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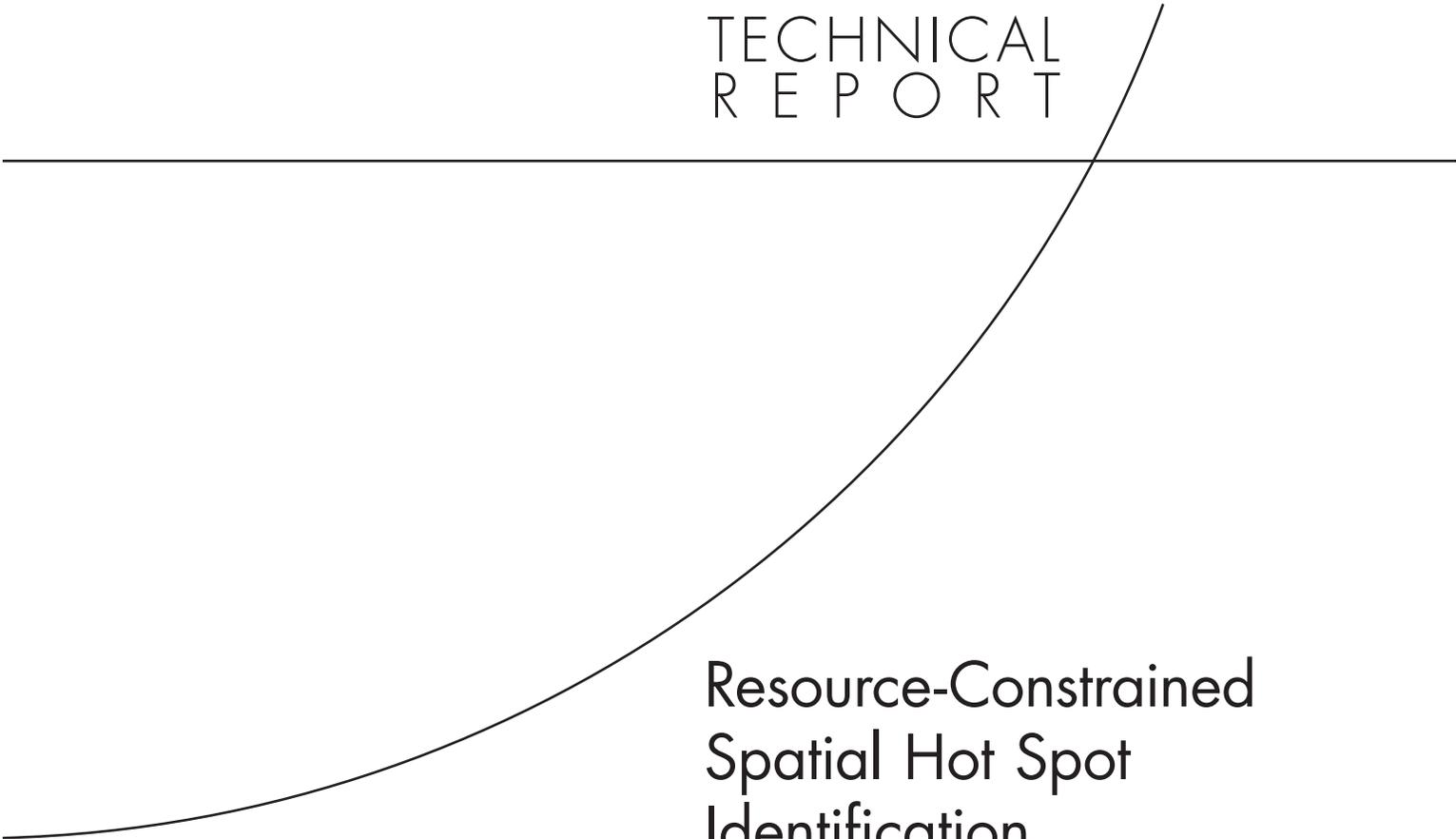View document details

Resource-Constrained Spatial Hot Spot Identification

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Summary

Crimes, improvised explosive device (IED) attacks, disease outbreaks, and other disorder events are not spread uniformly across space or time. Maps of historical data generated by geospatial analysis often indicate localized clusters of notable events. The rich literature on the use of spatial analysis across many research fields posits several theories that attempt to explain the strength of spatial relationships among events that lead to clustering. Independent of the underlying cause of the clusters of events, a standard set of tools is available to the geospatial analyst community that enables the user to identify and interpret disorder activity. Among these toolkits, there has been increasing use of "hot spot" analysis to identify areas where clusters of local disorder events are most prominent and where appropriate resources should be deployed to deter, interrupt, or prevent further undesirable activity.

Resource-Constrained Hot Spot Identification

Hot spot analysis is frequently used to guide decisions about the deployment of resources intended to address the disorder activity. When the amount of resources is insufficient to address the entirety of the problem, hot spot analysis can also be used by decisionmakers to select areas with more pronounced problems and then allocate resources to those focus areas. However, policymakers tasked with allocating resources to address these problems often are keenly aware that the resources at their disposal have limitations that may drive the effectiveness of the various courses of action they desire to pursue. The decisionmaker who seeks to find an efficient and effective means of deploying resources to address problem areas must consider that his/her courses of actions are subject to the three types of constraints:

1. **Spatial.** The deployable asset(s) may have a fixed effective range (e.g., a visual sensor with a fan-shaped 130° field of view and 500-m range).

2. **Temporal.** The deployable asset(s) may be only deployed or effective at particular times (e.g., the visual sensor is ineffective at night).

3. **Quantity.** The number of deployable asset(s) is finite (e.g., funding exists for only two visual sensors).

In practice, since the decisionmaking consumers of standard hot spot analyses consider these types of constraints after the analysis has been completed, the assets being considered for deployment are often later determined to be an ineffective match for the hot spot. Without considering these limitations before the execution of the hot spot analysis, the resulting hot spots are often too large, inappropriately shaped, or out of synchronization with deployable resources. The term *actionable* will be used to indicate when the constrained resources are *available and appropriately matched* with the problem against which they will be deployed. This introduces a demand for "need-driven" methods that not only group data based on spatial similarity among events, but also identify actionable clusters given resource constraints (Ge et al., 2007).

Actionable Hot Spots

This research presents the *actionable hot spots*[1] (AHS) methodology. An actionable hot spot is defined as a hot spot having the same property as the standard hot spot discussed earlier (higher-than-average concentration of events in the study area), with one notable addition: *An actionable hot spot is a hot spot that has been determined to be appropriately sized, shaped, and synchronized with the cluster of disorder events against which scarce resources will be applied.* The methodology is not meant to replace existing hot spot analysis methods — rather, it is an implementable extension to existing methods that leverages standard statistical and innovative algorithms to ensure that only actionable hot spots are identified. The result of using this extension is that the decisionmaker, in addition to any exploratory spatial analysis where resources have not been applied, is presented with a list of hot spots in which his/her scarce resources can be effective. The application of constraints yields a reduced set of solutions that both are implementable and can be used to more efficiently allocate scarce resources. Naturally, before imposing constraints on hot spots that will render them actionable, an analyst may first apply a variety of standard spatial analysis tools to better understand the underlying data and their spatial distribution, and

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[1]This term was coined by a RAND researcher, Richard Mesic.

perhaps test some hypotheses that he/she has established to explain the reasons behind the disorder activity. After the initial exploratory analysis has been conducted and when constraints need to be introduced to guide resource decisions, the AHS approach can be used. For the decisionmaker, this represents a significant change in the way geospatial analysis is used to support their resource allocation.

Research Questions

In this report, we address three research questions:

1. Can existing geospatial tools be modified to ensure that any identified hot spots are actionable, given known spatial resource constraints?

2. Can identified actionable hot spots be prioritized so that the decisionmaker can efficiently allocate scarce resources to yield maximum effectiveness against problem areas?

3. Can the AHS methodology be applied to guide resource allocation in research areas beyond the IED application for which it was originally developed?

Hot Spot Identification

In geospatial software packages such as $CrimeStat^{®}$, $GeoDa^{TM}$, and $ArcGIS^{®}$, the standard set of available hot spot analysis tools fall into three categories (Cameron and Leitner, 2005):[2]

Thematic Mapping. Concentrations of events are color-coded in discrete geographic areas that correspond to administrative boundaries (e.g., ZIP codes, Census tracts, police precincts).

Kernel Density Interpolation. A smooth surface is overlaid on a map reflecting the concentration of actual events, and spaces between events are assigned interpolated value based on the amount of nearby events.

Hierarchical Clustering. Events are grouped according to their nearness to other events.

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[2]This is not an exhaustive list of hot spot analysis categories, but it does include those approaches that use a sample of automated identification of hot spots rather than subjective visual interpretation.

The three categories of geospatial hot spots are illustrated in Figure S.1, reflecting maps of Boston burglary events in 1999 and provided by Cameron and Leitner (2005). The first map reflects burglary rates per 100,000 residents by Census tract, the second map reflects the density per square mile, and the final is a clustering of events contained within ellipses.[3] It should be noted that the use of hierarchical clustering has been extensively discussed in spatial analysis because it is one source of the well-known *modifiable areal unit problem* (MAUP) (Openshaw, 1984) that may lead to misinterpretation of results due to the arbitrary boundaries that are used to aggregate data. Application of AHS does not resolve the MAUP, so those who interpret the results should consider that the problem may still exist.

Figure S.1
Boston Burglary Rates, 1999

Thematic mapping	Kernel density interpolation	Hierarchical clustering

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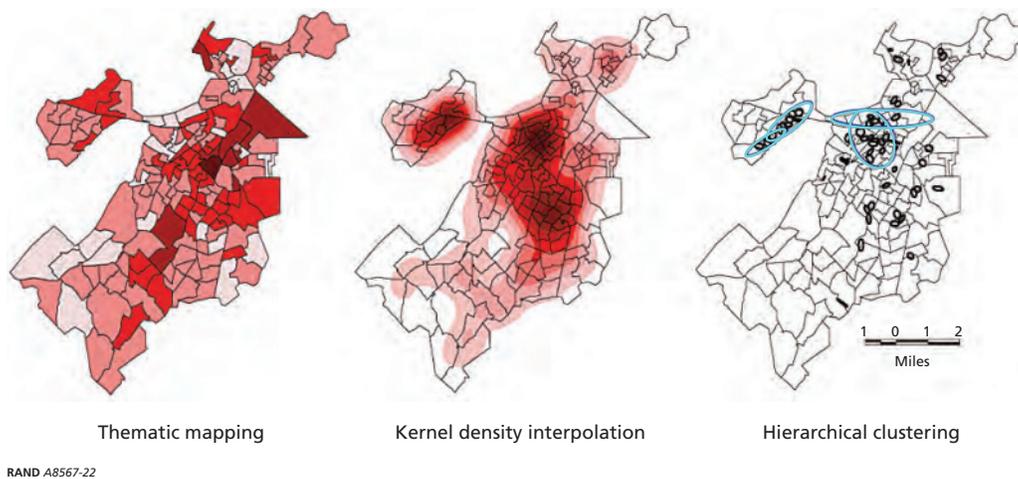
Source: Cameron and Leitner, 2005.

For each of the listed categories of hot spot analysis, it is possible to modify the underlying algorithms to reflect the AHS methodology. This will result in generation of hot spots that consider the spatial, temporal, and quantity resource constraints facing the decisionmaker tasked with deploying resources to problem areas. Modification of

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[3]Since the purpose of this illustration is to simply compare the maps resulting from the various approaches, the density and rate scales are not shown.

existing hierarchical clustering algorithms to enforce resource constraints is a rather simple exercise. Kernel density interpolation and thematic mapping approaches require considerably more effort to modify, but they, too, can be altered to consider resource constraints.

From Actionable Cluster to Actionable Hot Spots

After identifying spatially constrained clusters of disorder activity, the user will likely be left with many clusters. Three natural question arise:

1. Which clusters are hot spots?

2. Which clusters are hotter than others?

3. Given the resource quantity constraints, against which hot spots should resources be deployed to yield maximum benefit?

To be considered an actionable hot spot, it needs to be established that the concentration of events in the clusters is greater than in other parts of the study area. The standard approach to establishing a large concentration would calculate two concentration values:

1. across the study area — the total number of events in the study area is divided by the total size of the area size (in square kilometers or miles), and the resulting concentration is denoted by c_1

2. within each cluster — the total number of events in a cluster is divided by the total size of the cluster (using the same scale that was used for the calculation of the study area) to yield a cluster concentration denoted by c_2.

The cluster concentration is then divided by the study area concentration to yield a value $C = c_2/c_1$. If C is greater than $1.0 + \alpha$ (where $\alpha > 0$ may be defined as needed to highlight those hot spots that are distinctly different from the average density in the study area), the cluster has a higher relative concentration and is considered to be a hot spot. Actionable hot spots with higher relative concentration values are therefore considered to be "hotter" than hot spots with lower relative concentration values.

Prioritization

After actionable clusters have been determined to be actionable hot spots, the total number of these may exceed the resource quantity constraints of the decisionmaker. It is therefore required that the actionable hot spots that are candidates for resource deployment be prioritized in some fashion. Since the purpose of prioritization is to match the spatially constrained resources available in limited quantities with the problem, the prioritization should reflect the objective of the resource deployment and — if relevant to achieving that objective — temporal constraints. For example, if the objective is to reduce burglary in a small area and the deployable resource is a police patrol car available during the midnight – 8am shift, it would make little sense to put emphasis on historical events that occur during times when the patrol car is not active. A prioritization approach should put more emphasis on disorder events that occur at roughly the same time as the expected deployment of the resource.

For a given objective function and known constraints, this report proposes that each candidate actionable hot spot be weighted according to how well it is synchronized with the anticipated deployment of resources meant to combat future disorder events. The synchronization with the expected time of resource deployment can also be found through experimentation, but the basic shape of the weighting function should reflect knowledge of the deployment patterns.

Once each observation has been appropriately weighted, a cluster score may be computed, which is simply the sum of the weights in the hot spot. Prioritization then becomes simple: The actionable hot spots are ordered based on their marginal contribution to a cumulative total score (the total cumulative score will be equal to the sum of the weights for distinct events that fall within *all* identified hot spots). Resources should then be deployed first against the actionable hot spot with the highest marginal contribution to the cumulative score, followed by the one with the second highest score, etc., until the deployable resources are depleted. Since it is possible that hot spots may overlap and so events may be counted multiple times, only distinct events (those not already included in hot spots with higher marginal contributions) are counted toward marginal cluster scores. Of course, all of the events in the highest ranking hot spot will be used in the marginal score — the process of omitting nondistinct observations need only be applied to subsequent hot spots in order to accurately measure the marginal values.

Measuring Expected Performance

Although it is not possible to know how effective the resource will be once it is deployed, it is possible to use historical data to determine if the AHS-driven deployment of resources would have correctly selected areas where future events actually occurred. The performance metric is then the total number of events that occur within the recommended actionable hot spot during the resource deployment period.

For example, if the objective is to prevent burglary by sending out patrol cars to hot spots during the 8am – 4pm shift (temporal constraint), and if the cars have a patrol area of ten square city blocks (spatial constraint) and there are two patrol cars available for deployment for a period of seven days (quantity constraint), the computation of the historical metric would be done according to the following steps:

1. If the time when resource deployment will begin is represented by t (e.g., 8am on June 1, 2009), weighted actionable hot spots (given the constraints) would be computed using all relevant historical data available prior to t.

2. The two actionable hot spots with the highest weighted marginal scores would be selected for action.

3. For the next seven days beginning at time t, the number of distinct burglary events that occur within each hot spot (adjusting scores to avoid multiple counts of events that occur in more than one hot spot) during the 8am – 4pm period is counted. This is the expected performance metric.

With the performance metric, it is now possible to see whether the selection of actionable hot spots was successful. For decisionmakers comparing alternative resources for deployment, this approach will allow them to assess their potential ability to deter, disrupt, or prevent activity using various resources under consideration. Therefore, the AHS performance metric can be tested on historical data to yield an expected level of effectiveness and help choose the deployable resources that are likely to be most effective.

Case Studies

The actionable hot spot methodology was originally developed to help fight the IED problem in Iraq. Existing spatial analysis tools were modified, allowing decisionmakers to limit the number of candidate IED hot spots to areas that conformed to the physical limits of the resources tactical commanders intended to deploy

against IED emplacers. Through examples across different research areas, Chapter Five serves as a response to the third research question: *Can the actionable hot spots methodology be applied to guide resource allocation in research areas beyond the IED application for which it was originally developed?*

Any decisionmaker who is faced with deploying scarce resources to geographic areas where certain types of undesirable activity or phenomena occur may find this approach useful. This approach is not intended to replace any existing spatial analysis tools, but rather to augment them with the ability to conduct analysis where known constraints exist. To demonstrate the diversity of public policy areas under which this approach may be used, this report also provides three example applications: one in the maritime domain with national security implications (piracy in the Gulf of Aden), one in domestic health care delivery (colon cancer screening in a western U.S. state), and one in criminal justice (crime in a major metropolitan area). In each case, the actionable hot spot methodology was able to find clustering solutions that both respected the spatial, temporal, and quantity constraints and provided suggested future hot spots where events did actually occur.

We recognize that there are numerous models addressing resource allocation that have been specified for problems related to police, fire, emergency medical services, health care, etc., in addition to the IED emplacement problem. Our case studies explore research topics in which RAND is currently involved and where both the problem objectives and constraints have been clearly established by subject matter experts. Although a solution to the domestic health care delivery can be easily handled by well-known approaches such as the Maximal Covering Location Problem (MCLP) (Church and ReVelle, 1974; Church, 1984), we believe that the AHS approach provides an alternative solution that leverages commonly used hot spot identification tools and may appeal to geospatial analysts and policymakers unfamiliar with integer-programming approaches. Our approach may also add value in those types of resource allocation problems discussed in the other case studies — and perhaps additional topic areas; the prioritization phase of the AHS methodology captures shifts in spatial patterns that may occur as new target opportunities arise and/or the deployment of resources intended to interrupt future disorder events causes the actors to avoid detection. In that sense, we see the AHS approach as one possible way to address resource allocation problems when there is a repeating action-reaction exchange between those actors who deploy resources against disorder activities and those who are responsible for them.

Implications

Decisionmakers tasked with deterring, interrupting, or preventing undesired activities are limited by constraints caused by available, scarce resources; these resources often lack the ability to cover the vast geographic areas in which the problems occur. In the extensive body of research addressing the use of spatial analysis in criminal analysis, pattern recognition of insurgent and terrorist activity, and public health, the term *hot spot* has been adopted to indicate areas in which there is a greater than average number of problem events. This technical report provides a methodology that can be used to select and prioritize hot spots that can be matched with constrained resources. The methodology provides a means of measuring the expected effectiveness that would result by deploying resources against a problem using scarce resources. Not only does this approach provide a tool for aiding the decisionmaker as he/she chooses how to allocate existing resources, it also provides a mechanism for comparing the potential effectiveness of alternative resources.

The AHS methodology is not intended to replace any of the existing tools widely used by spatial analysts. Rather, it provides an enhancement to hot spot detection algorithms by enabling the geospatial analyst to match problem areas with the resources that they plan to deploy to combat the underlying problem. Users of $CrimeStat^{®}$, $GeoDa^{TM}$, and $ArcGIS^{®}$ across many fields may find utility in this approach when they are faced with constrained resources. Originally developed for a particular application, combating IED emplacement in Iraq, the approach had obvious applications in other fields. By modifying the original application to make it generalizable across a broad array of research topics, we have created a policy decision tool that may find utility across many topical areas (see Table S.1 for a nonexhaustive list of potential applications).

Table S.1
Potential Applications of Actionable Hot Spot Methodology

Topic	Application	Deployable Resource
National security	Maritime piracy	Visual surveillance assets Armed surface ships
	Counter-IED/indirect fire	Snipers Visual surveillance assets Infrared detectors Quick reaction forces
	Insurgent network detection	Visual surveillance assets Signal direction-finding assets
Homeland security	Border integrity	Visual surveillance assets Acoustic surveillance assets Border patrol agents
Criminal justice	Policing	Police patrols Visual surveillance assets Task forces
Health	Disease prevention	Screening clinics Targeted public service campaigns
	Pandemic crises	Immunization clinics Targeted public service campaigns
Labor and population	Economic disparity	Employment programs Poverty assistance