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Costs and Benefits of Capturing Urban Runoff with Competitive Bidding for Decentralized BMPs

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Urban stormwater runoff is both a source of pollution and a potentially valuable resource. Centralized facilities traditionally have been used to manage runoff. Decentralized Best Management Practice (BMP) options may be able to avoid the costs of purchasing expensive urban land needed for centralized facilities. We investigate the cost-effectiveness of implementing BMPs in a Los Angeles area watershed with two voluntary incentive mechanisms: competitive bidding and a fixed subsidy. The subsidy mechanism has lower BMP placement costs but generates relatively large excess profits for landowners. The bidding mechanism has higher BMP placement costs, but generates smaller excess profits and tends to be more cost-effective for the regulator particularly at higher runoff capture levels. We also compare the costs of bidding and centralized alternatives and find that the bidding alternative is significantly less costly than a centralized alternative for a range of stormwater capture goals. Finally, we examine the value of infiltrated stormwater and find that it is up to 38% of total BMP costs

1. Introduction

Urban stormwater runoff is both a significant pollution problem as well as a potential resource. The pollution problem results from the “urban sludge” (heavy metals, petroleum residue, salts, solid waste, etc.) that is carried off impermeable surfaces by storm events and washed into receiving water bodies where it damages ecological and recreational resources (Arnold and Gibbons 1996). If these pollutants can be effectively removed from stormwater then runoff also represents a potentially beneficial resource. Without urban development more of this runoff would naturally infiltrate and replenish groundwater stocks, but instead it is treated as a waste and disposed of accordingly (Ferguson 1994). Groundwater supplies in urban regions thus remain lower than they might be otherwise, which seems especially inefficient in arid regions such as the U.S. desert southwest. In light of recent predictions of increased likelihood of long-term drought in such areas (IPCC 2007, Seager et al. 2007), it is imperative to investigate cost-effective ways to capture, clean, and infiltrate more of this potential resource.

The dominant paradigm in stormwater management has been to avoid flooding by quickly conveying runoff to a receiving water body (Ferguson 1998). For this purpose, conveyance structures that centralize runoff are essential. Local stormwater agencies have continued to emphasize centralized solutions even as the emphasis on water quality in receiving waters has grown. These centralized facilities (such as detention pond, infiltration pits and trenches, artificial wetland, etc.) have the advantage of economies of scale where large capacities are cheap on a per-unit capacity basis. However, in order to use that capacity, such facilities must drain a large area. In dense urban areas it is often difficult to achieve this goal without impinging on private land, purchasing contiguous land parcels, or significantly redesigning redevelopment to accommodate centralized facilities.

Recent work has focused on the use of decentralized parcel-level best management practices (BMPs) for managing runoff or improving runoff quality across a larger area of a landscape. Arabi et al. (2006) uses a genetic algorithm approach to find the most cost-effective approach to implementing BMPs to control pollutants in agricultural runoff. Similar papers that use an optimization approach to find the best placement of parcel-level BMPs include Bekele and Nicklow (2005), Muleta and Nicklow (2005) and Srivastava et al. (2002) among others. Perez et al. (2005) examines optimal placement of infiltration BMPs in a watershed to control peak runoff.

Although decentralized BMPs cannot provide the same scale economies as centralized facilities, they do not require large contiguous land areas. Furthermore they can be placed on parcels with relatively low marginal land use value thus effectively reducing the total installation cost. This is particularly beneficial in dense urban areas where land values can be in the millions of dollars per acre. It is therefore an empirical question whether centralized or decentralized runoff control is more cost-effective.

In order to exploit their potential cost advantage, decentralized BMPs must be targeted at parcels with relatively lower costs of converting land to BMP area. If a regulatory agency oversees relatively few parcels, has good information about costs, and has the authority to order BMP installations, then it may be relatively straightforward for the agency to impose the least-cost placement of BMPs. However, with many parcels, limited information, and/or limited authority, the agency may not be able to implement this approach in practice. Instead the agency can employ relatively simple economic incentive policies to encourage BMP installations by private landowners.

At least two types of incentives have been examined previously: a fee/rebate system (Thurston 2006) and a tradable allowance system (Thurston et al. 2003; Thurston 2006). Both of these approaches involve both mandatory and voluntary components: the fee/rebate system includes a mandatory stormwater fee and a voluntary rebate; the tradable allowance system involves a mandatory "cap" on total runoff and voluntary trading of runoff allowances. In addition, both applications involve assignment of BMP types to parcels based on soil types, rather than allowing endogenous selection of BMP types by landowners. Purely voluntary competitive bidding also has been proposed in the recent literature (e.g., Roy et al. 2006), but to our knowledge its cost-effectiveness has not yet been evaluated.

Our research extends this work in several ways. First, the incentives we examine are purely voluntary and thus apply to regulatory agencies with limited authority to compel landowners to modify their properties to achieve runoff capture goals. In this scenario regulatory alternatives are limited and economic incentives must provide the entire motivation for landowner participation in the regulatory program. We believe this is more relevant for existing developments than new developments where BMP requirements can be more easily built into the permitting process. The stormwater fee rebates used by several cities (Doll and Lindsey 1999) are similar to the decentralized, incentive-based systems we propose in that they give financial incentives for on-site stormwater management. These incentives are structured as discounts on stormwater runoff charges and are based on retention or detention capacity. However, these rebates have incentive structures that do not appear to be designed to minimize stormwater capture costs.

Second, in keeping with the voluntary nature of our mechanisms, we allow each landowner to endogenously select the BMP type and capacity for each parcel, rather than assigning BMP types to parcels based on soil types or other characteristics. Third, we incorporate a hedonic analysis of land costs for our heterogeneous study area which shows substantial variability in land costs across parcels. Fourth, we explicitly model the economies of scale inherent in decentralized BMPs which previous studies typically have overlooked in favor of a constant marginal cost schedule.

We use this framework to estimate costs for two approaches to stormwater runoff reduction in our Southern California study area: a fixed subsidy paid per unit of runoff captured by decentralized BMPs, and a competitive bidding process designed to reduce total agency costs (i.e., budgetary costs for the regulatory agency) below those of the subsidy mechanism. We also estimate the cost for an equivalent amount of centralized treatment. Our baseline results show that competitive bidding is more cost-effective than either centralized treatment or a fixed subsidy for a range of stormwater capture goals. A sensitivity analysis further demonstrates this result is robust to various combinations of plausible parameter values. Finally we estimate the value of infiltrated water and find that it represents a significant fraction of total BMP costs.

2. Methodology

Our approach posits a constrained cost-minimization problem for the regulator: minimize the present value of land, construction, and maintenance costs while achieving a desired level of runoff capture. For the two decentralized mechanisms, we assume landowners act as profit-maximizers when faced with regulatory incentives. We limit our attention to two infiltration BMP options: infiltration pits and porous pavement. Infiltration BMPs are likely the best approach when trying to meet a broad array of water quality, supply, and ecological goals (Ferguson 1994). We also have good local cost data for these devices. We do not consider infiltration basins because evidence from Santa Monica City's stormwater program indicates that landowners rarely choose to install this option (DeWoody, 2007). We do not consider swales because Heaney et al. (2002) states that swales are not usually suitable for commercial/industrial and heavily urban areas similar to our study site. Future research should examine other BMPs; however, it is important to note that more BMP choices could only lower the costs or increase the effectiveness of the incentive-based approach.

This study considers the commercial, industrial, retail, and multi-family use parcels in the Sun Valley watershed near Los Angeles, California (918 parcels with sufficient information, see figure one for a map of the area). The entire watershed is 4.4 square miles situated on alluvial rock and gravel soils. Industrial and commercial uses make up 59 percent of the watershed, residential 35%, and open space 5% of the entire watershed (County of Los Angeles 2004). The watershed is approximately 63.3 percent impervious. This very heterogeneous watershed is representative of problematic runoff-generating urban landscapes. We exclude single-family houses from the parcels we consider because we believe that they are relatively poor candidates for financial incentives in mixed-use areas because it would be relatively difficult to monitor single-family houses to ensure BMP maintenance (due to the number of parcels that might be enrolled) and because economies of scale would be relatively limited on these smaller parcels. We first simulate runoff and capture for a wide array of parcel characteristics and BMP types and sizes for the Sun Valley precipitation record. Using these results, we construct reduced-form relationships between parcel characteristics, BMP capacity, and runoff capture for each infiltration rate. We use the reduced form equations to model the fixed subsidy mechanism and determine the optimal location and sizing of infiltration capacity across the watershed. We then construct the competitive bidding mechanisms intending to approximate the optimal mix of BMP types and capacities.

2.1. Runoff and BMP Modeling

We model runoff and BMP capture at the parcel level using the spreadsheet-based STORM (SS STORM) runoff and BMP modeling approach. SS STORM is a mass-balance based area-normalized stormwater flow routing and water quality simulation model (Lee el al. 2005). This model originated from STORM (Storage, Treatment, Overflow, Runoff Model) which has been used to find the best mix of stormwater storage and release control strategies over an extended period (Hydrologic Engineering Center 1977). This model can work with parcel level data on parking, roof, and permeable area. Standard local roll parcel data does not contain this information. In order to estimate these areas we obtained real estate sales data with the building footprint or roof area and the number of parking spaces on the property and matched the real estate parcels sales data to the local roll data for 550 parcels in and around Sun Valley. We used a regression approach to estimate the relationship between plot characteristics and pervious, rooftop, and parking area. We use these estimates of parking, roof, and impermeable area for runoff and land cost estimates in the optimization modeling. The procedure is presented in appendix A (see http://www.envisci.ucr.edu/faculty/baerenklau.html) Table 1 lists the estimates for the 918 non-single-family parcels in the Sun Valley area.

We customize SS STORM to the Sun Valley area by incorporating a five year hourly rain file from the nearby La Tuna Canyon rain station. In addition, we assume a number of other parameter values summarized in Table 2. In order to make the optimization modeling tractable, we use regression analysis to find reduced form specifications that match the simulation models. However, before reporting our results we take the BMP capacities generated by the optimization process and simulate runoff capture with SS STORM. Therefore all runoff capture results presented in the paper are derived from SS STORM simulations.

Centralized BMP runoff capture is modeled by using SS STORM to find the capacities necessary to capture a given proportion of runoff from the 231 hectare area (see Table 3 for the parameters). We assume the same roof, grass, and pavement proportions, infiltration rates, and precipitation data as in the decentralized runs. The modeling is approximate and does not consider conveyance travel times; therefore cost comparisons for an actual application should implement a more detailed flow-routing model.

2.2. Land, Construction, and Maintenance Costs

When landowners dedicate a portion of their parcel to a BMP, they likely forgo other potentially more valuable uses of that land. Losing the opportunity to otherwise employ that land area has a cost, but it is likely less than the cost of buying land because the owner does not lose all uses of the land. We assume that it would be prohibitively expensive to tear down buildings to replace them with BMPs. That leaves parking and permeable areas as area that could be used for BMPs. We assume the owner values area devoted to infiltration pits as permeable area and the area devoted to porous pavement as parking. Because parking is more valuable than permeable area in our sample, land costs are incurred only when infiltration pits displace existing parking area.

We use a three step process to estimate this land use cost that is explained in detail in DeWoody (2007). First, we estimate a hedonic regression equation that relates property values to variables including parking and permeable area. For this step we use real estate data covering the sales of non-single-family residential parcels from 1996-2005 over most of Los Angeles county. Next, we use this regression equation to estimate property values for each eligible Sun Valley parcel. Then we simulate the net cost of replacing parking area with permeable area by decreasing the parking area and increasing the permeable area by equal amounts and using the regression equation to predict a new property value. The difference in estimated property values between the original property and the modified property divided by the change in area is our estimate of the opportunity cost of converting parking area to infiltration pit area. Table 4 shows the summary statistics for the estimated opportunity costs of parking in the study area by land use. The unit land values are high enough so that only a few properties at the highest capture percentages incur land costs by converting parking area to infiltration pits. At these land prices, parking area is essentially fixed so in the interest of conserving space the hedonic regressions are not included in this paper.

Centralized BMPs also occupy land which, whether it is land that is explicitly purchased for the BMP or existing public land, will likely have an opportunity cost similar to the market value of land. For these land costs we use data on 1,398 land sales in the area from 2003-2005 from the COSTAR real estate database. Table 5 shows the median price per square meter for vacant land zoned for retail, commercial, or residential uses and for different areas of Los Angeles County. For the comparisons in this paper we use the \$696/m^2 value that is the mean for the San Fernando Valley area where Sun Valley is located. Comparison of Table 4 and Table 5 shows the estimated average parking use values for the parcels in Sun Valley are significantly less expensive than vacant land in the same geographic area.

Detailed descriptions of our construction and maintenance cost calculations are provided in DeWoody (2007). Here we summarize the cost functions used for our baseline results. (appendix B at http://www.envisci.ucr.edu/faculty/baerenklau.html describes the cost ranges used for our sensitivity analysis.) Construction costs for infiltration pits are estimated using the following equation which was chosen based on goodness of fit with available data:

$$cost = \gamma_1 (capacity)^{\gamma_2} \exp[\gamma_3 + \gamma_4(\gamma_5 + \ln[capacity])^2)] + \gamma_6 + \gamma_7 \ln(\gamma_8 + e^{\gamma_9 capacity}) \qquad (1)$$

Where: capacity (m^3) = area (m^2) × depth (m) × void fraction; γ_1=1665.46; γ_2=1.33; γ_3=1.55; γ_4=-0.049; γ_5=5.58; γ_6=-5622.60; γ_7=1464.29; γ_8= 47.67; and γ_9=0.074. The second two terms keep marginal costs in a narrow range for relatively large capacities where DeWoody (2007) has little data. For maintenance costs we use estimates from the Southeastern Wisconsin Regional Planning Commission (SWRPC 1991) updated to 2005 dollars using the Engineering News Record Los Angeles construction cost index. From this we derive a maintenance cost for infiltration pits of \$ 1.89E-04 /m^3 of void capacity/year. We also add 1.13% of capital costs per year to reflect periodic rehabilitation costs (EPA 1999).

The construction cost for porous pavement (specifically, porous concrete) has been estimated between \$48.44 /m^2 for large installations with porous soils and \$96.88 / m^2 for small installations with poor soils where existing asphalt must first be removed (Youngs, California Cement Council, verbal communication, 2006). We use an estimate of \$86.11 /m^2 in our baseline simulations that is appropriate for small installations with well-drained soils. We derive porous pavement maintenance cost estimates from SWPRC (1991) updated to 2005 dollars using the Los Angeles Engineering News Record construction cost index. This gives an annual maintenance cost for the Los Angeles area of \$0.0753 /m^2 of porous pavement.

For construction and maintenance cost data on centralized alternatives we use information contained in RWQCB-LA (2005), Caltrans (2001), USEPA (1999), and FHA (2003). We restrict our attention to two designs proposed by local regulators (RWQCB-LA 2005): infiltration trenches and infiltrations basins. We concentrate on these two designs because they are the key infiltration technologies identified as possible centralized devices by Los Angeles area water quality regulators (RWQCB-LA 2005). Since economies of scale are a critical part of the comparison between centralized facilities and decentralized BMPs it would not be useful to examine centralized facilities for which this information is not available. The cost for infiltration trenches is based on FHA (2003), inflated to 2005 dollars using Engineering News Record (ENR) cost indices:

$$cost = 1661.7\, capacity^{0.63} \tag{2}$$

where *capacity* is measured in cubic meters. EPA (1999) estimates the annual maintenance cost are between 5-10% of the construction cost; we use 7.5% as our baseline value. We add an additional 1.13 % of capital costs per year for rehabilitation costs based on periodic rehabilitation (EPA 1999) for a total maintenance and rehabilitation cost of 8.63% of capital costs per year.

FHA (2003) also estimates the construction cost of infiltration basins. These may be more cost-effective alternatives than infiltration trenches or sand filters for larger drainages (FHA 2003). After adjusting the costs to 2005 dollars, construction costs are:

$$cost = 205.16\, capacity^{0.69} \tag{3}$$

where *capacity* is measured in cubic meters. FHA does not estimate maintenance costs for this BMP, so we use an annual value of 5% of construction costs which is at the lower end of the range of the other centralized alternatives. We add an additional 1.72 % of capital costs per year for rehabilitation costs based on periodic rehabilitation (FHA 2003) for a total maintenance and rehabilitation cost of 6.72% of capital costs per year.

2.3. Enforcement and Monitoring Costs

For the comparison between centralized and decentralized systems it is not the level of enforcement and monitoring costs that matter, but the difference between decentralized and centralized costs. The enforcement, monitoring, and other transaction costs for an incentive-based system are difficult to determine. The limited evidence that exists suggests that these costs are high for residential properties. Only one of the cities in Doll and Lindsey's (1999) list of cities that implement incentives for BMP adoption allows residential owners to be eligible for the credits. This data lends further support to our decision to not include residences among the property types eligible for incentives.

It seems likely that the transaction costs for monitoring many small BMPs will be larger than for a few larger BMPs. However, centralized infrastructure, especially when placed in multiple-use open space such as parks, also needs regular monitoring and upkeep agreements. Though these costs may be lower than the enforcement and monitoring costs of a decentralized approach, they will still be significant. The cost difference in enforcement and monitoring is an open question for future research.

2.4. Optimal Placement and Sizing of Decentralized BMPs

We define "optimal" decentralized BMP implementation as the combination of BMP types, sizes, and locations that minimizes the present value of land, construction, and maintenance costs (which we call the "BMP placement cost") for all parcels while achieving the desired level of runoff capture. This ideal cost-minimizing solution may not be attainable in practice, but it provides a useful best-case scenario against which practical second-best solutions may be compared.

Any decentralized solution potentially involves many parcels. An important aspect of our specific problem is that parcels can be treated independently from one another. Runoff from any parcel enters directly into streets, gutters, and other conveyances where it flows to an eventual outfall (the Los Angeles River) without flowing back across any other parcels where it might be captured by other BMPs. This means there is no parcel-to-parcel runoff and therefore runoff capture on any parcel does not affect capture on any other parcels (Merrill, personal communication, 10/16/2007). This is a common situation in urban and suburban areas, especially with non-single family parcels and where parcel-to-parcel runoff is prohibited by law, which differentiates urban from rural and agricultural areas where parcel-to-parcel runoff is more common and thus parcels cannot be treated independently (Arabi et al. 2006). Furthermore, shallow groundwater mounding and lateral flow also is not an issue due to a very low groundwater table. Therefore infiltration at any parcel is not affected by infiltration at any other parcel.

Parcel independence also allows us to solve a simpler set of “dual” unconstrained profit-maximization problems instead of the more complicated “primal” constrained cost-minimization problem mentioned earlier (Silberberg 1990). The solution to the primal would require solving a high-dimensional problem with 3672 variables: a binary variable for each BMP type and a continuous variable for each BMP size at each of 918 parcels. This solution would generate optimal BMP locations and sizes. It also would allow us to calculate the marginal cost of capture ($/unit) at each parcel. A necessary condition for the cost-minimizing solution is that the marginal cost of capture is equal across all parcels with BMPs. We can use this condition to instead solve a set of “dual” problems in which we find the lowest common payment (subsidy) per unit of capture that induces independent profit-maximizing landowners to build enough BMP capacity to achieve the desired amount of runoff capture. Each of these 918 independent problems involves only 4 variables (2 binary and 2 continuous variables per parcel) and thus is much easier to solve than the primal problem. A simple grid search finds the optimal payment.

A potential problem with the dual approach is related to the shape of the marginal cost of capture function. As discussed previously, we find that the marginal cost of capture at the parcel level often decreases for small BMP sizes (low levels of capture) due to economies of scale, but eventually increases for larger BMP sizes (high levels of capture) due to the relative infrequency of large storms. Thus the marginal cost of capture is U-shaped (Figure two). If the marginal cost of capture were strictly increasing (and if certain other mathematical conditions are satisfied, including continuous differentiability of the cost function and convexity of the feasible solution set), offering landowners a fixed subsidy per unit of capture could achieve the optimal BMP placement and sizing as described in the dual problem above. But when marginal cost is U-shaped, a subsidy may not achieve the optimal result. This is because the subsidy induces each landowner with a U-shaped marginal cost curve to build either no capacity or a relatively large capacity (associated with the upward sloping part of the marginal cost curve). But it may be optimal for a landowner to build a relatively small capacity (associated with the downward sloping part of the curve) that also has the appropriate marginal cost. However, the optimal solution to our primal problem necessarily involves at most only one landowner building a capacity associated with the downward sloping part of his/her marginal cost curve; otherwise total cost can be reduced by increasing capture at one parcel and decreasing it at the other. Because we have hundreds of landowners, if one builds a sub-optimal capacity this will not have a significant effect on either the total BMP placement cost or the total runoff capture. Therefore we can be assured that a fixed subsidy per unit of runoff capture will result in BMP locations and capacities that are arbitrarily close to the optimal solution to our constrained cost-minimization problem.

2.5. Policy Options: Subsidy and Bidding Mechanisms

A practical problem with offering a fixed per-unit subsidy to encourage voluntary BMP installation is that landowners who choose to install BMPs do so because it is profitable. That is, their subsidy revenue exceeds their BMP placement cost, and therefore the agency cost (the present value of all the payments made to landowners) exceeds the BMP placement cost, possibly by a significant amount. One way to reduce the agency cost, relative to the subsidy case, is to utilize a competitive bidding process. Competitive bidding can reduce the total agency cost by creating an incentive for bidders to lower their offer prices, thereby effectively giving up some of the excess profit (defined here as the economic rent received from ownership of private information) they would earn in the subsidy case. The incentive is inherent in the competition among landowners who do not know how other landowners will bid: a higher price reduces the chance that a bid will be accepted, in which case the landowner earns no excess profit; whereas a lower price increases the chance that it will be accepted, in which case the landowner earns a positive excess profit. Thus each landowner tends to offer a lower price in hopes of earning at least some excess profit. The upshot is that if landowners can be induced to offer (bid) to install BMP capacities that are similar to those they would install in the subsidy case, a well-designed bidding process should reduce the total agency cost below that for the subsidy case.

In light of the preceding, we investigate the cost-effectiveness of both subsidy and bidding instruments for inducing voluntary installations of decentralized BMPs that achieve various annual aggregate runoff capture targets for the Sun Valley watershed. For the subsidy mechanism, our goal is to find the smallest annual per-unit payment that achieves the desired level of (estimated annual long-run average) runoff capture. Runoff capture is determined by the BMP capacity installed by each landowner, as determined by SS STORM. The capacity installed by each landowner is given by the solution to a parcel-level optimization problem whereby the landowner selects the BMP types and capacities that generate the most excess profit given the subsidy level being offered.

The subsidy mechanism compensates each participating landowner with an annual payment throughout the useful life of the BMP in exchange for incurring land and construction costs initially and maintenance costs periodically (other opportunity costs of participating in the program, such as acquiring information, submitting an application, and maintaining records, are not explicitly modeled here). Thus each landowner faces a problem no different from that of investing in a financial instrument that will pay a fixed annual dividend in the future. Each landowner also faces a strong incentive to remain in the program for the entire duration because early exit (i.e., removing the BMP or failing to perform required maintenance) from this payment schedule reduces the effective rate of return below the minimum acceptable rate. Therefore we assume each landowner acts to maximize the net present value of participating in the BMP subsidy scheme as though it were a financial instrument. In our baseline scenario we specify a time horizon of 30 years and a discount rate of 8% for the present value calculation. We select 30 years because it is a common time horizon for long-term investments (e.g., treasury bills, fixed mortgages). We select an 8% discount rate to reflect the opportunity cost of "investing" in the BMP rather than in other available low-risk investments such as government bonds. Therefore, if there is no combination of BMP types and capacities that can generate at least an 8% before-tax rate of return over a 30 year time period, we assume the landowner will choose not to participate in the subsidy program and will instead invest elsewhere. Later we conduct a sensitivity analysis of the discount rate

Mathematically, each landowner's optimization problem under the subsidy mechanism is expressed as:

$$\max_{\{I,P\}}\left[\sum_{t=1}^{30}\left(\frac{s\cdot PCPT\left(I+P\right)\cdot R-m_I I-m_P P}{\left(1+r\right)^t}\right)-C_I\left(I\right)-C_P\left(P\right)-L\left(I\right)\right] \qquad (4)$$

Where: I is the installed capacity of infiltration pits and P is the installed capacity of porous pavement; t is time measured in years; r is the annual discount rate; s is the per-unit subsidy; $PCPT$ is percent capture averaged over the five-year hydrological record; R is estimated annual runoff; m_I and m_P are maintenance costs per unit of capacity for each type of BMP; C_I and C_P are construction costs for each type of BMP (each a function of BMP capacity); and L is land cost for infiltration pits. We also impose upper and lower constraints on BMP capacity, both to prevent total BMP area from intruding into the building footprint (or exceeding the total paved area, for porous pavement) and to preclude construction of very small BMPs (no less than 50 square feet for infiltration pits and 100 square feet for porous pavement, but sometimes larger for very large parcels).

After converting this expression and the associated functions and constraints into a form that is amenable to numerical optimization, we end up with a mixed-integer non-linear programming problem that can be solved to obtain each landowner's optimal response to any given subsidy. We solve this problem using the GAMS programming language and the BARON commercial solver package to find the globally optimal solution for each landowner. It is then straightforward to add the subsidy payments and calculate the present value of agency costs and to determine the total capture. Since all costs reported in the paper are from the agency's point of view, a discount rate of 5% was used to calculate present values because this is in the middle of the range of values used by public agencies (Kohyama 2006). This is consistent with the decision to evaluate all costs from the public agency point of view. From a social point of view all profits that accrue to landowners are transfers and would not be counted as costs.

The bidding mechanism is largely based on the same functions and parameter values presented above for the subsidy mechanism. However, compared to the subsidy approach, the bidding mechanism provides landowners with an additional degree of freedom: not only can they specify the attributes of the BMPs, but they also can specify the payments they would require. Therefore, without additional structure, there is no longer a well-defined solution to the landowner's optimization problem. Furthermore, bidding potentially involves strategic behavior by landowners who are competing to have their bids accepted into the program, but who also want to earn excess profit. Despite the incentive to submit lower bids, some landowners may strategically bid above their true BMP placement costs in hopes of earning excess profit. Because the extent of such "bid shading" would be driven by the subjective beliefs and risk preferences of landowners, it is not obvious how landowners will respond to a bidding program and thus how cost-effective a bidding program will be without some additional assumptions about bidding behavior

There is a very large economics literature on mechanism design and auction theory. Latacz-Lohmann and Schilizzi (2005) provide an excellent survey focused on conservation auctions. The authors emphasize that auction theory offers little guidance for conservation auction design due to structural differences between conservation auctions and standard auctions that have been examined in the literature. They also state that empirical studies have produced mixed results, thus highlighting the importance of practical implementation issues in auction design. Space limitations prevent a more complete discussion of the rationale for our chosen bidding mechanism, but we note that its characteristics largely reflect the authors' conclusions. Future work will examine conservation auction theory in more detail.

In our baseline scenario we examine the best possible case where landowners do not attempt to "shade" their bids (however later we relax this assumption and incorporate bid shading in the sensitivity analysis of the discount rate). In other words, we assume competitive bidding drives down the rate of return from the BMP program to that of the best alternative investment (8%), thus generating no excess profit for bidders. (An 8% rate of return is high for safe investments, so it could also be regarded as combining a lower rate of return requirement with some bid shading.) This allows us to specify that any bid must satisfy a zero excess profit condition when the net present value is calculated at an 8% rate of return; however, it does not tell us which of many bids that satisfy this condition will be chosen by each bidder.

Therefore we must specify what constitutes a “good bid” before we can model how bids are generated. If all bidders were submitting bids for a uniform amount of runoff capture, then a good metric would be the bid price: the lower, the better. However, in this case landowners will submit bids for different BMPs based on the characteristics of their land. Therefore we need to specify a metric for ranking bids that involves different BMP capacities and bid prices. To do this, we define an “index function” that converts a bid of the form [infiltration pit capacity, porous pavement capacity, annual payment] into a numerical value with higher values corresponding to “better” bids. We then assume that each landowner submits the bid that maximizes this index function for his/her parcel subject to the zero excess profit condition, and that the regulator ranks all bids by the index values and accepts bids in rank order until the capture target is satisfied.

For any desired level of runoff capture, the ideal index function would induce landowners to submit bids with the same BMP capacities as would be induced by a subsidy that achieves the same level of capture *and* give up all excess profits that would be earned from the subsidy mechanism (i.e., bid their true BMP placement cost). This would allow placement of optimal BMP capacities at each parcel at the lowest possible cost. However, designing and implementing such an ideal index function generally is not possible when the agency has incomplete information. Intuitively, for our case, this is because landowners must be compensated for revealing their private information about land costs. Therefore we implement a simpler index function that encourages landowners to bid relatively large capacities (which the results for our subsidy mechanism reveal to be desirable) and relatively low prices.

Each landowner's optimization problem under the bidding mechanism is expressed as:

$$\max_{\{I,P,S\}}\left[\frac{\left(PCPT\left(I+P\right)\cdot R\right)^{\alpha}}{S}\right] \qquad s.t.\ \sum_{t=1}^{30}\left(\frac{S-m_I I-m_P P}{\left(1+r\right)^{t}}\right)-C_I\left(I\right)-C_P\left(P\right)-L\left(I\right)\geq 0 \tag{5}$$

The term in square brackets is the index function: the numerator is the total capture (with terms defined in Equation (4)) raised to the power α; the denominator is the bid price (a total annual payment rather than per-unit of capture as in the subsidy case). The second line is the zero excess profit condition which acts as a constraint. Setting-up the associated Lagrangian and deriving the first order conditions for a solution shows that α can be selected by the agency to "tune" the index function for different capture goals: a larger value tends to elicit bids for larger BMP capacities and thus better approximates the outcome of a relatively large per-unit subsidy. However because this index function is not ideal, it does not exactly replicate the optimal BMP locations and capacities produced by the subsidy mechanism; but it does provide an incentive for landowners to reduce their bid prices. Therefore, as modeled here, the agency faces a trade-off: departing from the optimal placement and sizing of BMPs tends to increase BMP placement costs and thus increases total agency costs, but competition among bidders tends to reduce excess profits and thus reduces total agency costs. The relative cost-effectiveness of the decentralized incentives is thus an empirical question.

3. Results

We analyze the cost and performance of both mechanisms for our baseline estimates described above and for a range of plausible parameter values described in the sensitivity analysis below. In nearly all cases, the bidding mechanism achieves the desired capture level at considerably less cost than the fixed subsidy. We also compare centralized and incentive-based alternatives and find that a bidding alternative is almost always less expensive than the centralized solution. Finally, we examine the value of runoff infiltration and find that it is a significant proportion of BMP costs.

3.1. Baseline Estimates

Table 6 shows the relative performance of the incentive instruments for different proportions of total runoff capture (Column 1) assuming baseline parameter values. Column 2 shows the minimum BMP placement cost. Column 3 shows the agency cost of achieving the capture proportion with a fixed subsidy. The subsidy is at least 35% more expensive than the lowest achievable cost. The difference between Columns 2 and 3 represents excess profit earned by participating landowners. The difference shown is excess profit from the regulator's perspective (discounted at 5%) rather than from the landowner's perspective (discounted at 8%). Landowners thus perceive the excess profit to be smaller. Columns 4 through 6 give the agency cost of achieving the given level of capture with the different bid indices (i.e., α = 1.0, 1.2, and 1.4, from left to right). The bidding mechanisms have lower costs for the same capture proportion at every level of capture and tend to be substantially more cost-effective at higher levels of capture: bid two is only 71% of the subsidy cost at 45% capture. This is because, in order to achieve a higher capture level, a subsidy provides a higher per-unit payment for all participants whereas a bidding approach raises the payment level only for the marginal participant. Thus the bidding approach approximates the aggregate cost curve better than the subsidy approach, particularly at high capture levels. Among the bidding mechanisms, bid two has the lowest average cost across the three capture percentages and thus is arguably the most preferred if one had to select a single mechanism for a range of capture values; therefore we use it below in our baseline comparison with a centralized approach.

The key issue in deciding when centralized or decentralized alternatives perform better is whether the land cost savings of a decentralized approach outweigh the capacity cost savings due to the economies of scale of centralized facilities. Table 7 shows that the land cost savings of an incentive-based system outweigh the economies of scale advantages of a centralized system. Bid two is significantly less expensive than either a centralized infiltration trench or infiltration basin for capture levels between 10 and 45 percent of total runoff for the baseline parameter values. The cost advantage is greatest at lower capture levels where bid two is less than half the cost of an infiltration trench (the most cost-effective centralized approach). At higher capture levels the cost difference narrows, but even at 45% capture the bid two cost is only 61% of the costs of the infiltration trench. Of course it is unlikely that a centralized facility could drain 231 ha in the Los Angeles area as is assumed in this analysis. For instance, the metals TMDL assumed that BMPs would be sized to drain an average of only 2.02 ha each (RWQCB-LA 2005). This implies that the cost advantage of a decentralized system would generally be greater than this comparison implies.

The land costs savings are the major factor in making an incentive based approach more cost-effective. Table 7 shows that construction and maintenance costs are much higher for bid two than the infiltration trench, as we expect given the greater economies of scale for the centralized alternatives. However, the land cost savings more than make up the difference. This implies that some sort of incentive-based mechanism is crucial for deploying parcel-level, decentralized BMPs. A traditional command-and-control regulatory approach might force landowners to displace high-value land uses, which would eliminate the cost advantage of decentralized BMPs.

Net costs of infiltration approaches are further reduced if one considers the value of the infiltrated water. Our analysis considers a range of water values: 1) a low value of \$0.40/m^3 from The Los Angeles Department of Water and Power; 2) a mid-range value of \$0.65/m^3 reflecting historical water supply risks from Cutter (2007); and 3) a high value of \$0.81/m^3 reflecting future drought risks due to climate change (Seager et al. 2007). For bid two, we then calculate the present value of infiltrated water for a range of capture proportions using the average yearly infiltration modeled over the 2001-2006 precipitation record. At low capture levels and with the highest water values infiltration benefits are 38.5% of costs (see Table 8). This percentage declines with the capture percentage due to the increasing marginal cost of capture.

3.2 Sensitivity Analysis

We construct plausible ranges for important parameters to test the robustness of our finding that bidding is more cost-effective than a subsidy or a centralized facility. We use a quantile regression approach to Equation (1) to predict the 25th and 75th percentile of construction costs for infiltration pits. We also establish a likely range of costs for porous pavement in our study area: \$70/m^2 to \$96.88/m^2. For centralized alternatives we find that our baseline estimates in Equations (2) and (3) are low compared to available Los Angeles data, so we use multiples of these estimates to establish mid-range and high cost estimates that better reflect the Los Angeles data (note that this means our baseline cost comparison in Table 7 favors centralized treatment). We also determine a range of values for the required landowner rate of return (5% and 11%), with the higher value incorporating our best estimate of the amount of bid shading we could expect from landowners who would normally demand an 8% return. And we consider a range of BMP infiltration rates: 25.4 mm/hr and 215.9 mm/hr. A more detailed explanation and justification for each of these ranges is given in appendix B (see http://www.envisci.ucr.edu/faculty/baerenklau.html.)

For each of three capture levels, we calculate agency costs for the subsidy and bidding mechanisms given each of the 16 possible combinations of decentralized BMP costs, required rate of return, and infiltration rate. Table 9 reports the cost difference between the subsidy and bidding approaches for the various combinations of BMP costs and infiltration rates and for each capture level. At 10% capture subsidies are sometimes superior to a given bid index (denoted by negative table entries) but never superior to all bid indices. At the higher capture levels bidding is nearly always more cost-effective except for one case. A subsidy is never more cost effective than bid two. This is consistent with the findings reported in Table 6 and demonstrates the robustness of our base case results.

We use the same simulations for a sensitivity analysis of the centralized and decentralized cost comparison (reported for the base case in Table 7). These results are summarized in Table 10, again for the 16 possible combinations of decentralized BMP costs, required rate of return, and infiltration rate. Each cell contains the difference between the infiltration trench cost and the mean of the three bid costs (i.e., $\alpha = 1.0$, 1.2, and 1.4) for the desired level of runoff capture. Negative numbers indicate that the infiltration trench is less expensive. This situation occurs in only 6 of 144 cases, and only when decentralized costs are set at high levels. In all other cases, bidding on average has lower costs, often by substantial amounts. The sensitivity analysis suggests that an incentive-based approach will be significantly cheaper than centralized facilities in nearly all situations.

4. Conclusion

This research shows that a decentralized incentive-based strategy that effectively targets BMPs at areas with low land use value is likely to be a cost-effective approach for reducing urban runoff. Whether an incentive-based strategy is more cost-effective than a centralized approach ultimately depends on whether the land cost advantage of incentive-based BMPs outweighs the economies of scale advantage of a centralized facility. We find that this trade-off favors decentralized incentive-based BMPs in all but very few cases, and only when decentralized costs are at the high end of the range we consider. Construction and maintenance costs are lower for the centralized alternative due to economies of scale, but land costs are much greater so the incentive-based approach is overall more cost-effective for our study area. Notably, realizing the land cost advantage of decentralized BMPs requires a mechanism for placing BMPs on areas with low land-use value, something which a command-and-control regulatory approach is unlikely to do.

This paper does not attempt to estimate a key benefit of incentive-based approaches –by rewarding the outcome rather than the technology incentive-based systems are expected to encourage technological advances. In a system such as we propose, where the incentive payment is based on the modeled performance of the BMP, there would need to be a process to certify and model new types of BMPs. A third party organization with academic, regulatory, and stormwater consulting firm representatives could perform this function. Also, our methodology does not fully capture the information benefits of a bidding system. In particular we do not directly model the landowner's opportunity cost of time and the greater the heterogeneity in this cost the more cost-effective bidding is likely to be relative to a subsidy.

We also compare bidding and subsidy approaches to implementing a decentralized, incentive-based system. A subsidy system implements the optimal BMP placement, but allows for excess profits by landowners. A bid system eliminates the excess profits at the cost of non-optimal BMP placement. We find that a well-designed bid index (e.g., bid two) is always more cost-effective than subsidies, and that the cost advantage grows with the capture percentage. This occurs because the bidding approach achieves greater capture by increasing payment to the marginal participant while the subsidy approach raises the capture level by increasing the payment to all participants. The analysis suggests that bidding is a better approach when the policy aim is to capture a significant portion of runoff.

There are costs of centralized and incentive-based systems that are not included in this analysis. Monitoring and enforcement costs may be higher with a decentralized alternative but we cannot estimate the cost differential. The cost curves for centralized infrastructure assume that the local government could purchase large undeveloped parcels in a location that could drain a large area without the need for additional conveyance infrastructure. It is unlikely that all of these conditions could be fulfilled in many areas in Los Angeles or any other heavily urbanized area. A survey of possible infiltration locations and characteristics in Los Angeles could give more realistic estimates of drainage areas and conveyance costs but such work is beyond the scope of this article.

Incentive-based BMPs will not provide a solution to many runoff problems. They are likely not cost-effective for single-family houses due to very limited economies of scale and the expense of monitoring and enforcement across the large number of parcels this would entail.

Also, on-parcel BMPs do not capture precipitation which falls directly on streets. Because single-family parcels and transportation corridors occupy significant portions of total land area, an incentive-based approach would necessarily complement centralized facilities that would still manage runoff from a large area.

However, it does appear that incentive-based BMPs would be a cost-effective way to either reduce the size of centralized facilities or eliminate the need for them in heavily commercial, industrial, or retail areas. An evaluation of the optimal mix of centralized and incentive-based, decentralized approaches is an interesting topic that is beyond the scope of this paper but will be an avenue for future research.

Notation

$\gamma_1,\ldots,\gamma_9$	constants for infiltration pit cost equation.
I	installed capacity of infiltration pits, m^3.
P	installed capacity of porous pavement, m^3.
t	time period, yr.
r	annual discount rate.
s	subsidy per unit of expected annual runoff capture (fixed subsidy mechanism), $\$/m^3$.
$PCPT$	expected percentage of annual runoff capture.
R	expected annual runoff, m^3.
m_I	expected annual maintenance cost per unit of capacity for infiltration pits, $\$/m^3$.
m_P	expected annual maintenance cost per unit of capacity for porous pavement, $\$/m^3$.
C_I	construction cost for infiltration pits, \$.
C_P	construction cost for porous pavement, \$.
L	land cost for infiltration pits, \$.
S	annual BMP payment (bidding mechanism), \$.
α	parameter selected by the agency to influence bid types.

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References

Arabi, M., R. S. Govindaraju and M. M. Hantush (2006), Cost-effective allocation of watershed management practices using a genetic algorithm, *Water Resour. Res., 42*(10), 14.

Arnold, C. L. and C. J. Gibbons (1996), Impervious surface coverage - The emergence of a key environmental indicator, *J. Am. Plan. Assoc., 62*(2), 243-258.

Bekele, E. G. and J. W. Nicklow (2005), Multiobjective management of ecosystem services by integrative watershed modeling and evolutionary algorithms, *Water Resour. Res., 41*(10), 10.

Caltrans (2001). Third Party BMP Retrofit Pilot Study Cost Review, Prepared for Caltrans Environmental Program, Office of Environmental Engineering.

CLA (2004), Sun Valley Watershed Management Plan, County of Los Angeles, Department of Public Works, Alhambra, CA.

Cutter, W. B. (2007), Valuing Groundwater Recharge in an Urban Context, *Land Econ., 83*(2).

DeWoody, A.E. (2007), Do Parcel-Level Stormwater Infiltration Systems Produce Positive Net Benefits in an Urban Setting? A Los Angeles Case Study to Optimize Social Benefits with Respect to System Capacity, MS Thesis, University of California, Riverside, CA.

Doll, A., P.F. Scodari, and G. Lindsey (1999), Credits as economic incentives for on-site stormwater management: issues and examples, *Proceedings of the U.S. Environmental Protection Agency National Conference on Retrofit Opportunities for Water Resource Protection in Urban Environments*. 1999. EPA/625/R-99/002, pp. 13–117, July.

ENR (2007), First Quarterly Cost Report, Engineering News Record, McGraw Hill Construction, pp. 1-47. 2007, New York, NY, March,.

FHA (2003), Storm water Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring, Federal Highway Administration, Washington, D.C.

Ferguson, B. K. (1994), Stormwater infiltration, Lewis Publishers, Boca Raton.

Ferguson, B. K. (1998), *Introduction to Stormwater: Concept, Purpose, Design*, John Wiley and Sons, New York, NY.

Heaney, J. P., Sample, D., and L. Wright (2002), Costs of Urban Stormwater Control, Office of Research and Development, US EPA, EPA/600/R-02/021, Washington. D.C.

HEC (1977), STORM-Storage, Treatment, Overflow, Runoff Model: User's Manual, Hydrologic Engineering Center, U.S. Army Corps of Engineers, 1-178, Davis, CA.

IPCC (2007), Climate Change 2007: Impacts, Adaptation, and Vulnerability, Intergovernmental Panel on Climate Change, UN Environmental Program, Brussels.

Kohyama, H (2006), Selecting Discount Rates for Budgetary Purposes. Harvard Law School, Federal Budget Policy Seminar, Briefing Paper No. 29. 1-37, Cambridge MA, 22 May.

Latacz-Lohmann, U. and S.Schilizzi (2007), Auctions for Conservation Contracts: A Review of the Theoretical and Empirical Literature. 2005, Report to the Scottish Executive Environment and Rural Affairs Department, 24 May.

Lee, J. G., J. P. Heaney and F. H. Lai (2005), Optimization of integrated urban wet-weather control strategies, *J. Water Resour. Plan. Manage. -ASCE, 131*(4), 307-315.

Muleta, M. K. and J. W. Nicklow (2005), Decision support for watershed management using evolutionary algorithms, *J. Water Resour. Plan. Manage. -ASCE, 131*(1), 35-44.

Perez-Pedini, C., J. F. Limbrunner and R. M. Vogel (2005), Optimal location of infiltration-based best management practices for storm water management, *J. Water Resour. Plan. Manage. -ASCE, 131*(6), 441-448.

Roy, A., M. Clagett, T. Hoagland, M. Morrison, W. Shuster, J. Templeton, H. Thurston, and H. Cabezas (2006), Decentralized Stormwater Management: Retrofitting Homes, Restoring Watersheds, Poster presentation, USEPA Science Forum, Washington D.C., 16-18 May.

RWQCB-LA (2005), Total Maximum Daily Loads for Metals: Los Angeles River and Tributaries, California Regional Water Quality Control Board, L. A. R. a. U. S. E. P. A. R. 9.

Seager, R., M. F. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. H. Li, J. Velez and N. Naik (2007), Model projections of an imminent transition to a more arid climate in southwestern North America, *Science, 316*(5828), 1181-1184.

SWRPC (1991), Costs of Urban Nonpoint Water Pollution Control Measures, Southeastern Wisconsin Regional Planning Commission, Technical Report No. 31, http://www.sewrpc.org

Silberberg, E. (1990), *The structure of economics : a mathematical analysis*, McGraw-Hill Pub. Co., New York, NY.

Srivastava, P., J. M. Hamlett and P. D. Robillard (2003), Watershed optimization of agricultural best management practices: Continuous simulation versus design storms, *J. Am. Water Resour. Assoc., 39*(5), 1043-1054.

Thurston, H. W., H. C. Goddard, D. Szlag and B. Lemberg (2003), Controlling storm-water runoff with tradable allowances for impervious surfaces, *J. Water Resour. Plan. Manage. -ASCE, 129*(5), 409-418.

Thurston, H. W.(2006), Opportunity costs of residential best management practices for stormwater runoff control, *J. Water Resour. Plan. Manage. -ASCE, 132*(2), 89-96.

USEPA (1999), Stormwater Technology Fact Sheet, U.S.Environmental Protection Agency and Office of Water, EPA 832-F-99-019. 1999. Washington, D.C.

Tables

Table 1: Estimated Parcel Characteristics for Sun Valley Study Area (non-single-family parcels only).

	Mean Area (square meters)				Proportion of Area			
Land Use	Parking	Roof	Other	Total	Parking	Roof	Other	Obs.
Duplex	136	165	283	584	0.23	0.28	0.49	51
Triplex	162	206	284	651	0.25	0.32	0.44	21
Quadplex	195	219	238	652	0.30	0.34	0.37	36
5plex	478	1,430	184	2,092	0.23	0.68	0.09	139
Commercial1	761	251	266	1,278	0.60	0.20	0.21	122
Commercial2	799	380	427	1,606	0.50	0.24	0.27	125
Industrial	888	846	2,038	3,773	0.24	0.22	0.54	424
Total	712	715	1,094	2,521	0.38	0.36	0.26	918

Table 2: Baseline Parameter Values for SS STORM.

Parameter	Value	Units
Infiltration Rate	76.2[a]	mm/hour
Infiltration Pit Depth	1.524	Meters
Infiltration Pit Void Proportion	0.4[b]	-
Porous Pavement Depth	0.3048	Meters
Porous Pavement Void Proportion	0.22[c]	-
Depression Storage-Roof	2.7	Mm
Depression Storage-Pavement	10	Mm
Depression Storage-permeable	13.5	Mm

[a] Based on sandy soil of the site

[b] Ferguson (1994)

[c] www.cncement.org gives a range of .15-.25.

Table 3: Baseline Centralized Facility Parameters for SS STORM.

Parameter	Value	Units
Infiltration Rate	76.2[a]	mm/hour
Infiltration Trench Depth	1.524	Meters
Infiltration Trench Void Proportion	0.4	-
Infiltration Basin Depth	0.762	Meters
Infiltration Basin Void Proportion	1	-
Depression Storage-Roof	2.7	mm
Depression Storage-Pavement	10	mm
Depression Storage-permeable	13.5	mm

[a] Based on sandy soil of the site

Table 4: Estimated Parking Land Use Costs for Sun Valley Parcels.

	($/Square Meter)	
Land Use	Mean	Median
Duplex	$0.65	$0.00
Triplex	7.86	0.00
Quadplex	32.08	31.75
5plex	330.56	315.60
Commercial1	251.23	126.69
Commercial2	296.44	130.57
Industrial	272.00	244.77
Total	250.91	203.22

Table 5: Costs for Vacant Land in Los Angeles.

($/m^2)

		Land Type*			
		Commercial	Industrial	Residential	Total
Geographic Area					
Southwest Los Angeles County					
	($/Square Meter)	$1,344	$493	$1,801	$1,385
	Observations	3,100	1,033	2,519	6,652
San Fernando West of Pasadena					
	($/Square Meter)	717	348	747	696
	Observations	721	226	1,270	2,217
San Gabriel Area					
	($/Square Meter)	637	280	659	580
	Observations	1,518	517	861	2,895
Total					
	($/Square Meter)	1,058	413	1,301	1,057
	Observations	5,339	1,776	4,650	11,765

* Vacant land sales listed in the Costar sales database from 2003-2005, adjusted to 2005 dollars.

Table 6: Cost of Subsidy and Bid Incentives by Capture Proportion for Baseline Parameter Values.

		Public Cost ($ Millions)*			
Capture Percentage	Regulator minimum cost ($ Millions)	Subsidy	Bid 1 (α=1.0)	Bid 2 (α=1.2)	Bid 3 (α=1.4)
10%	0.99	1.34	1.17	1.27	1.27
25%	2.96	4.60	3.85	3.87	3.86
45%	6.61	12.47	9.15	8.82	8.87

* The public costs are not upfront, but instead are annuitized over 30 years.

Table 7: Cost Comparison of Bidding Incentive and Centralized BMP Approach. ($ Millions)

BMP	% Capture	Construction	Maintenance	*Subtotal*	Land Cost	Opportunity Cost*	**Total Cost**
Infiltration Trench	10	0.178	0.236	*0.414*	1.911	0.000	2.325
	25	0.342	0.453	*0.795*	5.386	0.000	6.181
	45	0.546	0.724	*1.270*	11.336	0.000	12.606
Infiltration Basin	10	0.604	0.624	*1.228*	1.749	0.000	2.977
	25	1.252	1.293	*2.546*	5.028	0.000	7.574
	45	2.071	2.140	*4.211*	10.427	0.000	14.638
Bid 2	10	0.483	0.477	*0.959*	0.099	0.213	1.271
	25	1.881	1.220	*3.101*	0.099	0.670	3.870
	45	4.736	2.262	*6.999*	0.208	1.658	8.865

* Opportunity cost represents payments to landowners in excess of construction, maintenance and land costs needed to achieve the required rate of return on investment (8%).

Table 8: Value of Infiltrating Runoff.

		Water Value ($\$/m^3$)					
		$0.405		$0.61		$0.81	
% Capture	Infiltration (m^3/Year)	Value ($M)	Value/ Public Cost	Value ($M)	Value/ Public Cost	Value ($M)	Value/ Public Cost
10	39,326	$0.245	19.2%	$0.393	30.9%	$0.490	38.5%
25	96,955	$0.603	15.6%	$0.969	25.0%	$1.207	31.2%
45	174,096	$1.083	12.3%	$1.740	19.7%	$2.168	24.6%

Table 9: Subsidy Less Bid Cost Across BMP Cost Ranges and Infiltration Rates. ($ Millions)

			Decentralized Costs*							
Bid Index	Infiltration Rate	% Capture	HHH	HHL	HLH	HLL	LHH	LHL	LLH	LLL
1										
	High									
		10%	0.103	0.102	0.103	0.103	0.124	0.040	0.111	0.111
		25%	0.756	0.328	0.631	0.727	0.325	0.114	0.378	0.394
		45%	-	-	2.388	2.060	-	-	1.320	1.082
	Low									
		10%	0.146	-0.154	0.094	0.094	-0.087	-0.221	0.069	0.076
		25%	0.745	0.452	0.647	0.670	0.384	-	0.421	0.423
		45%	-	-	1.941	1.923	-	-	1.496	-
2										
	High									
		10%	0.106	0.108	0.114	0.114	0.122	0.021	0.112	0.112
		25%	0.846	0.456	0.699	0.758	0.360	0.256	0.401	0.439
		45%	2.508	2.066	2.703	2.382	1.761	1.365	1.576	1.365
	Low									
		10%	0.218	0.304	0.068	0.068	0.001	0.056	0.042	0.053
		25%	1.515	1.714	0.727	0.736	1.154	0.783	0.508	0.510
		45%	7.308	4.449	3.460	3.315	3.938	2.357	2.528	2.631
3										
	High									
		10%	-0.004	-0.012	0.075	0.075	0.081	-0.013	0.103	0.019
		25%	0.864	0.169	0.543	0.725	0.316	0.113	0.384	0.439
		45%	2.391	1.985	2.728	2.429	1.710	1.389	1.628	1.392
	Low									
		10%	-0.040	-0.088	-0.003	-0.003	-0.098	-0.174	-0.190	-0.178
		25%	0.725	1.630	0.635	0.310	0.962	0.636	-0.131	0.325
		45%	7.025	4.634	3.141	3.663	3.942	2.031	2.525	2.832

* The first letter refers to the discount rate (H=11%, L=5%). The second letter refers to the infiltration pit cost (H=75th percentile of costs, L=25th percentile). The third letter refers to the porous pavement costs (H=$96.88 m^2, L=$70 m^2). Under some conditions, bid one does not provide a strong enough incentive to achieve the higher levels of capture; these are denoted by empty cells.

Table 10: Cost Comparison of Bidding Incentive and Centralized BMP Approach. Mean of Infiltration Trench Less Bid Costs. ($ Millions)

			Decentralized Costs*							
Centralized Costs	Infiltration Rate	% Capture	HHH	HHL	HLH	HLL	LHH	LHL	LLH	LLL
Low										
	High									
		10%	0.02	0.07	0.76	0.76	0.43	0.48	0.85	0.82
		25%	-0.55	-0.16	1.51	1.53	0.79	1.13	1.91	1.94
		45%	-1.49	-0.18	2.15	2.31	1.52	2.44	3.31	3.49
	Low									
		10%	0.85	0.76	2.85	2.85	1.86	1.82	3.06	3.06
		25%	1.41	1.55	7.48	7.36	4.76	5.04	8.17	8.32
		45%	0.83	2.27	12.83	13.04	8.68	9.92	15.34	15.86
Mid										
	High									
		10%	0.28	0.33	1.02	1.02	0.70	0.75	1.11	1.09
		25%	-0.05	0.34	2.02	2.03	1.29	1.64	2.42	2.45
		45%	-0.69	0.62	2.95	3.11	2.32	3.24	4.11	4.29
	Low									
		10%	1.46	1.37	3.46	3.46	2.47	2.43	3.67	3.67
		25%	2.61	2.75	8.68	8.56	5.95	6.24	9.36	9.52
		45%	2.73	4.17	14.73	14.94	10.58	11.81	17.24	17.76
High										
	High									
		10%	1.27	1.32	2.01	2.01	1.69	1.74	2.10	2.08
		25%	1.84	2.23	3.90	3.92	3.18	3.52	4.30	4.33
		45%	2.32	3.63	5.96	6.12	5.34	6.25	7.12	7.30
	Low									
		10%	3.75	3.66	5.75	5.75	4.76	4.72	5.96	5.96
		25%	7.09	7.23	13.16	13.04	10.44	10.72	13.85	14.00
		45%	9.84	11.28	21.83	22.04	17.68	18.92	24.34	24.86

* The first letter refers to the discount rate (H=11%, L=5%). The second letter refers to the infiltration pit cost (H=75th percentile of costs, L=25th percentile). The third letter refers to the porous pavement costs (H=\$96.88 m^2, L=\$70 m^2).

Figures

Figure 1: Map of Sun Valley Watershed:

See attached file.

Figure 2: U-Shaped Marginal Cost.