Police Stations for instant reaction: A Maximal Homicide Coverage Location Problem

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Abstract. The probability of facing prison is one of the major factors that deters individuals from committing crimes. The degree of impact of this variable is affected both by the severity of penalties, and by the probability of being caught, which largely depends on the level of police coverage in the jurisdiction. Thus, we consider a maximal covering location problem where the objective is to provide maximal coverage of weighted potential homicide spots through the construction of police stations for instant reaction, subject to a budget constraint. Our empirical application is performed in Medellín (Colombia), one of the cities with the highest homicide rate in the World. Specifically , we call the Google Maps Application Programming Interface (API) to estimate average travelling time between police stations and criminal spots, then we use a Simulated Annealing algorithm to find the best feasible allocation of stations subject to a set of suggested budgets. We confirm that the maximum coverage follows a diminishing marginal process over the budget.

1 Introduction

Extended periods of violence entail large costs on society; in addition to losses in quality and length of life, enormous amounts of fiscal and private spending on unproductive activities such as defense, criminal justice and prison systems, and destruction of physical and human capital, crime and violence create uncertainty about the future, restricting investment and innovation, which ends up bringing negative effects on growth and productivity.

Research such as that of Soares (2006) suggests that, when considering some intangibles, the average cost of violence for Latin America may be as high as 14 percent of GDP, an estimate larger than for the other regions. This figure could be particularly important in countries exposed to long periods of conflict and high crime rates such as Colombia.

Given the high relevance of social interactions and individual decisions, and the high costs that criminals acts bring, the detail in the explanation, causes and consequences of this important issue has become a matter of priority analysis for the society as a whole.

An early analysis from an economic point of view in this field was that of Becker (1968), which allowed us to understand the crime as part of optimal microeconomic decisions, giving theoretical support to this social problem, and unleashing a series of empirical studies that seek to deepen this social conflict and have made a much more disaggregated examination.

Some researchers (Ackerman and Murray (2004), Bourguignon (1999) and Becker (1968)) have found that socioeconomic conditions of individuals have an important influence on the

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decision to commit a crime, then societies with higher levels of poverty, exclusion, income inequality, among others, tend to have higher crime rates. However, the change in these variables usually occurs gradually and the effects of interventions in these fields may only be seen in the long run.

Given the slow pace of socioeconomic interventions to reduce violence, different interventions are then necessary to relieve the problem in the short term. The work of Becker (1968) allows seeing that when committing a crime individuals face a situation that offers some benefits (economic in most cases), but entails some costs (both moral costs, and the punishment they could face). As the costs get higher, for example due to a higher probability of being punished or a stronger severity of the penalties that criminal might face, the individual will have less incentive to commit the crime.

In that sense, approaches such as Lee and McCrary (2009) and Levitt (1998) conclude that to the extent that penalties are higher, the lower the crime rate is, an effect that is consolidated by two mechanisms, the first called the deterrence effect, which means that more serious sentences deter potential criminals to carry out their act, and the incapacitation effect because the more time those who committed crimes spend in prison, the larger is the time it takes them to re-offend.

In addition, Di Tella and Schargrodsky (2004) and Chalflin and McCrary (2013) find positive and significant effects of the presence of police force on crime reduction, with much stronger effects on violent crimes than in property crimes.

In summary, literature suggests that criminal behavior in the long run is more strongly determined by the socioeconomic conditions of individuals, so that circumstances such as poverty, exclusion, income inequality, lack of government presence and poor provision of social services have an influence on violence. Meanwhile, in a shorter period of time, law enforcement instruments become more important, and in this vein the severity of penalties for crimes and high capture probabilities, ensured by a greater proximity of the police, create incentives for individuals on the decision whether to commit a crime or not.

Recent research (Cozens (2008), Andresen (2006) and Wang et al. (2013)) also suggests that criminal activity is concentrated at specific points within cities, which has led to the implementation of new methodologies and aproaches.These studies indicate that when making any analysis of criminal acts, it is important to consider the structure of where the incident occurred, as this social problem tends to cluster geographically.

In that line Ackerman and Murray (2004) propose an analytic-descriptive methodology to study crime in cities: identify problematic neighborhoods and identify problematic areas within neighborhoods ("hot spots"), then evaluate its relationship with the characteristics of the place (socioeconomic, land use and environmental demographic structures) and the clustering of crime. Analyzing the case of Lima, Ohio (a small city with a picky crime problem), they found that the pattern of violent crime has remained remarkably constant in Lima since 1998 and is concentrated in census tracts with low socioeconomic status. They note that this methodology allows to approximate efficient spatial allocation of law enforcement agencies in order to counter the criminal acts[1].

This latter part is the main motivation for this research, because once the criminal hot spots are identified, an efficient location of the law enforcement agencies can ensure greater coverage of these problematic clusters, generating a greater impact in reducing crime rates.

In this research, we consider a maximal homicide covering location problem where the objective is to provide maximal coverage of weighted potential criminal spots in Medellín (Colombia), one of the cities with the highest crime rate in the World, subject to a constraint given by the budget for the construction of Police agencies. We use a Simulated Annealing algorithm to find the best feasible Allocation of police stations subject to a set of suggested budgets, and we confirm that the maximum coverage follows a diminishing marginal process over the budget.

The rest of the paper is organized as follows. In Section 2 we conduct a short contextualizing of the phenomenon of crime in Colombia emphasizing Medellín (Colombia). In Section 3 we make a brief description of the Police Stations, Colombian Police enforcement agencies. In Section 4 we discuss the strategy to solve the maximal covering location problem. Section 5 describes the data and procedures performed in more detail. Section 6 Concludes.

2 Crime in Colombia and Medellín

High rates of homicide and crime in Colombia and their persistence during the last decades is a worrisome fact, and its dynamics causes and effects have attracted numerous studies over the years. Although in the decades of 50 and 60 took place in the country an era called "La época de la Violencia" (The era of violence), a phenomenon that finds its origins in political and institutional disputes, in which some guerrilla groups and groups outside the law were formed, as the missing M19 and others still in force as the FARC and ELN; it is only from the mid-70s when, in a simultaneous process of strengthening of drug trafficking organizations in the country, variables such as the homicide rate began a rapid ascent, passing from averages of 16 murders per hundred thousand in the first half of the 70s to peaks of even 89 homicides per hundred thousand in early 90s.

As highlighted in Sánchez and nez (2001) comparing these figures allowed to demonstrate the seriousness of the problem, in fact when performing a comparison considering violent countries like Brazil and Mexico, it is found that homicide rates in Colombia were four times those of these two countries in the region, seven times that of the United States and about seventy times that of European countries. Despite the dismantling of major drug cartels in the early nineties and a subsequent drop in homicide rates to less exorbitant indexes, levels of

[1] Di Tella and Schargrodsky (2004) find in their research that the police forces had a local effect with no significative impact outside the area in which the police was allocated, then a correct allocation of these units is of fundamental importance.

violence remained higher than desired, yet presenting persistent cycles with a recrudescence of such indicators.

Medellín's case has not been out of the national reality, Giraldo (2008) explained how variations in the homicide rate in the city have evolved in line with the national conflict behavior. So in the late 80's, the increase in homicides responded to the narcoterrorism onslaught, situation that also explains much of the behavior of the index during the first years of the 90's. Giraldo (2008) stated that at the end of the 90s and beginning of the century, violence in the city was associated with urban guerrilla and paramilitary, central government neglect of the phenomenon that was occurring in cities and the loss of security monopoly by the local government. Similarly, decreases in this variable are also associated with central government actions, such as the dismantling of the Medellín cartel in the mid-90s, urban intervention actions as the eradicating of guerrillas in the western sector of the city through the "Orion Operation" in late 2002, and the subsequent demobilization of the Paramilitary "Bloque Cacique Nutibara" with an extensive control of criminal activities in the city for that date.

Medina et al. (2011) also enhanced the high correlation in the evolution of crime nationally, and the three main cities (Bogotá, Medellín and Cali), stating that confrontations with illegal groups and drug trafficking organizations, have been crucial (in a quite synchronized form) in the variation of national homicide rates in particular in the city of Medellín.

By focusing on the city of Medellín, Medina et al. (2011) detailed that, despite the demise of Pablo Escobar and the Medellín Cartel in the 90s, the capacity for reinvention of drug trafficking groups, and the ability to achieve their objectives through violent means has allowed various groups involved in this activity, appear and disappear sequentially in the context of the city without sighted no definitive solution.

According to Medina et al. (2011) despite the high costs that the constant presence of illegal armed and drug-related groups in recent decades have brought to the city, affecting not only dimensions traditionally analyzed as life expectancy, but also aspects related to inhabitants life satisfaction, the city seems to have used to the violent conditions imposed by organized crime.

Although the various phenomena of drug trafficking groups operating outside law, and the evolution of crime rates show a high correlation and possible causality in this regard, numerous studies have tried to ascertain the actual causes of crime in the country and particularly the city of Medellín. For example, Sánchez and nez (2001) found that for seven cities of the country, the main explanation of the increase in the homicide rate is the increase in drug trafficking and, in a lesser extent, the judicial system malfunction. In the particular case of Medellín, drug phenomenon explains about 80% of the increase in the homicide rate in the 80s. In making estimates at municipality panel level, they also found that variables such as poverty, inequality, political participation, presence of armed groups, drug trafficking and inefficiency of justice is also highly related to the homicide rate.

According to these authors, the presence of illegal armed groups, the inefficiency of the judicial system, the intensity of interaction between armed and drug trafficking groups explains about 90% of the differences between the municipalities with highest rates of homicide and those whit the lowest rates (highest and lowest quintile, respectively) and between 3% and 13% is explained by variables such as poverty, inequality, political exclusion and poor access to education.

Bonilla (2009) also contributed to the discussion finding that the change in the composition of the population pushed up the murder rate, although this effect is apparently not very important because it explains only 13.5% of total homicides increase. The percentage is greatly reduced when controlling by variables such as time fixed effects and individuals age. Thus, the author concluded that changes in the homicide rate in recent years have little correlation with demographic changes.

When analyzing the effect that variables such as household income and inequality had on crime, Bourguignon et al. (2003) found that the part of the population whose living standards are 80% below the average (5 or 6 poorest deciles aproximately) are more related to the determination of the crime. Thus, changes in the distribution of income that do not affect the population that is above that threshold will not influence the crime rate.

In this sense, Posada and Montenegro (1994) did a department-level analysis which shows that poverty-related variables do not cause homicidal violence, finding even a negative relationship between the two variables, which in turn indicated that the increase in the rate of murders was associated with output growth, social wealth increase and a weak judicial system. Finally, the authors highlighted the existence of a threshold where the increase in crime affects investment and saving and reduce economic growth.

Although, as in the international literature, most of the studies in Colombia point to socioeconomic conditions as one of the main determinants of crime in the long term, some actions are necesary to face the problem in the short term, increasing individual costs for those who commit crimes.

Thus, and following the work of Lee and McCrary (2009) and Levitt (1998), Guarï¿½n et al. (2013) took advantage of the discontinuity in punishment at age 18 to assess if that change has a deterrent effect on arrests, finding important deterrence an incapacitation effects of punishment especially on those crimes related to drug consumption and trafficking. Then, the costs associated with a greater punishment deters criminals in the city of Medellín.

Following the same logic used above and explained in the international literature, higher levels of police coverage will be associated with higher odds of capture, and therefore with higher costs of committing a crime. The police presence to address criminal phenomena immediately in the city is given by the law enforcement agencies called CAI that will be presented bellow.

3 A brief description of the CAIs

As described in Policia (2009), a police station for instant reaction (Spanish: Comando de Atención Inmediata, or CAI) is one of the lowest jurisdiction police unit, strategically located on the urban perimeters of municipalities, towns, slums or neighborhoods of the major Colombian cities which have this territorial division, and is responsible for guiding and strengthening the urban surveillance made by the National Police, protecting the citizens rights and freedom. Medellín, as the second largest city of the country, has also in its terriotory this kind of police units.

The first CAIs in the city of Medellín were created in 1987, in line with the community integration policies implemented by the National Police, with the responsibility of ensuring the safety of its jurisdiction and timely attending the requirements of its inhabitants. As also indicated in Policia (2009), its location reflects strategic factors previously defined as: high traffic streets, easy access for citizens, industrial, residential and commercial development centers and city hotspots that have the highest crime rates.

Policia (2009) also indicated how the creation of these commands obeyed to the need of decentralizing the services of the regular police stations, allowing operational autonomy based on the changes in the traditional system of common surveillance by assigning security responsibility to the commanders of each CAI jurisdiction.

However, a few years after its creation, during the direct confrontation of Pablo Escobar and the group "Los Extraditables"[2] with Colombian police that took place especially in Medellín, the CAIs became into an usual Narcoterrorism target, suffering various kind of attacks ranging from armed harassment to attacks with grenades and dynamite. These facts and the connivance of some members of the CAIs with criminal gangs, generated the diactivation of these facilities.

A decade after its closure, and in view of having overcome the main circumstances that led to this, municipal government took up new efforts seeking to revive the CAIs figure, decentralizing services stations and looking for greater effectiveness in addressing security issues that plagued the city, giving as a result the launching of 23 CAIs in different neighborhoods units of the city.

Each modern CAI must have, a computer, a laptop for the vehicles, a printer, a camera, bulletproof vest level 3 (one by police), metal handcuffs (one by police), a mechanical equipment (in case of fire, confined space rescues, rescue calls for help, etc.) A mirror to check underneath vehicles, among other things. To Build a CAI an area of 100 square meters is needed and it costs on average 60 thousand dollars, excluding the cost of land which has a large variation throughout the city.

4 Methodology

An important policy objective would be to analyze an optimal location of CAIs such that generates the maximun coverage of the clusters with the highest homicide rates subject to a

[2] Group of drug dealers who opposed the extradition of Colombians.

budget constraint that takes into consideration the price level per square meter over the city of Medellín.

The above is a Maximun Coverage Location Problem (MCLP), in which one seeks a set of locations for a number of facilities on a space in such a way that a covere target is maximized. The MCLP was first introduced by Church and Revelle (1974) and since then, many other extensions and variations to the original research have been made.

Many applications of the MCPL have been implemented to determine the optimum location of different facilities based on the distribution of potential consumers, being used for example for the allocation of schools, parks, gas stations and emergency facilities such as fire stations, hospitals and police units.

The variation in approaches is often around the type of implemented parameters (deterministic or probabilistic), the type of solution (Exact and Heuristic) and the solution procedure, where the problems with deterministic parameters and heuristic solutions found by using Lagrangean relaxation are the most popular (Galvao et al. (2000), Bernan and Krass (2002) and Karasakal and Karasakal (2004)).

In the case of emergency response units, especially those of police type, literature often uses recent records (Location of crimes, fires, crashes, etc.) to form spots that represent potential claims along the space to be analyzed. Given these locations and the specific problems to be solved (Equal claiming share corresponding for each unit, specific movement restrictions, etc.) the authors apply the MCLP that fits their needs (Keskin et al. (2012), Curtin et al. (2010), Ying and Mu (2012), Guo and Qi (2014) and Gu et al. (2010)).

One major difference with other works done in the case of police facilities until now is that, in addition to taking into consideration the value of the land where potential CAIs will be built, in our paper coverage of the objective crime spots will not be measured as the euclidean distance between the points considered, none using the road layout of the city, but using an approximation of the actual average time that takes to travel from the origin point to the destination point for which we call the Google Maps Application Programming Interface (API) to estimate that average travelling time.

Although a exact method may be capable of solving this Maximal Coverge Location Problem, it would only work well for a small number of possible facilities as it would suffer from combinatorial explosion. So an exercise with 100 possible facilities would require the evaluation of 1.27×10^{100} different combinations.[3] This kind of problem belong to the NP-hard class (Kariv and Hakimi (1979)) and the time and computer amount of memory used to solve such problems repeatedly in real cases become prohibitive, so general heuristic methods become the most attractive alternative.

On this basis Arostegui et al. (2006) evaluated some of the most well known general heuristic methods applied to some Location Problems under time-limited, solution-limited, and unrestricted conditions. They found that in most cases Tabu Search and Simulated Annealing

[3] This figure was derived from the calculation $\sum_{i=1}^{100} \binom{100}{i}$.

show the best performance with no clear difference between both of them when the time of the heuristic is unrestricted. This result is in line with that of Drezner et al. (2002) who also found tha a variant of the Simulated Annealing gave the most satisfactory results among five heuristics evaluated to solve a Location Problem in a discrete space.

Given the obove, we use a Simulated Annealing (SA) algorithm to solve our MCLP. Our SA is based on that proposed by Kirkpatrick et al. (1983), which is in turn a modification of the Metropolis-Hastings algorithm developed by Metropolis et al. (1983). This methodology has also been used with success in papers like Cambolat and Massow (2009) and Davari et al. (2011), among others.

As is pointed out by Davari et al. (2011) Simulated Annealing is a local procedure that is capable of searching stochastically and is designed not to get stuck in a local optimum. SA name comes from the fact that the process emulates those of the metals industry, where major changes are allowed at the beginning of the process, while the material is hot, but as it cools less alterations can be made.

That is precisely the logic behind Simulated Annealing procedure. An initial solution is raised, and a new potential solution is chosen from the feasible region; if the latter has a better fit than the first, is accepted as the new solution, otherwise it is accepted with a probability that will fall to the extent that the iterative process forwards. In our case, the feasible region will be influenced not only by the geographic area but also by the allocated budget.

5 Data, Procedures and Results

5.1 Land prices

In our research, the center of analysis is the city of Medellín. For construction of feasibility regions[4], for each budget level, we must have a data set with land prices citywide. For this objective, we use the ECV 2011 Survey (Encuesta de Calidad de Vida, in English Life Quality Survey) implemented annually in the city since 2004 to track the socioeconomic conditions of the inhabitants of the 16 communes in which Medellín is divided. In the survey, respondents answer questions about actual rent or self-assessment rent of their home.

In the 2011 survey, 60% of interviwed families had home ownership, 33% paid a rent and the remaining 7% lived in other forms of occupation. The actual value of their rent is a good indicator that will allow us to evaluate the market value of the property in question. But most people live in a owned home, and they tend to overestimate the value of their home. To approximate the value of this overestimate, we make a comparison of the average actual rent and the average self-assessment of rent in every neighborhood of the city. Figure 1 shows how people perform an overestimation of approximately 11.7% of the value of their home. We will make this correction for our calculations .

[4] All possible combinations of units that could be built.

We also have available the number and type of rooms of the house, but its size in square meters is not specified, then we cannot make a direct calculation of the value of rent per unit of space. Taking data from the major rental agencies in the city, that put online the size in square meters of houses for rent, and the number and type of rooms tha the houses have, we find the average size of the latter,[5] which allows us to estimate the average size of the respondents' houses, by making use of the number and type of rooms in ECV.

With these data we can calculate the estimated value of rent per square meter for each household in the survey. The relationship between the rent and the market value of the land of the properties was studied by Jaramillo and Cuervo (2014) who indicated that by 2011 the ratio rent/price of the house by socioeconomic stratum was: 0.6% (high) 0.55% (Medium) 0.68% (low stratum).[6] Using these ratios we can finally find the price per square meter for each point in the city where an interview was conducted.

Once these points are georeferenced, and given the representativeness of the survey at the commune level, we can calculate the average value per square meter for each point of the city, as a distance weighted average price found through the ECV. Figure 2 shows an example of this process where the average price per square meter at the centroid of each neighborhood was estimated, finding the highest prices in the south and southwest of the city, risen to over US$1500 per square meter figures; and cheaper land located on the outskirts of the east and northeast of the city with values ranging from US$160 per square meter.

5.2 Crime Points

To identify potential demand points, two main sources of information are used, the first one is the census of catches in the city of Medellín, available for the period Jan/2002-Oct/2012. Despite 90.9% of the captures in the period in the city of Medellín were made in the act, this data, although it could be a useful proxy, does not meet all the desired conditions for the construction of a crime spot because their values are clearly affected by variables such as the expertise of criminals to carry out their activities behind the authority. To solve this problem, we use the records of crimes against life of SIJIN (Criminal Investigation Branch), which has the census of homicides carried out in the city and the common injuries records. Since homicide allows in most cases a record of the event, the latter data set reproduces unbiased estimates of the crime rate.

We also use the census of georeferenced CAIs in the city of Medellín, to determine the crime points that are already covered by the police force.[7]

Figure 3 shows the evolution of the homicide rate in the city (number of homicides in parentheses) where a significant drop in this variable is evident during the 2004-2008 period, with a new increase from 2009. The drop in 2012 has a dashed line, as the data just covers

[5] We found that in Medellín each living room adds on average 8.5 mts^2, each dining room adds 11.8 mts^2, a garage adds 21.1 m^2 and each bedroom adds 22.2 m^2 .

[6] Socioeconomic stratum is a classification used by the Colombian government to calculate households eligibility for subsidies. The lower the stratum, the higher the household needs.

[7] Following Policia (2009), we say a point is covered when is reachable in a time of 3 minutes or less from a CAI.

until October of that year. In order to give greater validity to our research, we will consider the two most recent years for which data is available, these being 2011 and 2012.

The census of homicides records the address of the event, allowing georeferencing these crimes. Figure 4 shows the spatial distribution of homicides in the city of Medellín in the period in question (2011-2012). To avoid points plotted on top of each other a spherical random noise is added to the data before plotting.

As mentioned before there are a total of 23 CAIs currently operating in the city, then some of the crime points analyzed are already covered. Figure 5 shows the location of the built CAIs (red dots) and the covered points (gray points). As shown in the figure, coverage buffer is not linear, since it is determined by the vial availability, roads senses and flow speed in the sector. Figure 6 shows the spatial distribution of not covered points, which will become a key input for the following.

5.3 Clusters

As the literature highlights, the criminal acts in cities tend to cluster spatially, then a more plausible approach than the use of all of the points, would be the construction of weighted clusters that represent those points. For this purpose we use the k-means cluster procedure as follows.

Given the set of n points shown in Figure 6, the k-means clustering procedure seeks to divide it into C sets while minimizing the within-cluster heterogeneity. Then the objective is to find S (S=$\{S_1$,S_2,...,$S_C\}$) that minimizes $\sum_{i=1}^{C}\sum_{j=1}^{n_i} d(l_{ij}, l_i)$, where l_i and n_i are the centroid and size of cluster i, respectively, and $d(.)$ is the euclidean distance function. Figure 7 shows the result of performing the exercise for $C = 500$ clusters, the size of each circle indicates the number of points each cluster represents, therefore, the weight that each cluster will have in the optimization process.

5.4 Specific Simulated Annealing Process

At this point we have all the necessary inputs for the optimization process using the SA algorithm. Whose technical details will be defined below.

Homicide clusters are representative areas of crime spots, therefore, besides being the best reference for the definition of demand, their centroids are the best candidates for the possible location of CAIs.

Let M be the budget amount for the construction of the CAIs. The problem feasibility region is given by all combinations of possible CAIs that can be achieved with such budget. Then, it is necessary to know the cost of building a CAI in each of the locations determined by the 500 clusters. The price per square meter at the centroid of each cluster (V_C) is calculated using the estimates from ECV data as follows:

$$V_C = \frac{\sum\limits_{i \in ECV} \phi(d(l_C, ls_i))Vs_i}{\sum\limits_{i \in ECV} \phi(d(l_c, ls_i))} \tag{5.1}$$

Where $\phi(d(l_C, ls_i))$ is the normal density function with mean 0 and standar deviation 0.5, evaluated over the euclidean distance between the location of the centroid of the cluster C (l_C) and the location of the ith household of the ECV (ls_i), Vs_i is the price per square meter in the location of that household. Let V be the vector of prices per square meter estimated at the location of each of the 500 clusters.

Let D be the 500×500 time distance matriz between each of the clusters' centroids, calculated using the Google API Tool. And let $A = f(D)$ be a 500×500 matrix that in the (i, j) position has a 1 if the jth cluster is covered by the ith cluster, that is, 1 if police could go from the ith cluster to the jth cluster in less than 3 minutes, and 0 otherwise.[8]

Let P be a vector of dimension 500 with the weighted demand, whose values are the number of homicides that each cluster represents. Let X_L be a vector of dimension 500 containing *ones* in the positions associated with the clusters of the solution L, where L is any combination of clusters, and *zeros* in the remaining positions. Let $N(X')$ be a function that changes the values of the transposed vector X' to *one* when they are greater than 0 and let them unmodified otherwise.

Given the above, the coverage in this case can be measured as $Cov = N(X_L' A)_{1\times 500} P_{500\times 1}$, wich is the number of homicides that are covered by L. Then the aim of the optimization can be written as:

$$\underset{L}{\arg\max}\ Cov = N(X_L' A)P \text{ subject to } 100X_L' V + 60X_L' X_L \leq M$$

Where the first term of the constraint refers to the cost of the land, and the second to the cost of the costruction of the CAIs. Specifically, 100 is the CAI's area in square meters and 60 is the cost of construction and equipment in thousands of dollars. Note that $X_L' X_L$ is the number of CAIs associated with the solution L.

As has already been explained in advance, to carry out this estimation we use a Simulated Annealing algorithm that will follow the next steps:

1. Propose $L_t \epsilon FR$, and estimate $Cov(L_t)$
2. Propose L^*_{t+1} where we randomly drop or add 2 elements to L_t
3. If $L^*_{t+1} \notin FR$, repeat step 2
4. $L_{t+1} = L^*_{t+1}$ with probability P_{t+1}
5. $P_{t+1} = 1$ if $Cov(L^*_{t+1}) > Cov(L_t)$, $P_{t+1} = e^{\frac{-\Delta}{T(t,E)}}$ if $Cov(L^*_{t+1}) \leq Cov(L_t)$

Where t is the current iteration, E is the number of total iterations to be run, FR is the feasible region, Δ is the difference between $Cov(L^*_{t+1})$ and $Cov(L_t)$, and $T(t, E)$ is the

[8]Note that neither D nor A are symmetric, since the city's road network means that the route and speed to go from i to j are different to go from j to i.

"temperature" of the process. This temperature will follow the function $T(t, E) = 500 * (1 - \frac{10}{E})^t)$, this structure is similar to that used in SA literature and ensures that in the first iterations, the probability of accepting a solution with lower coverage is high, avoiding falling into local optima.

For our research a total of 10000 iterations have worked well to the budgets amount taken in consideration.

Figures 8 to 11 show an example of how the optimization process works, appearing a searching process with a high stochastic component in the early stages and reaching a high stability in the last iterations.

In addition, figures 12 to 20 show the georeferenced optimal solution for each budget taken into account, where the red dots are the selected locations for building a CAI, red circles are the cluster whose centroids were selected, black circles are the clusters that would be covered by the new CAIs and gray circles are the clusters that remain uncovered. Here again, the size of the circle is associated with the number of homicides that each cluster represents.

6 Conclusions

As may be evident from the results, low budgets can quite restrict coverage and possible optimal constructions of CAIs, specifically, budgets lower than US$100,000 do not allow the construction of more than one CAI, limiting coverage to no more than 4% of demand.

To the extent that larger budgets are allocated, more freedom will be present in the process of optimization and better results will be gotten in the coverage field. However, as it is evident in figure 21, which shows the evolution of the maximum coverage for every budget analyzed, target variable features marginally decreacing variations with respect to the budget constraint.

We also found the exact solution to the set of problems analyzed here, this results are also shown in figure 21. We can see that the solution found by Simulated Annealing is very close to the exact solution, but for the former, the total resources used (time and system memory) is significantly lower than for the latter. This aspect is crucial when feasible region for the probleme increase.

While resources of US$100,000 not reach even a 4% coverage of the homicides map, with a budget of US$10,000,000 a total coverage of over 70% is achieved.

If government would like to achieve a coverage of 50% percent of the of the potential demand, a budget of approximately US$2,500,000 needs to be allocated.

Although downtown is one of the places with the highest homicide rates in the city, only with budgets higher than US$2,500,000 a location in the area is selected . This is due to 3 main factors, the first is that some of the murders in this area is already covered by the currently active CAIs, then would not enter in the current optimization process; second, downtown is a very commercially active area, so with the money that one builds a CAI there one can build more on the outskirts; and third, the low speed in downtown makes it very difficult to achieve a high coverage. These factors might suggest that CAI does not appear to be the best method to tackle the problem of violence in downtown.

Finally, it must be highlighted that the optimization procedure carried out in this research can be modified and used in obtaining optimal locations of different structures to fight the crime in the city.

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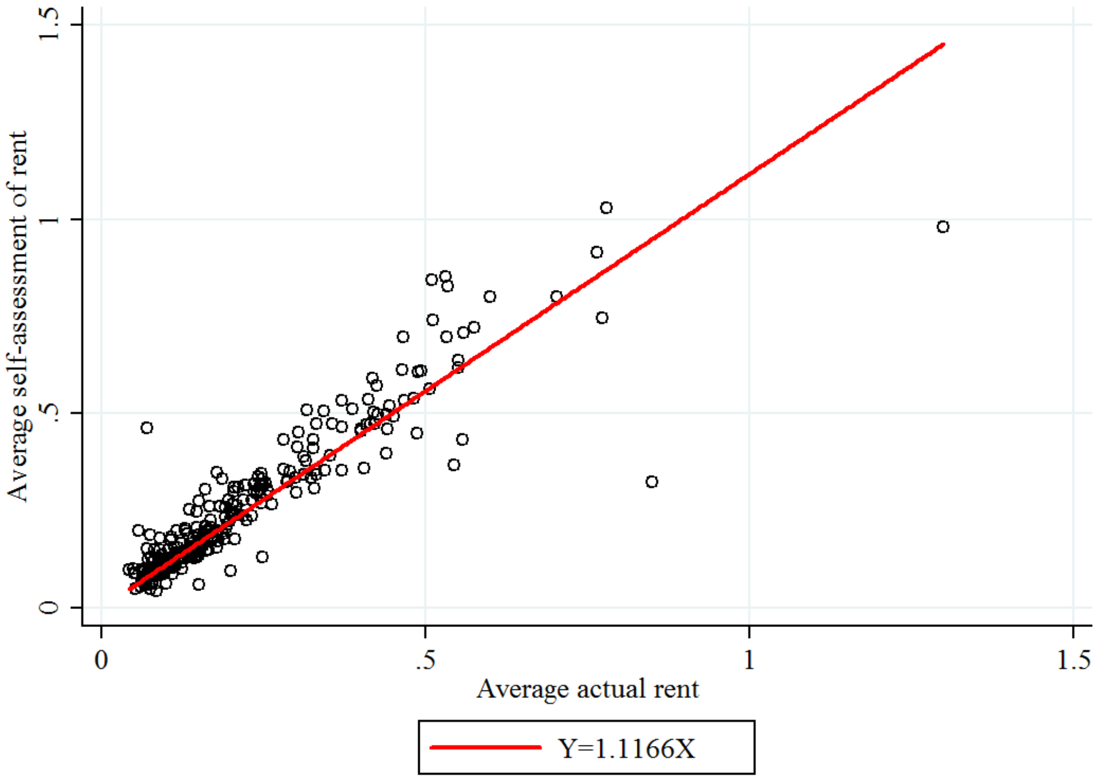
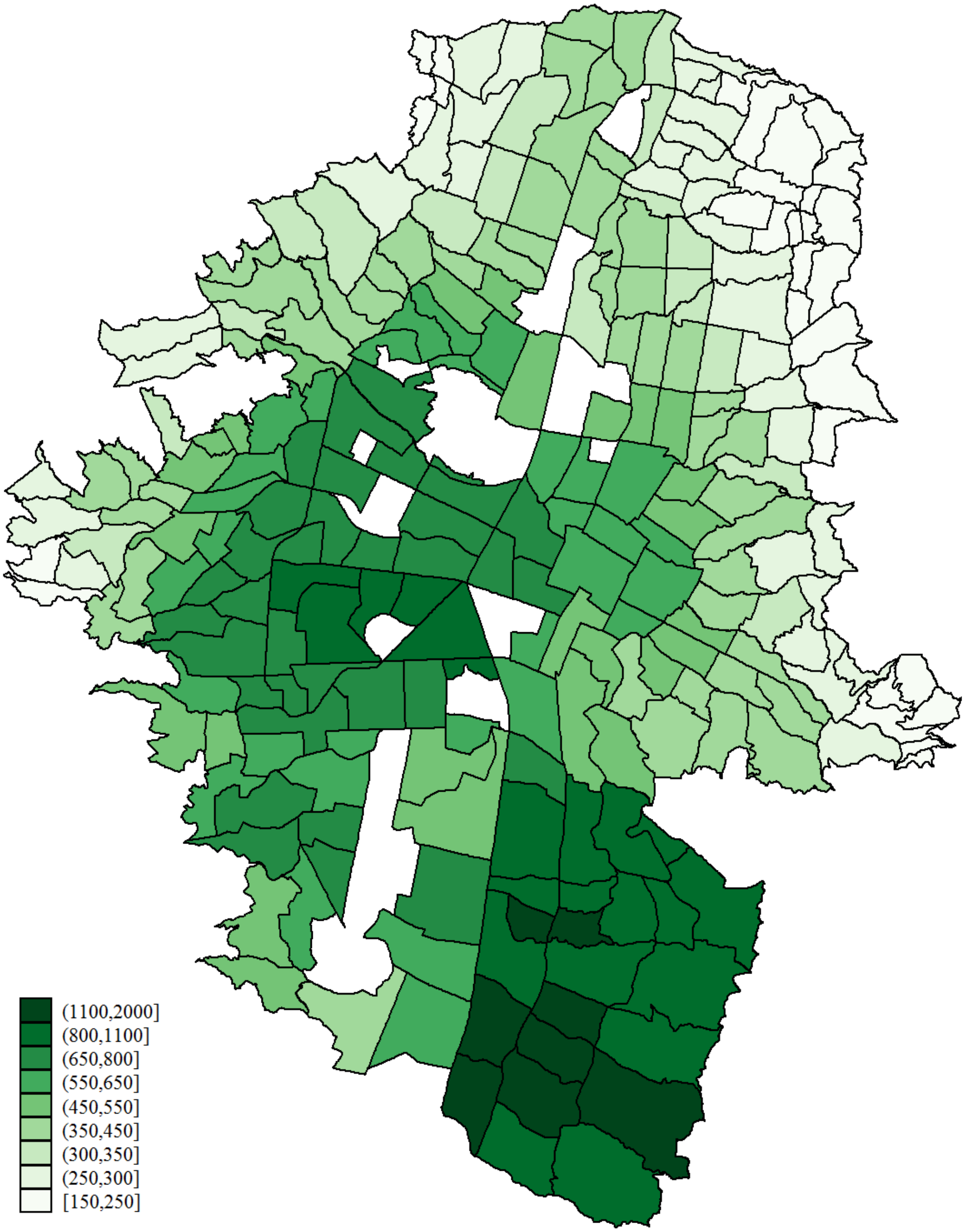
Figure 1: Self-assessment of rent



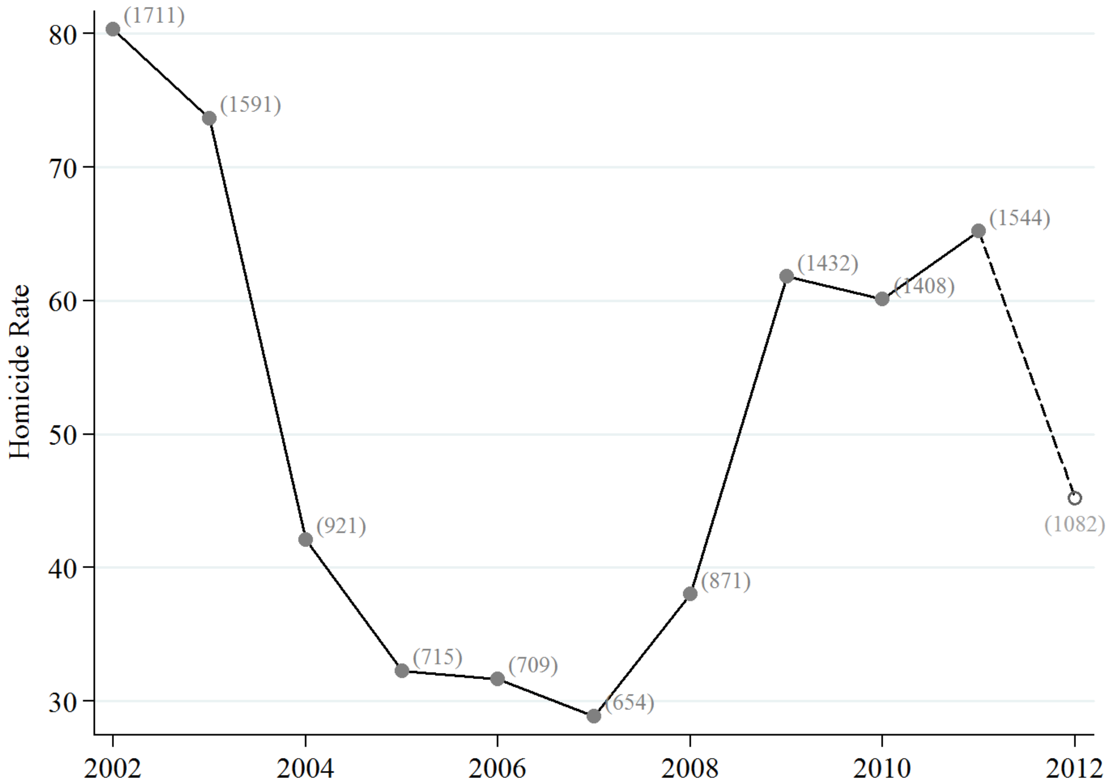
Source: Own calculations based on information from the ECV 2011 Survey.

Figure 2: Land Price in Medellín (Colombia)



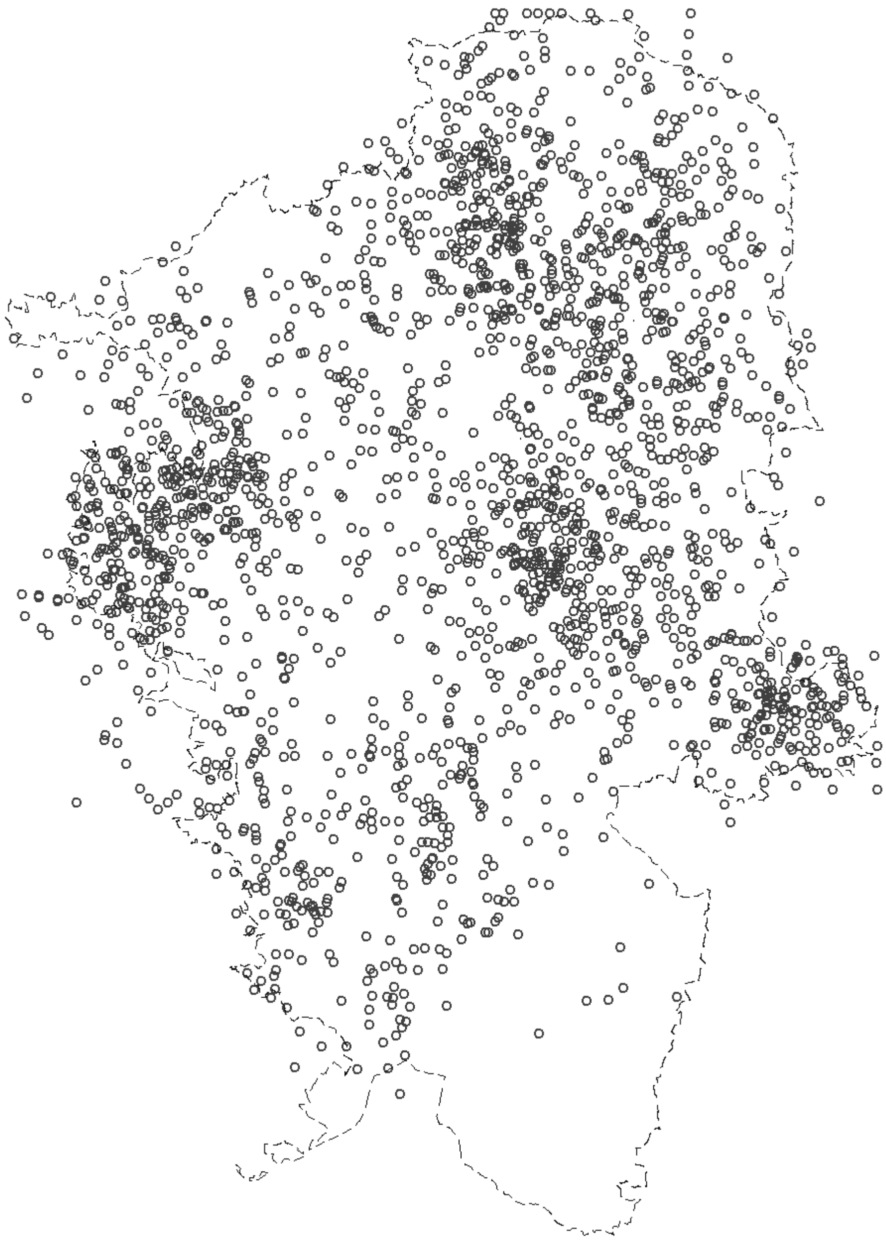
Source: Own calculations based on information from the ECV 2011.

Figure 3: Homicide Census



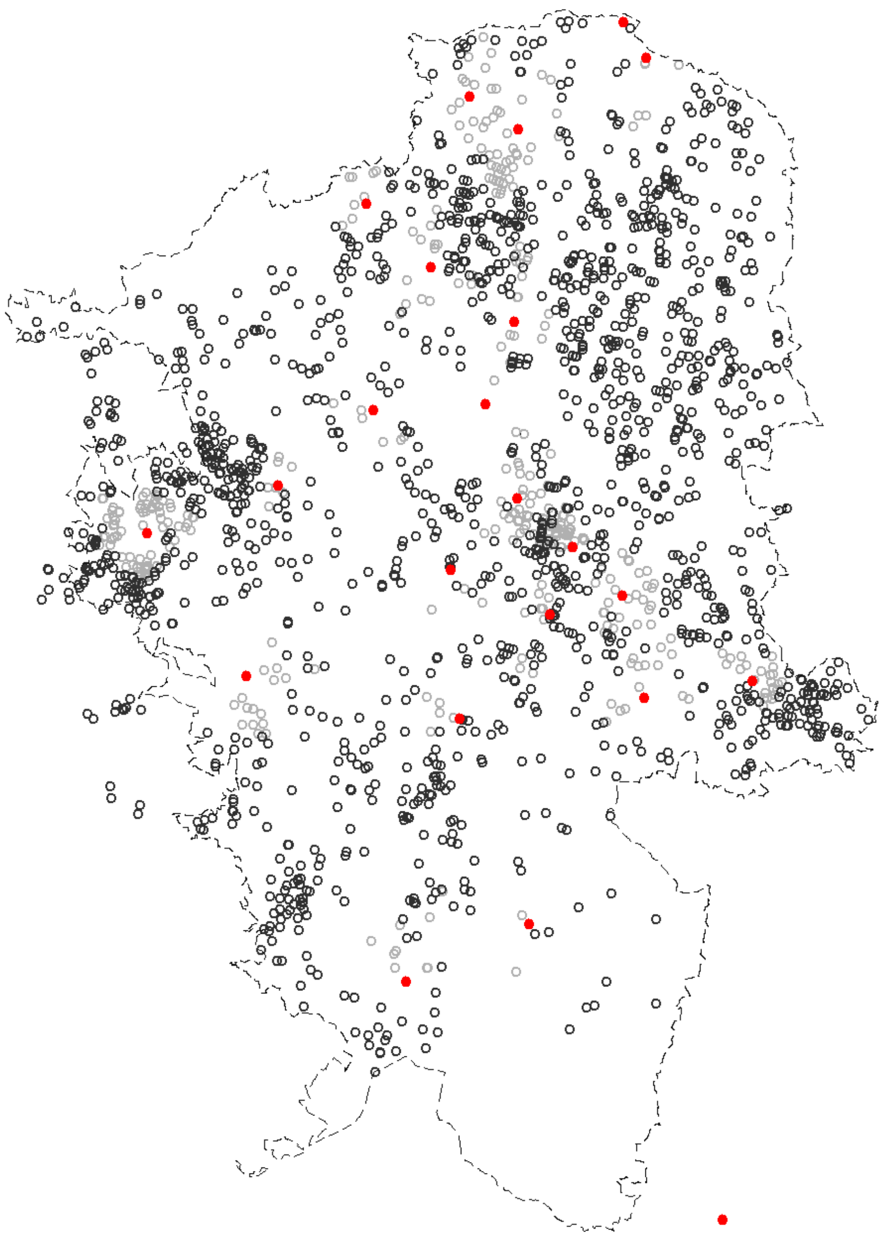
Source: Own calculations based on information from the Medellín Metropolitan Police.

Figure 4: Homicide 2011-2012



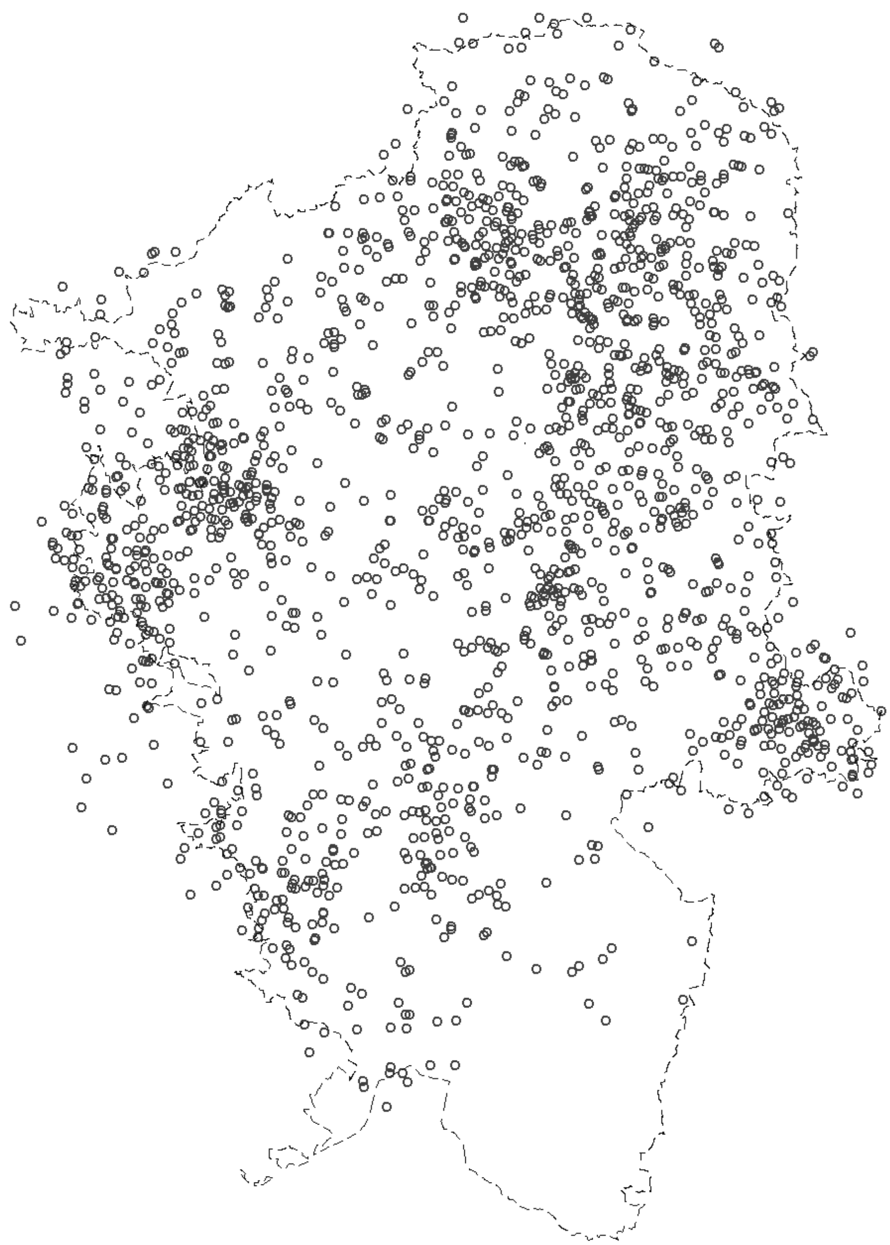
Source: Own calculations based on information from the Medellín Metropolitan Police.

Figure 5: Actual Covered Area



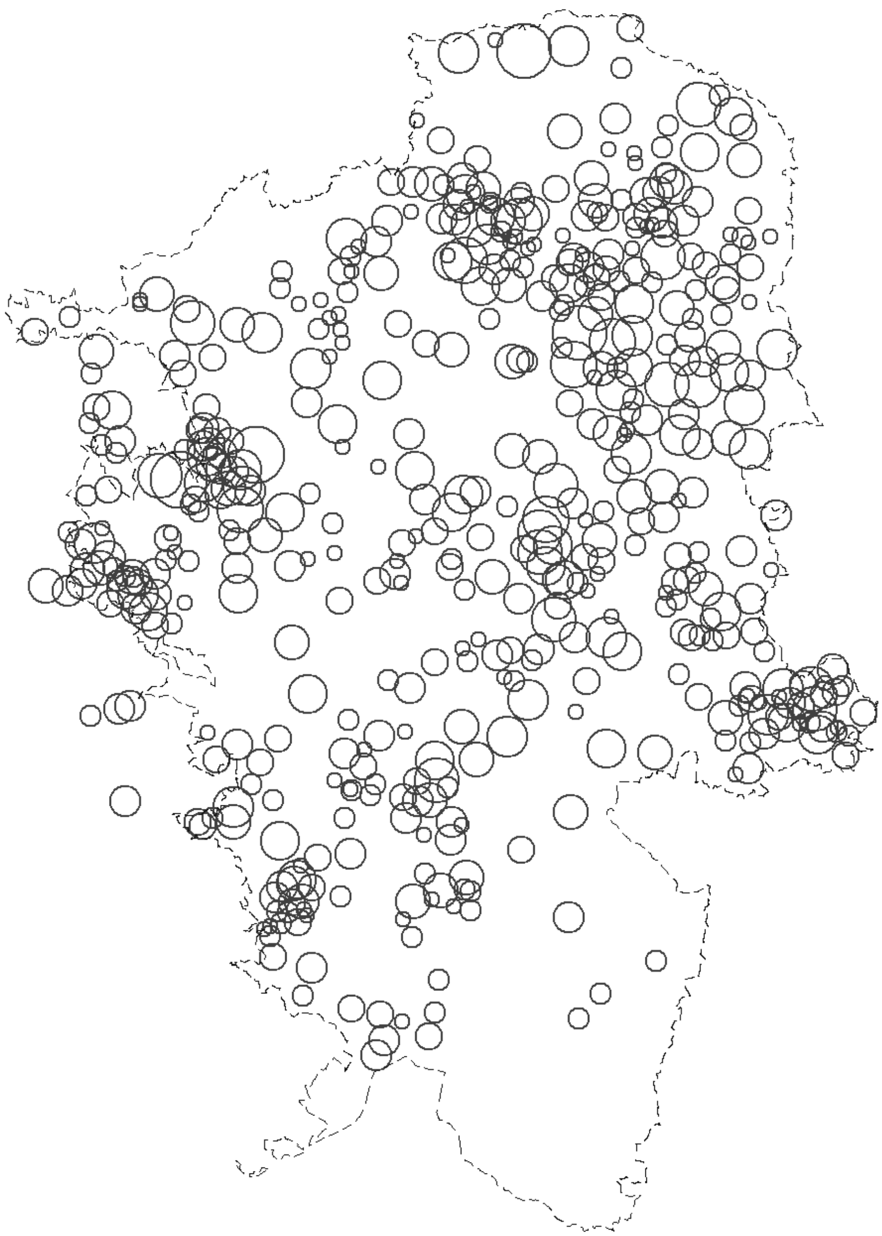
Source: Own calculations based on information from the Medellín Metropolitan Police.

Figure 6: Potencial Crime Spots



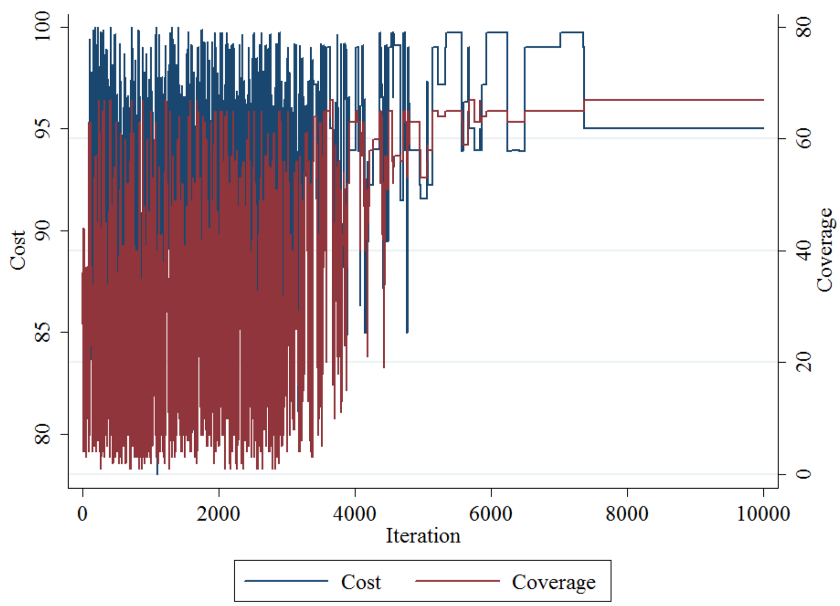
Source: Own calculations based on information from the Medellín Metropolitan Police.

Figure 7: Clusters



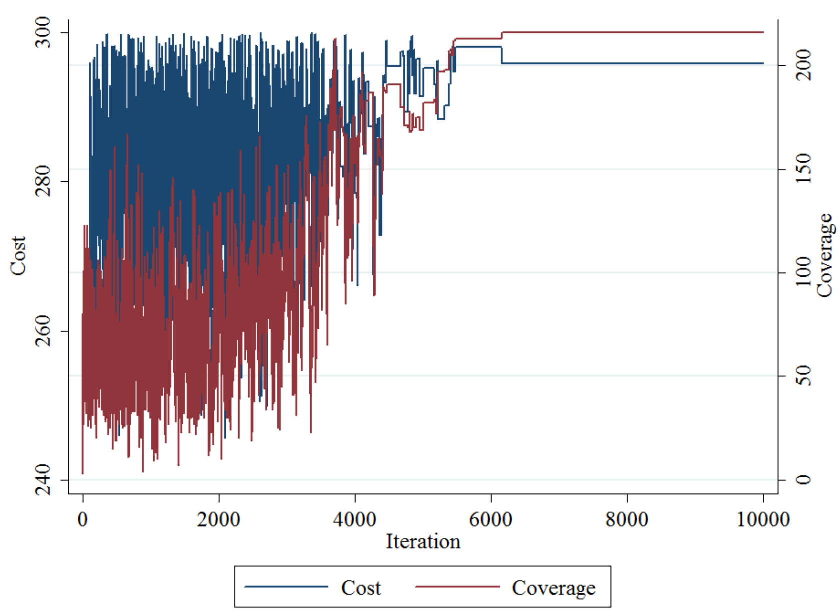
Source: Own calculations based on information from the Medellín Metropolitan Police.

Figure 8: SA with US$100K Budget



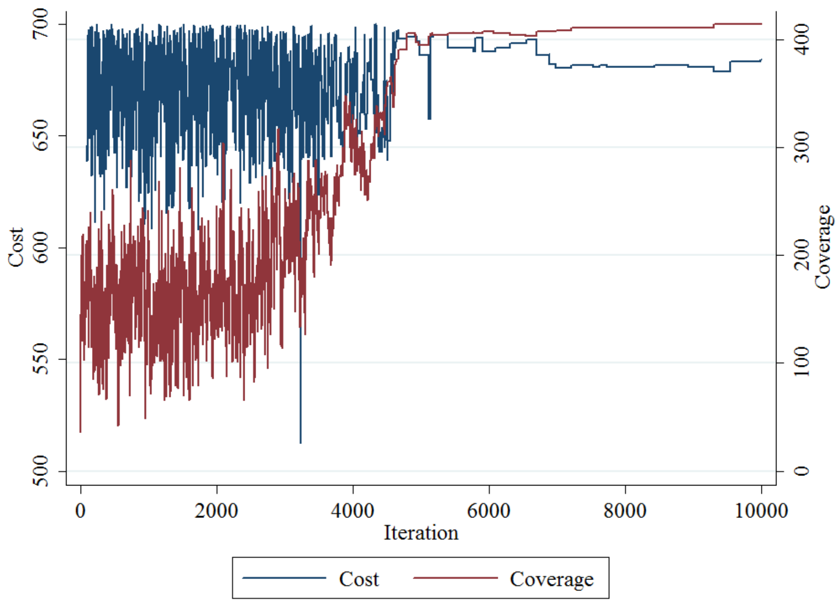
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 9: SA with US$300K Budget



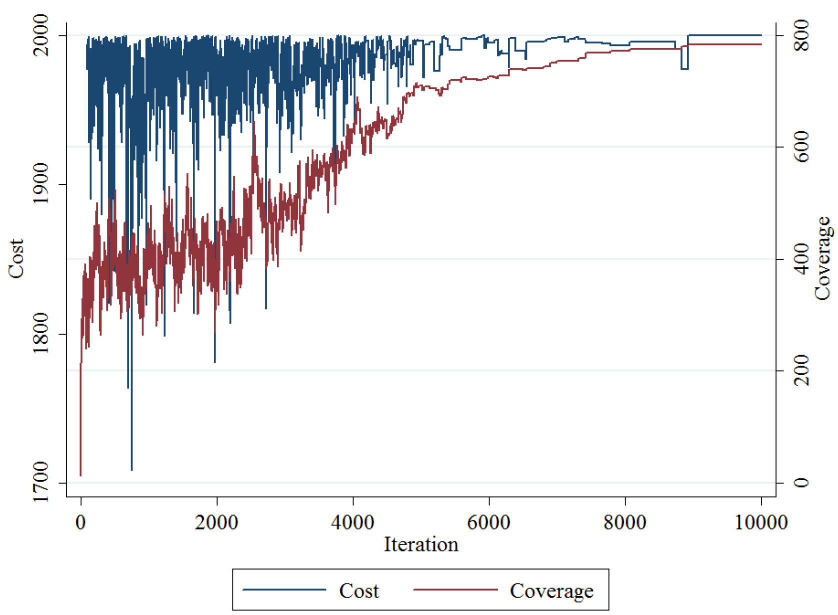
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 10: SA with US$700K Budget



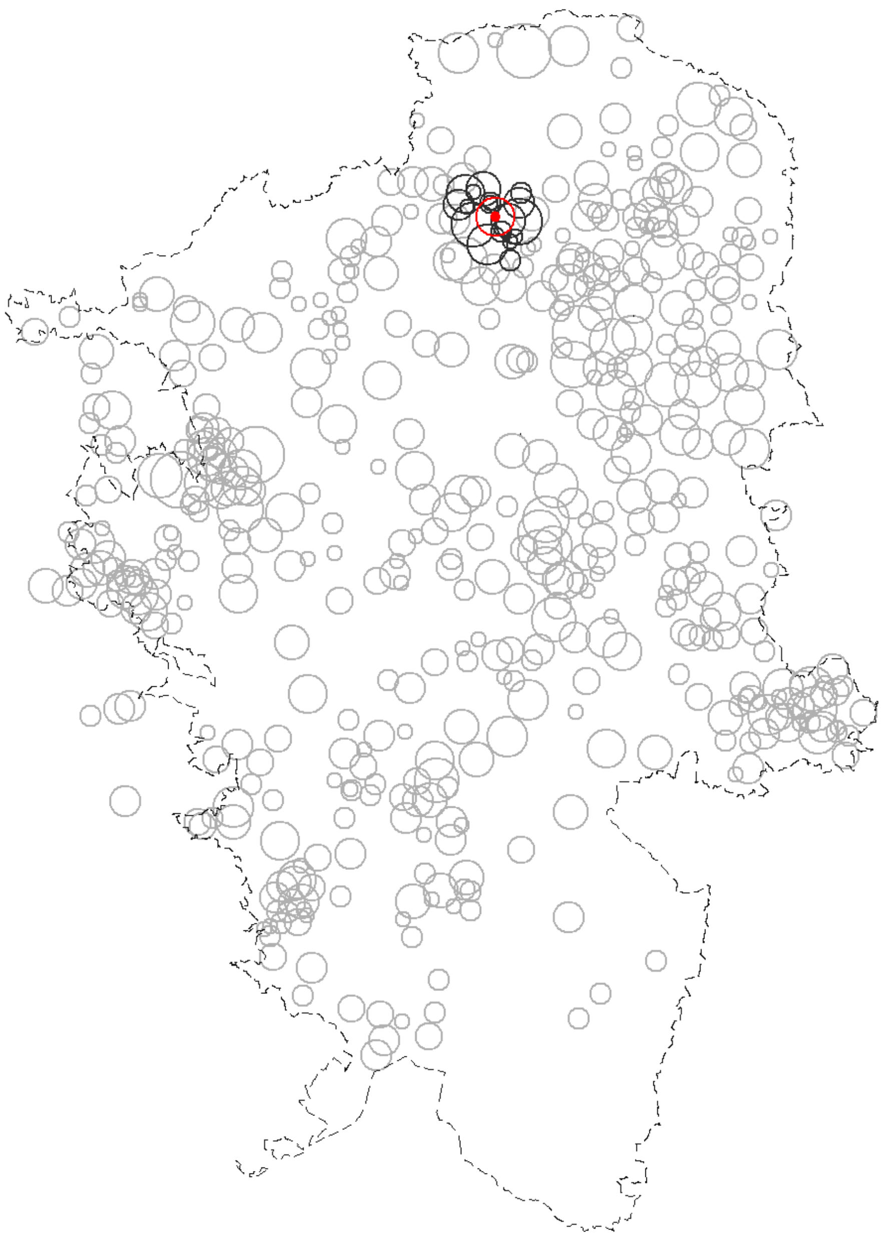
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 11: SA with US$2000K Budget



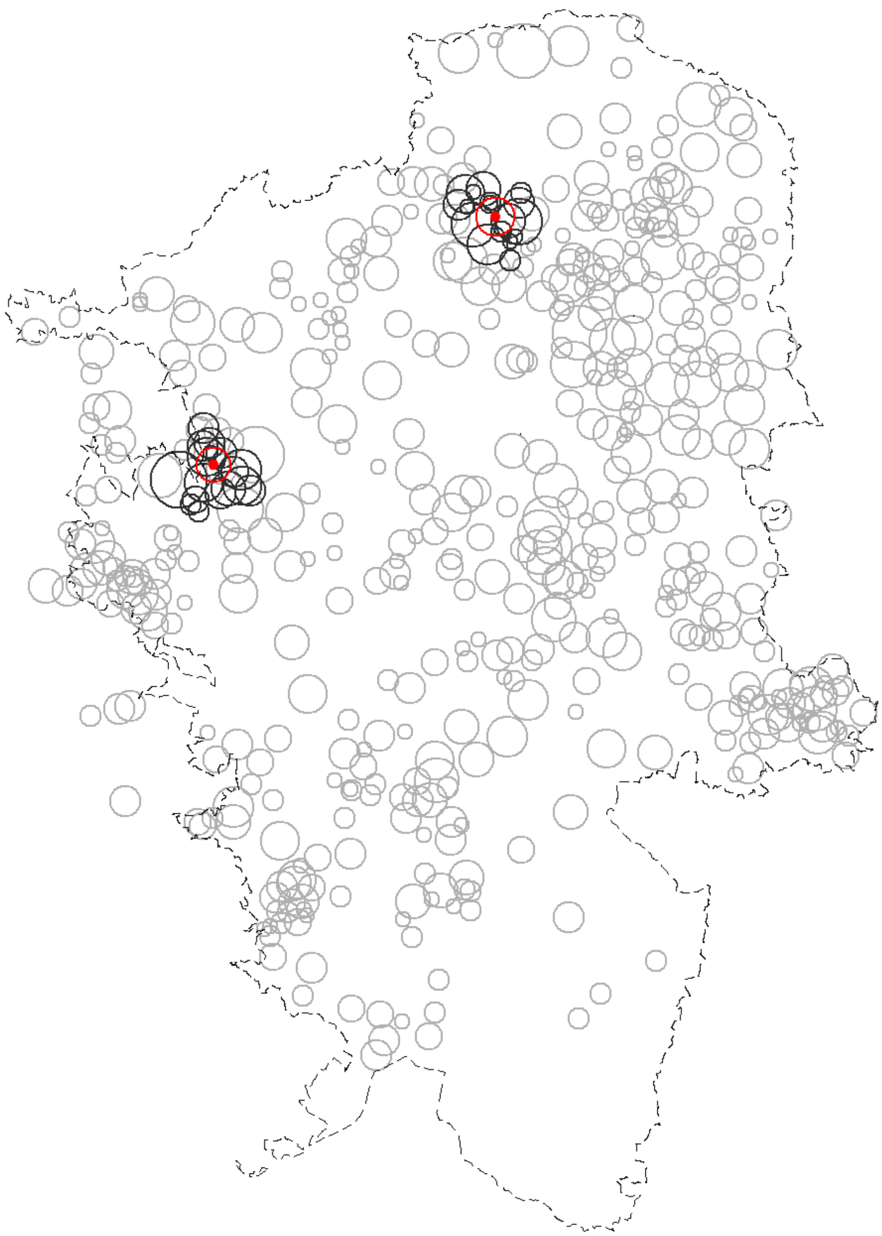
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 12: Optimal Location with a US$100K Budget



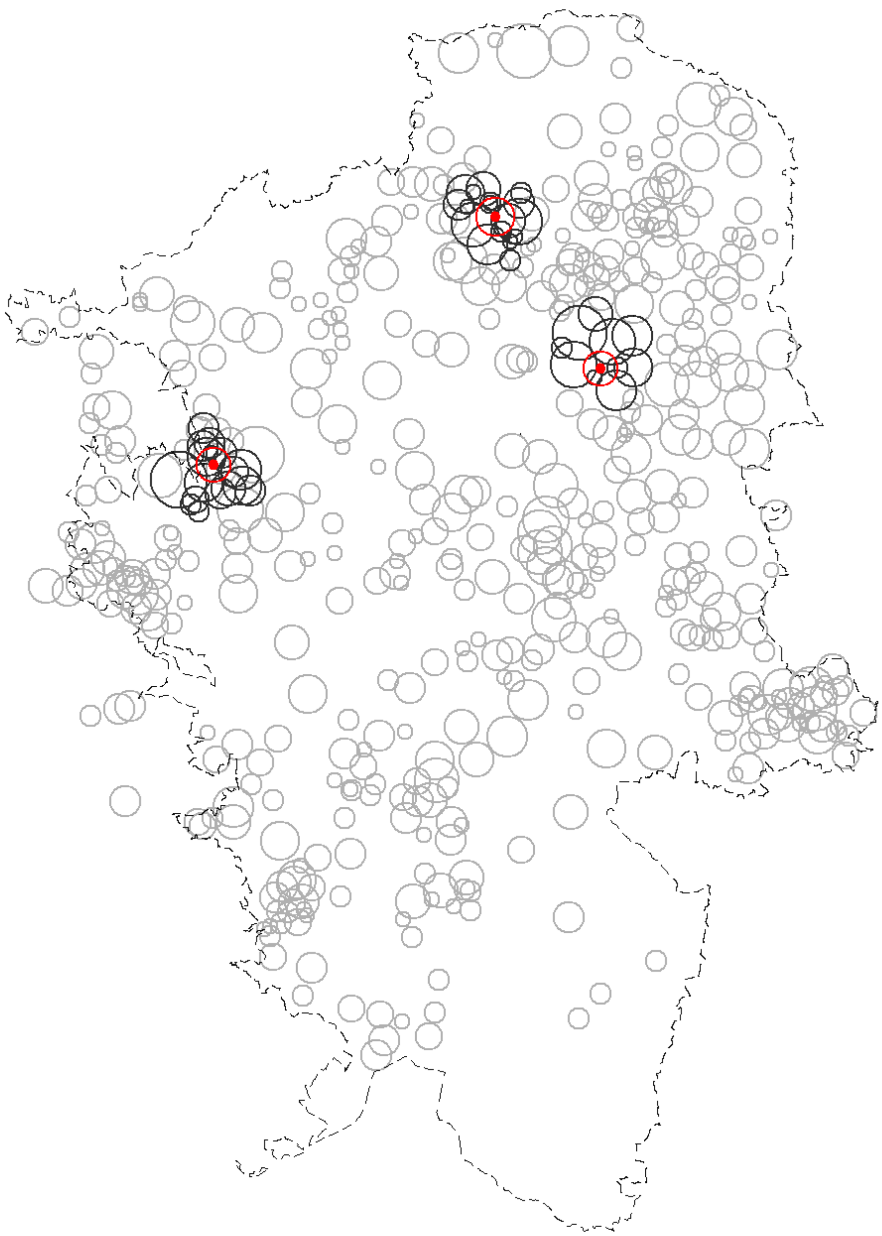
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 13: Optimal Location with a US$200K Budget



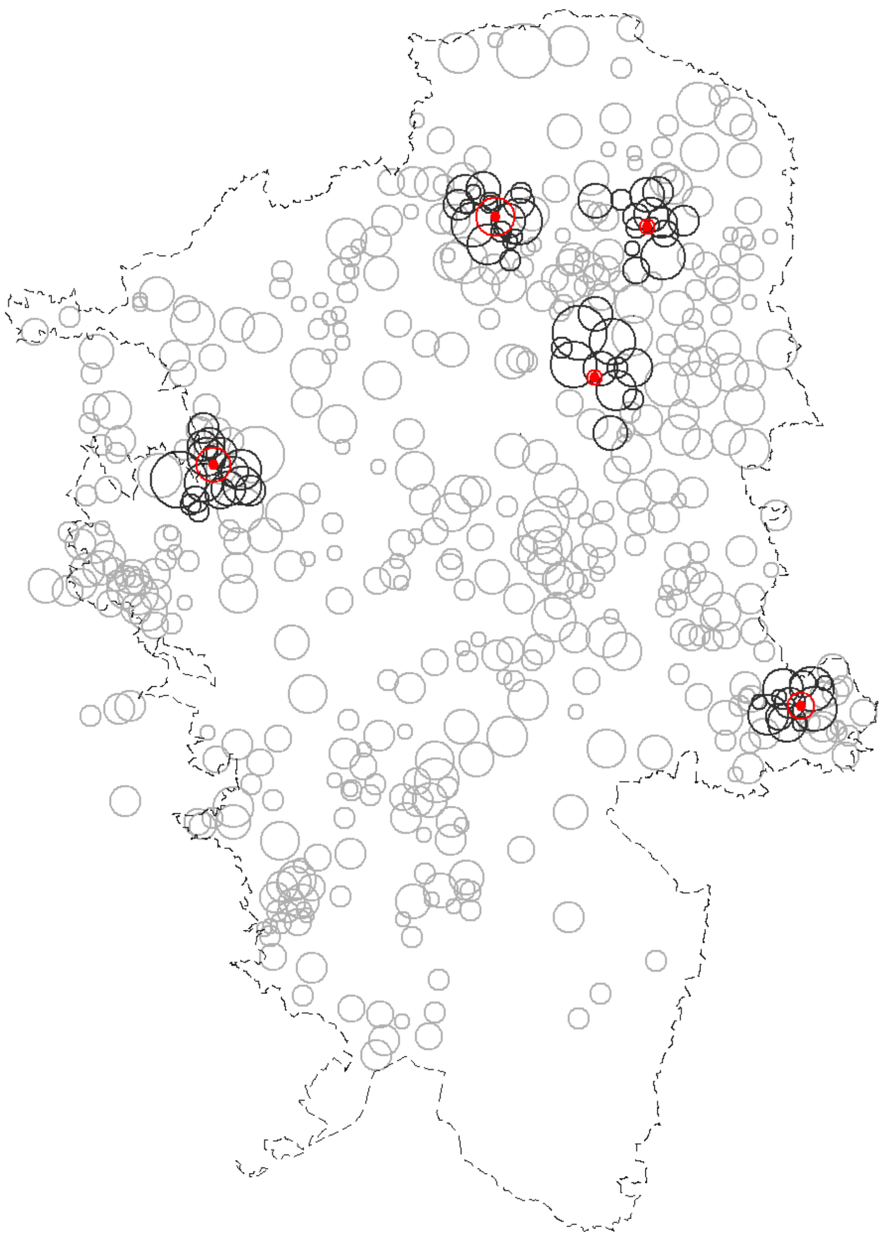
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 14: Optimal Location with a US$300K Budget



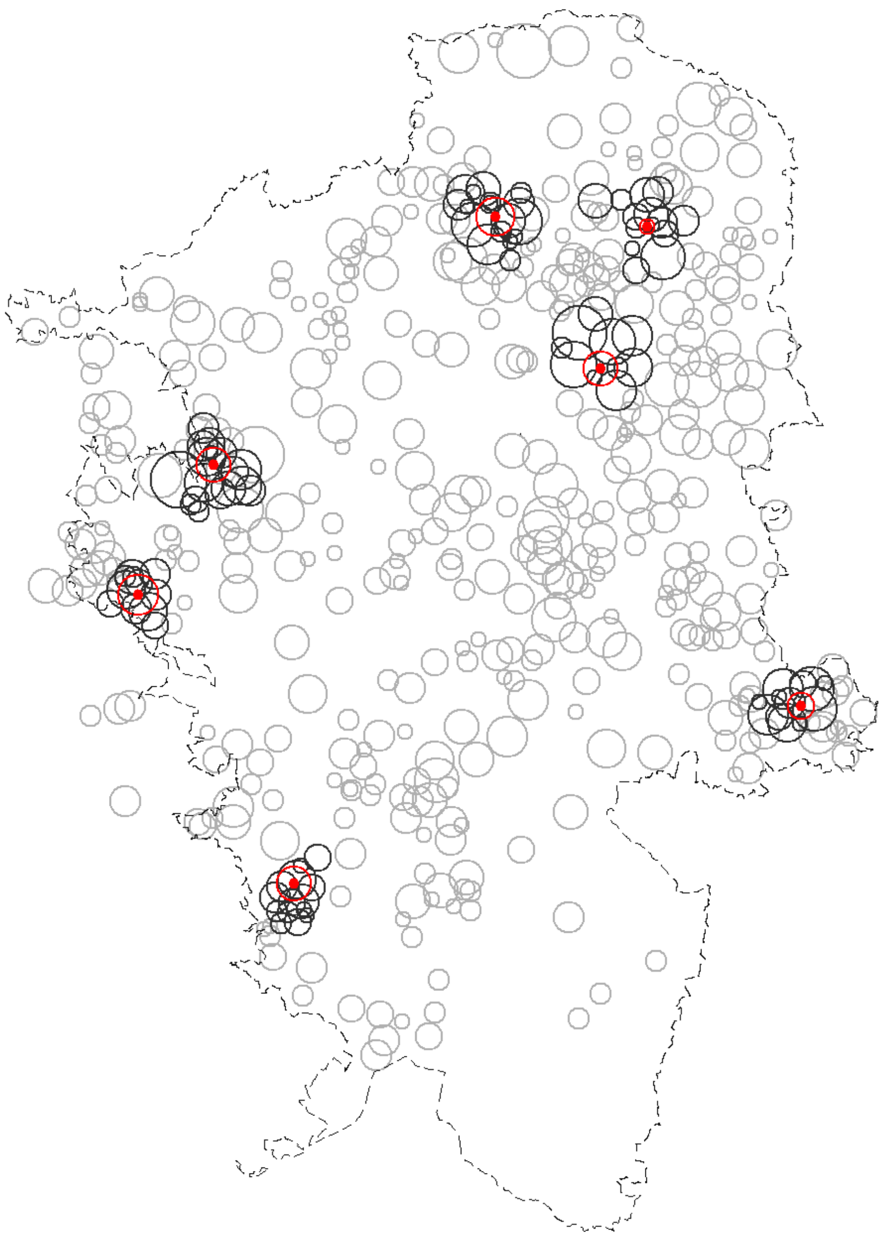
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 15: Optimal Location with a US$500K Budget



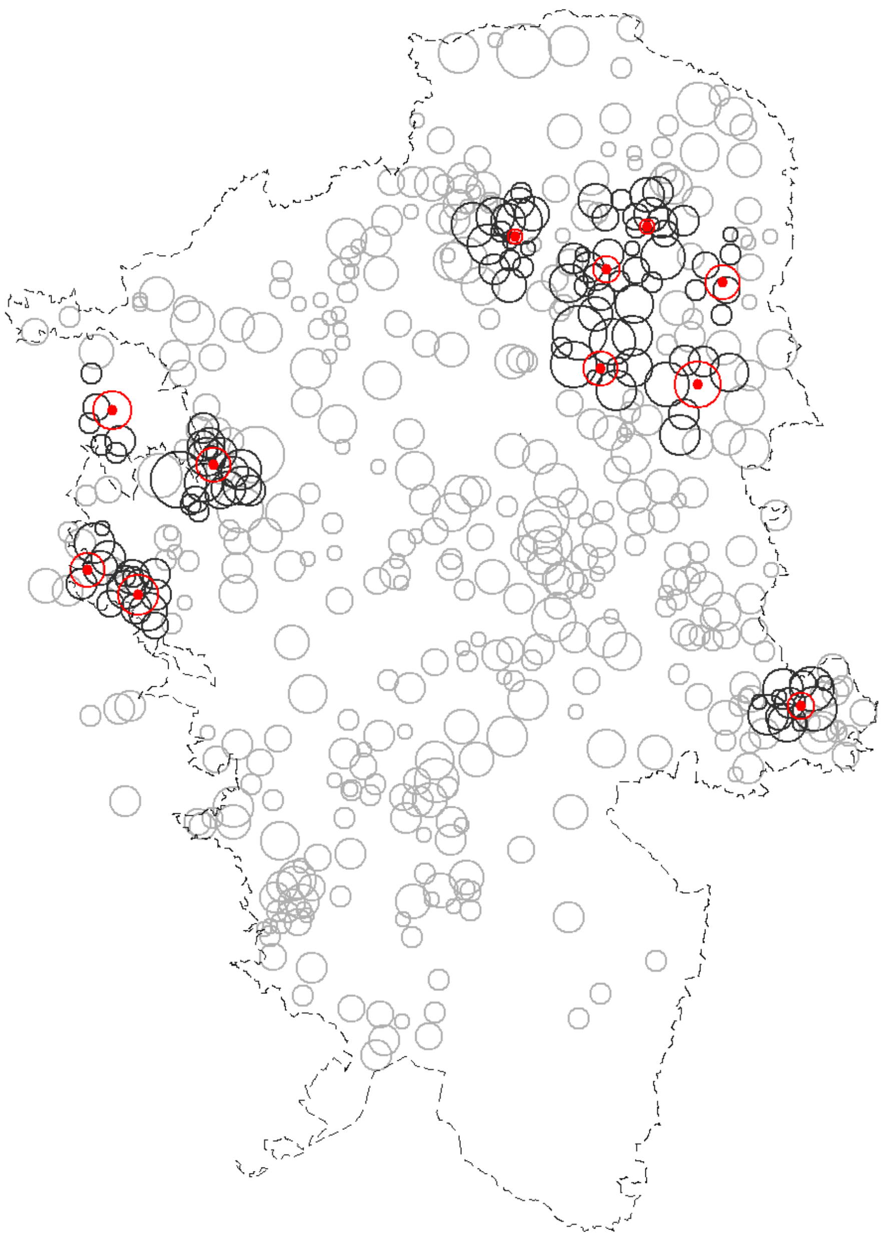
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 16: Optimal Location with a US$700K Budget



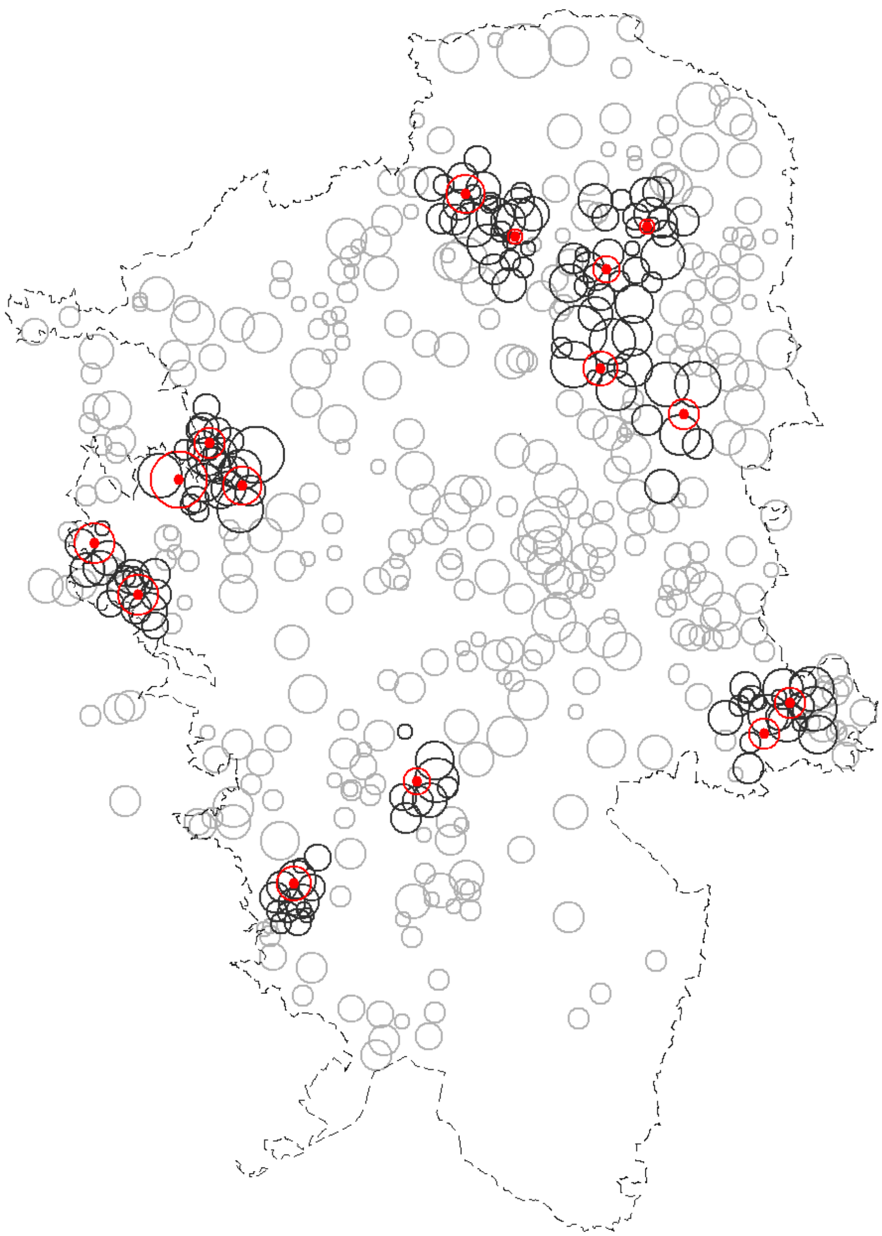
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 17: Optimal Location with a US$1000K Budget



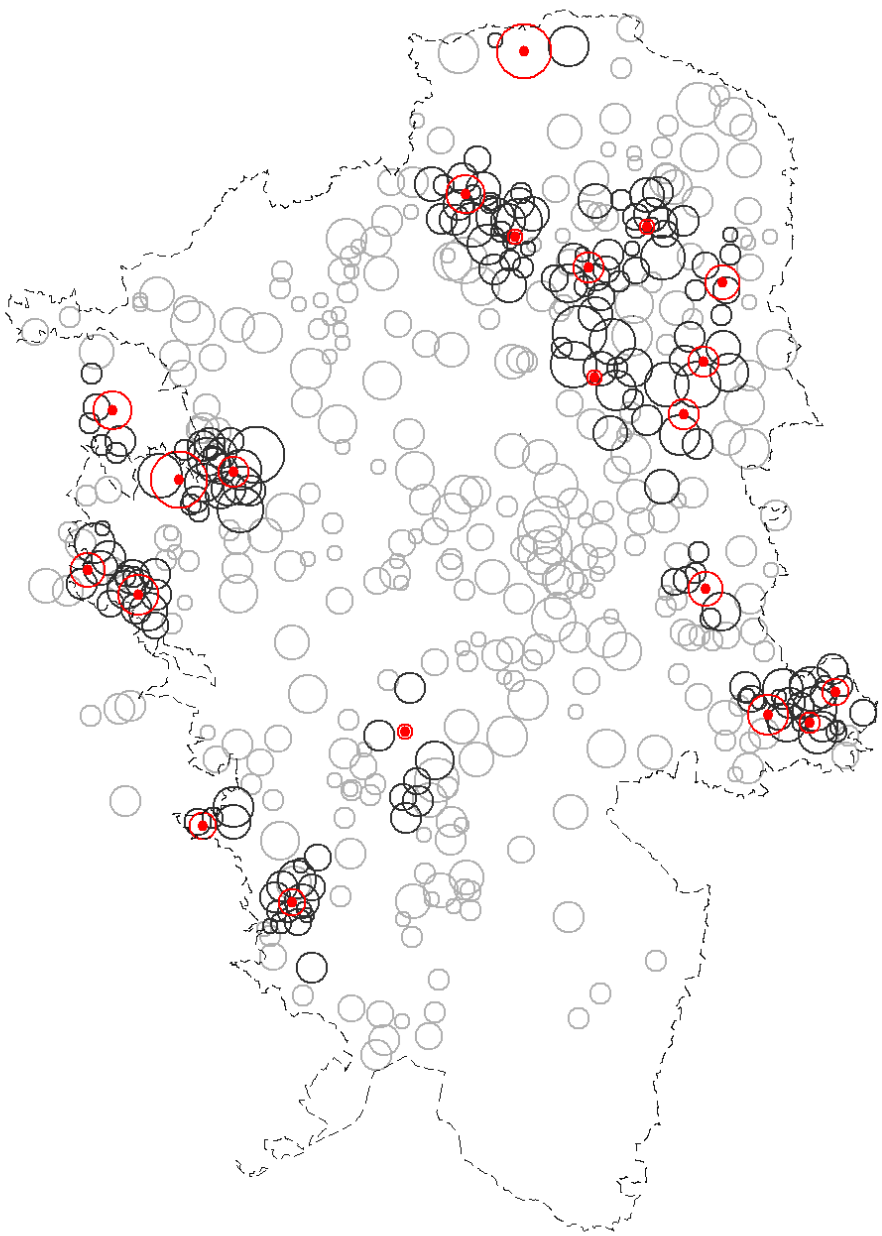
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 18: Optimal Location with a US$1500K Budget



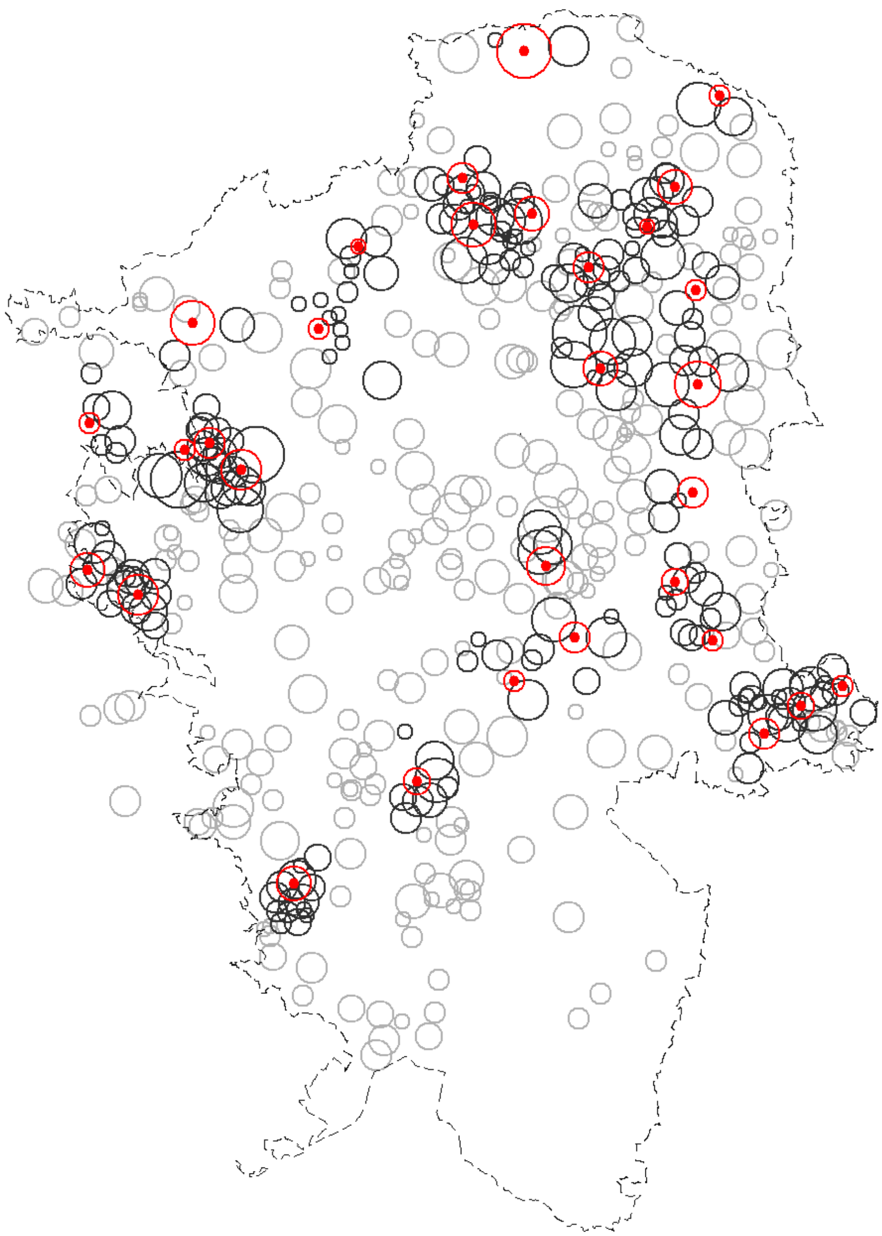
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 19: Optimal Location with a US$2000K Budget



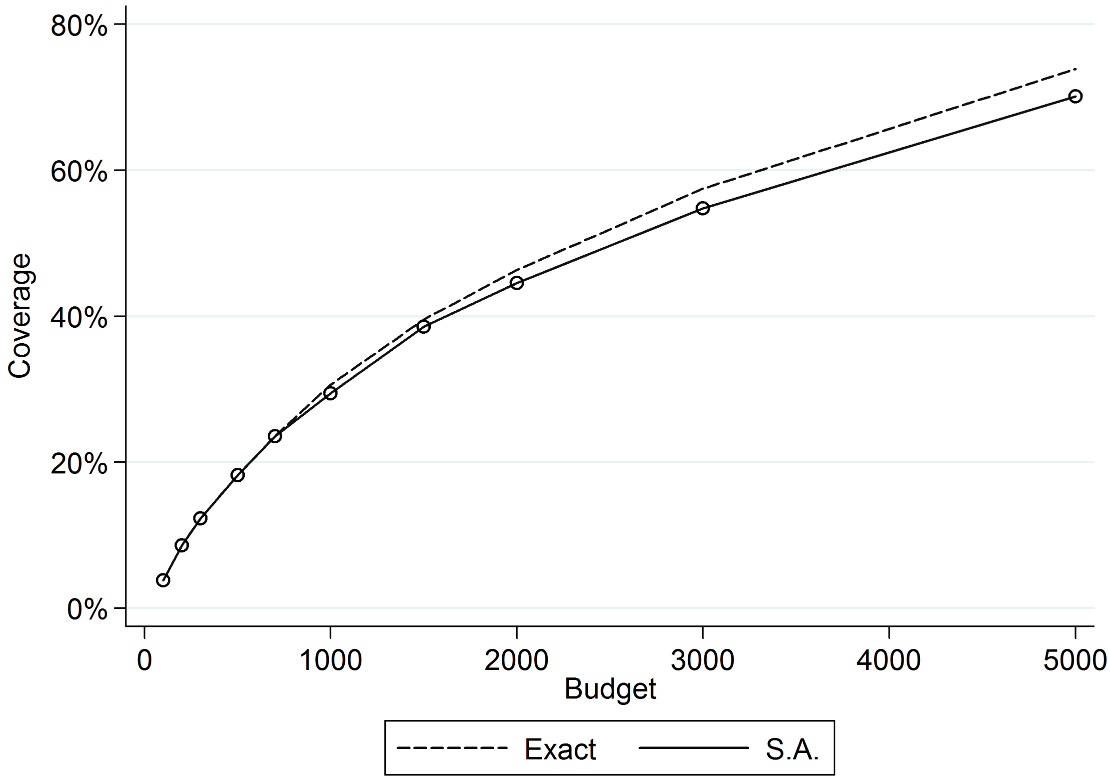
Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 20: Optimal Location with a US$3000K Budget



Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.

Figure 21: Coverage vs. Budget



Source: Own calculations based on information from the Medellín Metropolitan Police and the ECV 2011 Survey.