Trading of Environmental Licenses (Cap-and-Trade) in VENSIM

Credit Price proved highly sensitive to the balance between Created and Deficit Credits. Accumulated deficits increased prices and encouraged new LID installations, while greater availability of credits stabilized prices at lower levels, reducing marginal incentives. This oscillatory behavior reflects typical adjustment dynamics observed in regulated markets.

The simulation was applied to a hypothetical watershed in Brasília with 1,000 potential users, allowing examination of behavioral mechanisms influencing LID adoption under a cap-and-trade framework. Three subsystems were central to model behavior: (i) evolution of the LID stock, (ii) price formation, and (iii) social responses through acceptance and attractiveness. In addition, Figure 2 shows continuous but decelerating growth in the Number of LIDs. Early adoption is slow because initial storage capacity is low and cumulative benefits are not yet perceived. As social acceptance increases, installation accelerates, but long-term growth converges toward an asymptote due to saturation and replacement dynamics. This pattern is consistent with diffusion processes shaped by behavioral inertia, finite market size, and device depreciation.

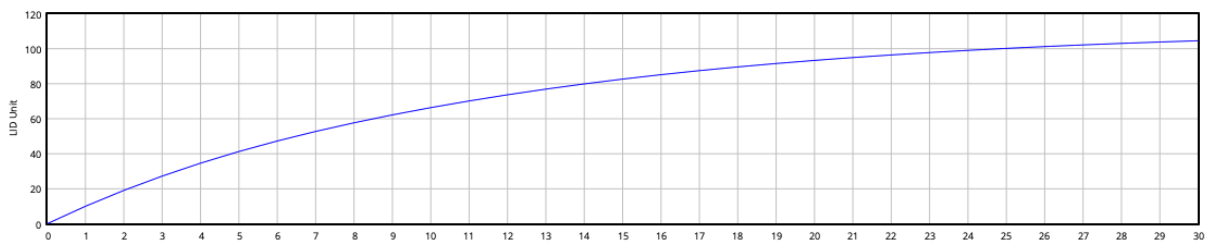


Figure 2 – Number of LIDs installed. The x-axis represents time (years) and the y-axis is the LID installed

Social behavior evolved gradually, as shown in Figure 3. Figure 3 represents the social subsystem, which exhibited gradual and cumulative behavior. LID Acceptance and LID Acceptance increased over time as perceived hydrological benefits accumulated, moderated by perception delays. LID Attractiveness responded more quickly, creating a reinforcing loop in which higher acceptance stimulated adoption, which in turn increased storage capacity. Although scrapping introduced minor oscillations, the overall expansion of LIDs supported the stabilization of credit deficits and prices.

The interaction of hydrological, economic, and social feedback loops became evident: 1) Hydrological–economic: Increased rainfall → more storage → more credits → lower prices. 2) Economic–social: Higher prices → stronger incentives → greater adoption. 3) Social–hydrological: Higher attractiveness → more LIDs → higher storage capacity.

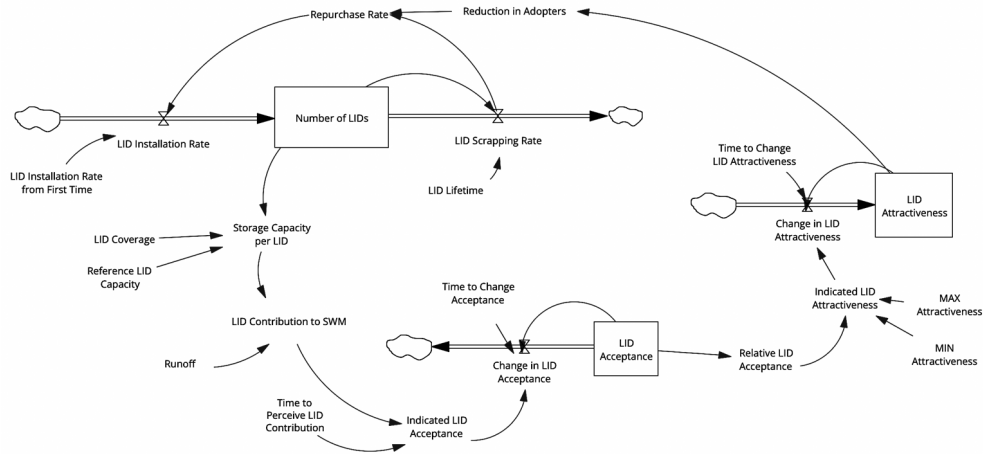


Figure 3 – Simplified scheme for Acceptance and Attractiveness to LID

Finally, the U-shaped pattern in Figure 4 reflects the social perception cycle. Attractiveness declined initially due to falling credit prices and limited early recognition of hydrological benefits, generating a temporary demotivation phase. This was intensified by an initial oversupply of credits, as LID adoption grew faster than near-term credit demand. As installed units accumulated and benefits became more visible, attractiveness recovered and entered a reinforcing cycle that supported long-term adoption.

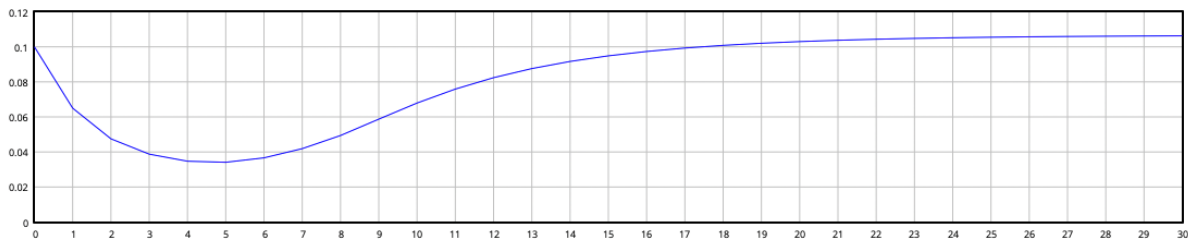


Figure 4 – LID Attractiveness. The x-axis represents the years (30 years of simulation) and the y-axis represents the LID attractiveness rate (dimensionless).

The results indicate that a cap-and-trade mechanism has strong potential to promote LID adoption, as prices adjust endogenously to hydrological and behavioral changes, social acceptance evolves with perceived system performance, and long-term reinforcing loops help sustain adoption over time. However, the system also presents important limitations in its early stages: an initial price collapse may reduce incentives, delays in user perception slow behavioral responses, and temporary credit oversupply can distort market signals. To address these challenges, policy design should incorporate measures such as establishing price floors or controlling the release of credits during initial phases, adjusting CAP levels adaptively as adoption increases, and improving communication strategies to reduce perception delays and strengthen user confidence.

4 CONCLUSION

This work illustrates potential of a cap-and-trade mechanism to stimulate the adoption of low-impact development (LID) infrastructure in urban watersheds. Results suggests that LID adoption can be reinforced through endogenous price signals, growing social acceptance, and cumulative hydrological benefits. The model reveals important advances: credit prices respond automatically to changes in storage and user participation, social perception strengthens as system performance becomes evident, and long-term reinforcing loops support sustained diffusion of LID technologies.

Despite these promising results, the simulations also expose significant limitations that must be addressed before practical implementation. The system is potentially vulnerable to early price collapse, which can weaken adoption incentives; delays in user perception slow behavioral responses; and temporary oversupply of credits

may distort market signals. These findings suggest that real-world applications would require regulatory safeguards—such as phased introduction of credits, adaptive CAP calibration, and improved communication strategies—to ensure market stability during the initial years of operation. Having established the theoretical viability of the approach, future research should expand the model’s scope. This includes simulating multiple types of LID devices with distinct efficiencies and costs, incorporating diverse land-use and urban-density patterns.

LIST OF REFERENCES

Wilkerson, B., Romanenko, E. and Barton, D.N. (2022). *Modeling reverse auction-based subsidies and stormwater fee policies for Low Impact Development (LID) adoption: a system dynamics analysis*. *Sustainable Cities and Society*, 79, 103602.