# A proposed smart market for impervious cover runoff under rainfall uncertainty

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## Abstract

Damage caused from stormwater runoff is becoming more frequent and occurring in places that were previously free of these problems. In order to reduce this problem, authorities have looked at different mechanisms for controlling and minimising the costs of floods. This paper proposes a smart market (SM) for runoff from impervious cover to reduce the mitigation and prevention costs for damages in the catchment. As rainfall events are uncertain, the SM must incorporate this stochasticity into the model formulation. Two stage stochastic programming (TSSP) with recourse is proposed to deal with uncertainty of rainfall events. The recourse actions or penalties would be priced according to the cost of damage or mitigation at different places in the catchment. The market would allow hedging against a range of rainfall events until an established maximum rainfall event, and above it, penalties for more extreme events.

We expect the proposed SM would encourage users to internalize the expected costs of their runoff and cost of flooding. In addition, as the SM reduces transaction costs, there will be efficient allocation outcomes at minimum cost for society. The clearing prices and allocations would be based on auction bids, desirable environmental standards and the expected cost of flooding.

**Key words:** Smart market, impervious cover, runoff, flooding, stochastic programming.

## 1 Introduction

Society faces high costs due to environmental degradation from stormwater runoff (RO). In recent years, the occurrence of problems due to excess of stormwater and, therefore, flooding is getting worse. The frequency of these disasters has been a consequence of human activities, changes in land management and development in hazard areas. Rogers and Defee II (2005) observed that impacts on catchment outflow arose when development, impervious cover and edge density of roads increased. Those entailed more frequent flooding and threatened natural habitat in rural and urbanized areas (E.P.A. 1993; Strappazzon et al. 2003; Walls and McConnell 2004; Eigenraam et al. 2005; Tang et al. 2005; Westra, Zimmerman and Vondracek 2005; Bradshaw et al. 2007; Hill, Pugh and Mullen 2007; Pappas et al. 2008).

Environmental problems have motivated governments and policymakers to create mechanisms and policies to achieve economic development with minimum environmental impact in order to avoid tragedy of the commons (Hardin 1968). Only a few studies have been set up to solve the problems related to storm-water runoff and floods through market-based instruments. One system with market instruments is transferable development rights (TDR), which has been tried to indirectly control flooding problems (McConnell, Walls and Kopits 2006; Walls and McConnell 2007). Other systems use fees and rebates, tradable runoff allowances (Thurston et al. 2003), flood management and risk analysis (Harman, Bramley and Funnell 2002; Purnell 2002; Sayers, Hall and Meadowcroft 2002; Ermolieva and Ermoliev 2005; Liu and Huang 2009), or merely command and control (Parker 1995).

Despite the theoretical plausibility of these methods, empirical evidence has shown problems with efficiencies, prices, allocations and, especially, transaction costs.

An alternative proposal to solve stormwater runoff problems, while reducing transaction costs, would be a smart market. A smart market (SM) is an auction system assisted by mathematical and computing tools (McCabe, Rassenti and Smith 1989; McCabe, Rassenti and Smith 1991), to manage complexities and third-party effects which are impossible to handle with ordinary auctions. The main difference between a smart market and an ordinary auction is that the former allows management of directly doing trading. The SM would reduce the transaction costs because users do not need to search for trading partners, bargaining is simpler, price information can be made available, and the manager ensures market discipline. Thus, theoretically, a SM would enable the attainment of efficient allocations and prices, as well as a greater surplus for society (McCabe, Rassenti and Smith 1989; McCabe, Rassenti and Smith 1991; Murphy et al. 2000; Gallien and Wein 2005; Raffensperger, Milke and Read 2008; Murphy et al. 2009; Raffensperger and Cochrane 2009).

Concerning the SM operation, Sayers et al., (2002) noted that dealing with flood management is quite complex and that any integrated management would necessarily need to be supported by a computer-based system. This statement reinforces the need for a smart market which is able to incorporate the consequences of land changes and trade in the catchment.

A deterministic smart market for impervious cover to control problem from excess of runoff was proposed by Raffensperger and Cochrane (2009). In this market, users trade consent to change impervious cover as measured by the Curve Number of the land while the authority limits a maximum capacity of storm water runoff at channel control points. Although this study introduces the idea of the SM, it does not consider the stochastic nature of rainfall. The current proposal tries to extend the research of Raffensperger and Cochrane to a SM that incorporates the stochasticity of the rainfall events.

Hydrological phenomena and, especially, rainfall events are complex and hard to predict. Calculations about rainfall are often based on simple averages, which creates problems when designing infrastructure and developing policy instruments. Ignoring the stochastic nature of rainfall events may lead to poor decisions and inefficient outcomes with significant social cost. Malcolm and Zenios (1994) suggest incorporating uncertainty into planning and design of infrastructure, to allow obtaining robust solutions and outcomes. That also is applicable to SM design.

The next section describes the smart market. The third section presents the model, and the fourth section shows how the SM would operate.

## 2 Smart market under rainfall uncertainty

Under uncertainty of rainfall events, the authority should make decisions about design, planning and environmental thresholds to minimise risk and keep society safe from flooding. The decision is influenced by rainfall distribution and the cost of extreme events. The regulator must deal with these concerns and should consider them in the design of the SM, to encourage hedging against a range of events.

A smart market under uncertainty works based on mathematical programming. This paper will use a two stage stochastic program (TSSP) with recourse. The main source of uncertainty will be the rainfall events.

The TSSP with recourse model is particularly useful as it allows working with infeasibilities due to extreme events (Li, Huang and Nie 2009). Tilmant et al. (2008) noted a stochastic model would be useful to help to hedge against extreme events such as drought and floods. Thus, the TSSP with recourse approach would model the randomness from different rainfall events and would consider violation of the constraints.

Stochastic formulations with recourse have been applied to different economic problems. For example, in electricity markets Carrion et al. (2007) proposed a stochastic program with recourse for solving an electricity supply problem of a large consumer. Calatrava and Garrido (2005) analysed different water market systems under uncertainty for water supply in Spain. Tilmant et al. (2008) presented a stochastic program for valuing the marginal water value in an integrated economic hydrologic model of a multipurpose multireservoir system for which the main activities requiring water were agriculture and hydroelectric production. Hollinshead and Lund (2006) minimized the expected cost of long-term, spot and option water purchases to meet environmental demands with a three stage stochastic formulation with recourse. The authors did not penalize their formulation against extreme drought corrections in dry years, which could result in infeasibilities.

The stochastic nature of the rainfall is incorporated in the SM model by relating the distribution of probabilities of rainfall events with the impact coefficients due to land uses, best management practices (BMPs) and technologies. Those impact coefficients correspond to the flow of runoff per unit of time (runoff hydrographs) at different points across the channel, and they vary according to the rainfall scenarios.

The SM for impervious cover maximizes the expected economic surplus for trading the level of impervious cover for land and accounting for recourse actions or penalties. The market considers the users' willingness to pay for impacting the channel's system and the corresponding environmental thresholds established by the authority.

Recourse actions and penalties are associated with flooding costs for extreme storms. Thus, the market would present incentives to reduce runoff and consequently to reduce damage due to flooding. Additionally, the health of a catchment would be hedged against a range of storms. Figure 1 illustrates a possible scenario for the rainfall distribution and flooding cost. The dashed line indicates the cost increase due to storms greater in intensity than the hegded range, $E_d$. Those costs of flooding would be considered in the model as penalties.

The penalties related to flooding cost are incorporated into the SM model. The mathematical formulation is presented in the next section.

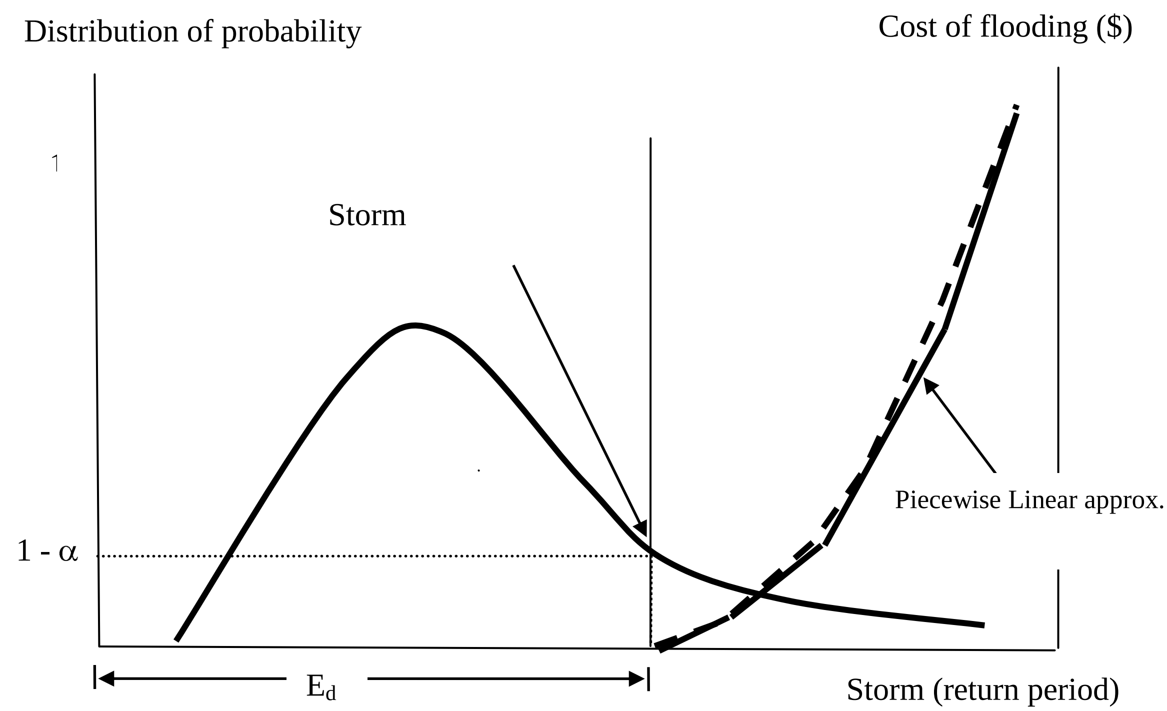


Figure 1 Rainfall event of probabilities distribution and flooding costs for extreme events. $E_d$ represents the range of storms that the market would be hedged against and $\alpha$ represents the level of certainty.

# 3 Math models

**Indices**

$i$ = 1,…,$N$ user.

$j$ = 1,…,$J$ land type.

$b$ = 1,...,$B$ bid step.

$k$ = 1,...,$K$ control point.

$r$ = 1,…,$R$ range (interval) in the piecewise linear approximation.

$s$ = 1,…,$S$ scenarios of rainfall (storms).

$t,u,r$ = 1,…,$T$ time.

**Parameters**

$C_{i,j}$ = Total initial land of type $j$ owned by user $i$ (ha).

$D^{max}_{i,j,b}$ = Maximum amount of land type $j$ (ha) that user $i$ in the bid step $b$ is willing to buy at price $P^{D}_{i,j,b}$.

$S^{max}_{i,j,b}$ = Maximum amount of land type $j$ (ha) that user $i$ in bid step $b$ is willing to sell at price $P^{S}_{i,j,b}$.

$P^{D}_{i,j,b}$ = Demand price ($/ha) for land type *j* from user *i* and bid step *b*.

$P^{S}_{i,j,b}$ = Bid price ($/ha) for land type *j* from user *i* and bid step *b*.

$L^{t}_{k}$ = Maximum allowable runoff ($m^3$/time) at channel the control point *k*, time *t*. These maximum capacities depend on the channel sectional shape at the control point *k*.

$P^{f}_{k,r}$ = Piecewise linear cost of flooding at control point *k*. This represents a linear cost under marginal changes in the total quantities in $m^3$ at a place in range *r*. This $m^3$/time cost will be incorporated as a penalty.

$\phi^{s}$ = Probability of storm scenario *s*. This parameter satisfies the following properties: $0 \le \phi^{s} \le 1,\ \sum_{s}^{S} \phi^{s} = 1,\ \phi^{s \cup s'} = \phi^{s} + \phi^{s'}$.

$H^{t-u+1,s}_{i,j,k}$ = Marginal impact of land type *j* from user *i* at control point *k* and scenario *s*, at the end of period $t - 1$ after one $m^3$ of runoff was discharged from user *i*. This coefficient relates marginal impact at control points according to land type *j* and users' properties conditions and scenarios, e.g., $m^3$/(time ha). *u* is the lag time between the discharged flow from a property and the flow that reaches the control point.

**Decision variables**

$qsell_{i,j,b}$ = Amount in hectares (ha) type *j* of runoff and bid steps *b* = 1,...,*B* sold by user *i*.

$qbuy_{i,j,b}$ = Amount in hectares (ha) type *j* of runoff and bid steps *b* = 1,...,*B* bought by user *i*.

$g_{i,j}$ = Total hectares type *j* for user *i* (ha).

$\mu_{i,j}$ = Expected land use price for firm *i* and land type *j* ($/ha).

$\phi^{s} \lambda^{s}_{t,k}$ = Expected price to discharge at the control point *k*, time *t* and scenario *s* ($ $m^3$/time).

$f^{s}_{k,m}$ = Recourse action which accounts for the maximum level of flooding in scenario *s* at control point *k* in range *r* ($m^3$/time).

**Model** SmartMarketIC

Maximize $\sum_{i}^{N}\sum_{j}^{J}\sum_{b}^{B} P^{D}_{i,j,b}\ qbuy_{i,j,b} - \sum_{i}^{N}\sum_{j}^{J}\sum_{b}^{B} P^{S}_{i,j,b}\ qsell_{i,j,b} - \sum_{s}^{S}\phi^{s}\sum_{k}^{K}\sum_{r}^{R} P^{f}_{k,r}\ f^{s}_{k,r}$

Subject to

1) $qbuy_{i,j,b} \le D^{max}_{i,j,b}$ : $\beta_{i,j,b}$. for all *i,j,b*

2) $qsell_{i,j,b} \le S^{max}_{i,j,b}$ : $\gamma_{i,j,b}$. for all *i,j,b*

3) $g_{i,j} = \sum_{b}^{B} qbuy_{i,j,b} - \sum_{b}^{B} qsell_{i,j,b} + C_{i,j}$ : $\mu_{i,j}$ (free) for all *i,j*

4) $\sum_{i}^{N}\sum_{j}^{J} H^{t-u+1,s}_{i,j,k}\ g_{i,j} \le L^{t}_{k} + \sum_{r}^{R} f^{s}_{k,r}$ : $\phi^{s}\lambda^{s}_{t,k}$ for all *t,k,s*

5) $\sum_{j}^{J}\sum_{b}^{B} qbuy_{i,j,b} - \sum_{j}^{J}\sum_{b}^{B} qsell_{i,j,b} = 0$ : $\nu_{i}$ (free) for all *i*

*6)* $0 \le f^{s}_{k,r} \le F^{max}_{k,r}$ : $\theta^{-}_{k,r}$, $\theta^{+}_{k,r}$ for all *k,r*

7) $qbuy_{i,j,b}$, $qsell_{i,j,b} \ge 0$, and $g_{i,j}$ (free) : $\zeta_{i,j,b}$, $\delta_{i,j,b}$, for all *i,j,b*

**Explanation**

The objective function maximizes the expected total economic surplus from trading impervious cover-runoff less the penalties for flood damage under different rainfall events. This formulation considers a discrete distribution of probabilities for rainfall events and recourse actions for flooding damage at different control points. The model assumes that users bid rationality and truthfully.

1) Total expected area bought in each tranche or step is bounded by demand quantities.

2) Total expected area sold in each tranche is bounded by bid quantities.

3) The final amount of area of land type *j* of user *i* equals the net traded plus *i*'s initial allocation. The dual variable $\mu_{i,j}$ of this constraint is the expected marginal value for another unit of land type *j* for user *i* across the different rainfall scenarios according to the impact at each control points.

4) For each scenario *s*, the total runoff at control point *k* in period *t* should be less than the maximum capacity in the channel. The dual price $\phi^s \lambda^s_{t,k}$ represents the expected marginal social welfare if the authority allows another unit, e.g., $m^3$/hr, at the control point *k*.

5) The total land sold for each user must be equal to the total land bought. This constraint ensures that all users will retain their initial land holding. For instance, if a user sold 0.25 hectares with 40% impervious cover, then she/he must buy 0.25 hectares with other imperviousness.

The model allows efficient allocation and provides prices for each participant, $\mu_{i,j}$. This price is a weighted value of impacts at different control points across all scenarios. It measures the expected improvement in social welfare due to the authority increasing the channel capacity by one unit, resulting in a corresponding reduction in the expected cost of flooding at the control point. The dual price decomposition of $\mu_{i,j}$ is as follows:

7) $\mu_{i,j} = -\sum_s^S \phi^s \sum_k^K \sum_{t=u}^T H_{i,j,k}^{t-u+1,s} \; \lambda^s_{t,k}$ for all *i,j* : $g_{i,j}$

8) $- \phi^s \lambda^{s\,*}_{t,k} - \theta^-_{k,r} + \theta^+_k = -\phi^s \; P^f_{k,r}$ for all *k,s* : $f^s_{k,r}$

The price depends on the probable flooding costs $\phi^s \; P^f_k$ at the control point (equations 7 and 8). This expected cost will increase for each land use with greater impervious cover. Participants who want to increase their imperviousness would face a higher price due to the expected cost from extreme events. In other respects, if $\lambda^s_{t,k} > 0$, then by complementary slackness ($\theta^s_k = 0$) the new condition will be $\lambda^s_{t,k} = P^f_k$ . Thus, if the constraint were bounded in only one time-period, the new condition would be $\lambda^s_{t,k} = P^f_k$, and so $\mu_{i,j} = -\sum_s^S \phi^s \sum_k^K \sum_{t=u}^T H_{i,j,k}^{t-u+1,s} \, P^f_k$ .

The dual price $\mu_{i,j}$ will be used to charge or pay each user *i* in the catchment $\sum_j^J \mu_{i,j} \left( \sum_b^B qsell_{i,j,b} - \sum_b^B qbuy_{i,j,b} \right)$ and, finally, after clearing the market, the regulator would receive a net payment (NP) for all transactions $NP = \sum_i^N \sum_j^J \mu_{i,j} \left( \sum_b^B qsell_{i,j,b} - \sum_b^B qbuy_{i,j,b} \right)$. The auction is not necessarily revenue neutral.

## 4 How the market will work

The proposed SM would work as an auction system where the demand is represented by users that want to increase their impervious cover and the supply is defined by those persons that want to reduce their impervious cover. The SM considers tranches of sell offers and buy bids, to buy or sell impervious cover. As mentioned in Section 2, imperviousness is measured by an empirical parameter called the curve number (CN) which measures runoff from a rainfall event based on the land owner's hydrologic soil group, land use, management practice, and hydrologic conditions. Given the suitability of the curve number to represent the impervious cover, the SM would trade CN rights for a piece of land.

Concerning administration and control of the SM, a regional environmental authority would facilitate the CN trade. Trading will be done in a centrally-controlled auction where users will trade impervious cover quota (rights). These quotas may be for long- or short-term, but they cannot be issued for an indefinite time period.

Users may bid in advance for the impervious cover quota according to a timeframe which would depend on the hydrological seasons and the main economic activities. For instance, a catchment comprised mainly of farms would run with regard to the agricultural season, i.e., twice or four times per year; but in an urban catchment, the market may run monthly. In any case, the optimal timeframe is depends on catchment land uses and consequently, the timeframe should be evaluated constantly by the authority.

Because users may bids in advance, the impervious covers can be planned across a year or longer time frames. Those actions can also be linked to a contract which stipulates future physical actions on the land use regarding impervious cover or equivalent imperviousness at a specified time. Users who do not inherit impervious cover rights or those who want to develop new project can also participate in the spot market.

Outside the market, users may evaluate the cost of different options to control their own runoff, whilst satisfying the regulator that they would not change their initial runoff hydrograph. This could be quite expensive. The change of imperviousness and technology might increase the runoff from the property, raising penalties if a user does not comply with obligations. To simplify the calculation of impervious cover, the regulator could develop a web site where participants could estimate their land covers.

Concerning the role of the SM operator, the authority will first need to validate the property condition (impervious surface) for each participant in the catchment, and different methods could be used for this purpose. For instance, the manager could use a satellite-derived impervious map area to estimate the imperviousness of the area (Dougherty et al. 2004).

Secondly, individual impacts and runoff hydrographs need to be estimated in the catchment at control points by scenarios. The estimation can be done by hydrological and hydraulic models based on geographical information systems (GIS) such as the simulators HEC-HMS, HEC-RAS and SWMM. These models calculate the components of a hydrological cycle and are able to simulate runoff hydrographs in a routed channel or pipe system. In addition, the authority will estimate the distribution of rainfall events in the catchment. Thus, users' impacts can be measured as impact coefficients by time and by scenario.

Thirdly, the regulator must define the threshold at different control points. The threshold can be defined as maximum capacity of channels, pipes, and streams. With those thresholds, the authority can estimate the probable cost of flooding for extreme events. The costs would enable a more accurate assessment of the risk that the authority faces, while leaving the health of the catchment to be hedged against a range of events.

Fourthly, to accurately measure the impact coefficients, the regulator needs to monitor the individual impact coefficients along channels, especially in environmentally sensitive areas. These coefficients should be evaluated and controlled periodically to update the SM model.

Finally, the authority, with all previous issues, will clear the market and obtain prices and allocations.

# 5 Conclusion

In this paper, we have presented a smart market to manage problem of flooding. The market model considers a TSSP with recourse to incorporate the uncertainty of rainfall events. This market allows obtaining efficient allocation and prices while transaction cost are reduced. In addition, the authority could keep the health of the catchment within a range of storms.

This market does not account the risk of greater events, nor incorporate those in the market model. This topic will be further studied along our research, in particular the risks involved in the market design and how they would effect allocations and prices. In addition, the research will incorporate water quality into the market, where this quality will be measured as sediment discharge.

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