Measuring The Benefits of GIS Use: Two Transportation Case Studies

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Abstract: *The U.S. Geological Survey (USGS) is researching methods to improve the measurement of the benefits of using geographic information system (GIS) technology. As part of this research, case studies of GIS transportation applications were conducted at the Oak Ridge National Laboratory and the Wisconsin Department of Transportation. Benefits can be expressed as reduced costs or as improved quality of applications. The key to measuring benefits is to identify what has changed because of the GIS. By narrowing the focus to a single effect on a single user, it is possible to ask pertinent questions about value, and to reasonably measure benefits that previously had appeared to be nonquantifiable.*

Government transportation managers are under increasing pressure to do more and more with less and less. Ways must be found to make scarce budget dollars travel further. GIS technology is one possible answer to this dilemma, and transportation departments are turning to GIS with growing frequency. However, to get the most out of GIS technology, it is vital to be able to measure the potential benefits from its use. It takes a sizable initial investment to establish a GIS installation; such an investment is unlikely to be approved without solid documentation of significant potential benefits. Then, once a GIS capability has been established, there are many possible projects competing for scarce GIS resources. Without a reliable way to estimate benefits, lower-valued projects may be allowed to consume resources that could better be used on more valuable projects.

The technique used to develop estimates of benefits is a cost-benefit study. Theoretically, benefit estimates should be based on the societal marginal willingness to pay for GIS-provided improvements over the present system (Peterson and Sorg 1987). In the absence of externalities and monopoly, societal willingness to pay is measured by market prices. However, it is in the nature of government involvement in GIS operation that markets cannot set meaningful prices for many of the changes. E.J. Mishan (1982) comments that, although such intangible benefits can be measured in principle, there are likely to be difficulties in practice of putting reliable figures on them. Researchers at the U.S. Forest Service report that, although much progress has been made in recent years in the valuation of non-priced and non-priceable goods, emphasis has been on those things most readily measurable (Peterson and Sorg 1987).

Evidence of the difficulty of measuring intangible benefits can be found in cost-benefit studies in support of GIS acquisitions. The Bureau of Indian Affairs (BIA) analyzed the results of the installation of GIS at three test sites. They found that the GIS offers benefits above and beyond the outputs produced by manual alternatives, but treated most in an expository manner and made no attempt to place dollar values on the benefits (BIA 1988). A study by the Michigan Department of Transportation (MDOT) identified 156 potential benefits from the adoption of GIS technology, but could quantify only 19 (MDOT 1988). According to the Federal Geographic Data Committee (FGDC), although intangible benefits are difficult to quantify, many such benefits are the strongest arguments for having a GIS (Guptill 1988). Research conducted by the USGS provides a practical technique for improving the measurement of the benefits of using GIS technology.

Two Types of Benefits

Many different taxonomies of benefits are available for use in cost-benefit studies. The analyst might distinguish between primary benefits (from direct effects, intended effects) and secondary benefits (from ripple effects) (Tietenberg 1992). A common distinction is between tangible benefits (those which reasonably can

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be assigned a monetary value) and intangible benefits (those which can't) (Haveman and Weisbrod 1973). Another choice is between use-value and non-use (intrinsic) value (Smith 1984).

A particularly useful distinction for measuring benefits from the use of GIS technology is between efficiency benefits and effectiveness benefits. **Efficiency benefits** result when a GIS is used to do a task previously done without a GIS; the same quality of output is produced, but at lower cost. For example, cut and fill calculations can be made by applying planimetric techniques to contour lines on a graphic map, or by manipulating digital elevation data in a GIS. Both methods yield the same results, but a GIS is much faster and easier.

Effectiveness benefits result when a GIS is used to improve the quality of a current output, or to produce an output not previously available; the GIS is used to do something that could not or would not be done without it. For example, a GIS can quickly and easily produce maps showing how the proposed route for a new road would impact a series of environmentally sensitive resources. Such maps could be manually drafted, but the process would be so expensive that they probably would not be prepared. A GIS can also overlay a large number of separate environmental themes and calculate an overall impact. When there are more than just a few overlays, this is a task that is simply not feasible using non-GIS techniques.

The USGS research uses the efficiency/effectiveness taxonomy, not because it is conceptually superior to other taxonomies, but because it has practical advantages in measuring benefits. The distinction between efficiency benefits and effectiveness benefits is important because their sources are different, and techniques that will measure one will not measure the other. The source of efficiency benefits is a reduction in the cost of running an application. Estimating costs is easier, in general, than estimating benefits (Tietenberg 1992), and most cost-benefit studies do a good job of measuring efficiency benefits. The source of effectiveness benefits is a change in the output of the application. Because the value of new or improved GIS outputs can be difficult to estimate, all too often cost-benefit studies call these benefits intangible or nonquantifiable, and do not measure them at all.

Measuring GIS Benefits

During late 1990 and 1991, the USGS conducted more than 60 case studies of GIS applications. These applications were run by more than 40 different government agencies, and cover a wide range of topics. The case studies established practical techniques for distinguishing between efficiency and effectiveness benefits, and for reliably estimating the general level of both (Gillespie 1991a).

The key to measuring benefits is to identify what has changed because of the GIS. For efficiency benefits, the GIS output is the same as the previous manual output; what has changed is the resources needed to produce that output. This benefit is measured as the reduction in variable costs for running the application. In the 30 USGS case studies where efficiency benefits were important, the bulk of this cost was usually personnel costs. There was seldom any difficulty in measuring efficiency benefits.

For effectiveness benefits, it is the output of the application that has changed. The value of this benefit depends on the effect the changed output has on each user. Note that this is a very pragmatic definition. It says that a GIS output has value only to the extent that it causes changes in behavior. This ignores the entire class of benefits called existence value. Existence value is the willingness to pay for the knowledge that a resource exists, even if the individual has no intention of using the resource (Brookshire, Eubanks and Sorg 1987). Ignoring existence value means that, all other things being equal, the USGS measurements are conservative estimates of the level of effectiveness benefits.

In the 47 USGS case studies where effectiveness benefits were important, once the specific effect on a user of a change in the GIS output was identified, it was possible to estimate the value of the effect. Effectiveness benefits for an application are the sum of the value of the effects of each change in output for each of the users of the output.

Two of the USGS case studies are transportation applications; a hazardous waste-routing project by the Oak Ridge National Laboratory (ORNL) (Gillespie 1991b), and the pavement-management program of the Wisconsin Department of Transportation (WDOT) (Gillespie 1991c). These studies do more than just show the value of applying GIS technology to two specific transportation projects. They also demonstrate general techniques that can be used on traditionally hard-to-measure effectiveness benefits to significantly improve cost-benefit analyses.

Case Study—Moving Nuclear Wastes

One and a half billion tons of hazardous materials are transported each year in the United States (OTA 1986). GIS technology is increasingly being applied to analyze hazardous-materials transport decisions (Abkowitz 1990). One such application is performed by the GIS unit at ORNL.

There are 80 nuclear reactor sites operating in the United States. Radioactive waste products (principally, spent fuel rods) are being produced and stored at each site. Storage capacity is nearly exhausted at some sites. The radioactive wastes at each reactor site will need to be transported to a Department of Energy (DOE) nuclear waste disposal site. There is risk involved in the movement of radioactive wastes. The GIS unit at ORNL examines the feasible routes from each reactor to the disposal site, and determines the population-at-risk along each route (Durfee *et al.* 1988).

The ORNL GIS unit obtained 1980 census population counts and centroids at the level of census block groups and enumeration districts. The researchers then divided the entire country into 45 million grid cells, and calculated the population density within each cell. Using the GIS system, they then drew contour lines that connected cells of equal density. The proposed route and population density contours were overlaid on a general base map. The GIS then calculated a variety of different measures of population-at-risk:

- Total population within the route corridor.
- Average population density within corridor.
- Number of miles of route at each level of density.

The ORNL GIS unit does not believe it is possible to duplicate this GIS output via any manual method. If there were a population density contour map, it would be possible to manually plot a proposed route, and then to calculate population-at-risk with planimetric techniques. However, no such contour map exists, and it is not practical to manually create one from the 45 million density grid cells. There is no way for them to generate accurate population-at-risk information without the GIS; this means that these GIS benefits are effectiveness benefits.

The GIS output is different in that it provides information that would not be available without the GIS. DOE managers are the only users of the information. The effect of the new information the GIS provides is that DOE managers are able to select routes for transporting nuclear wastes that result in less risk to the general populace. What is the value of the selection of lower risk routes? The general level of effectiveness benefits was estimated by measuring three factors:

1) The likelihood that the GIS information will cause a lower risk route to be chosen.
2) The magnitude of the reduction in population-at-risk.
3) The value of the risk avoided.

As to the first factor, managers at the ORNL estimate that, even without the GIS information, the lowest risk route would still be selected in about half of the cases, but that a lack of GIS information would result in a higher risk route being selected in the other half of the cases.

For the second factor, the ORNL study found that the variation in population density among the various feasible routes was about 15 percent. This means that a route chosen without density information would probably involve, on average, 7.5 percent greater population density than the optimal route. The reduction in population-at-risk due to the GIS output is equal to the reduced chance of choosing a higher risk route, times the difference in density between the chosen route and the optimal route (50 percent x 7.5 percent = 3.75 percent). Most GIS routing studies find a variation in population along potential routes much higher than 15 percent (Lepofsky 1993). The relatively small variation found in the ORNL study is due to strict DOE rules that significantly reduce the number of feasible routes from each reactor.

As to the third factor, one possible approach is to identify the likelihood of an incident (significant accidental release of radiation) during transport, and multiply this by the expected cost of an incident. However, ORNL managers believe that, due to the nature of the shipping casks, the probability of an incident is extremely low. More important is the collective dose from the routine external radiation level from the casks. The public at risk are those near enough to a loaded transportation cask that they can receive a measurable dose. If fewer people are exposed to the risk of radiation exposure, then the expected collective radiation dose received by the public will be smaller. This in turn reduces the expected cost from radiation exposure during the transport of radioactive wastes. The expected cost can be determined by multiplying the expected collective radiation dose times the cost of a standard unit of dose.

Radiation doses are measured in rem's (roentgen equivalent, man). The DOE estimates that collective radiation doses from transporting spent fuel rods from the 80 reactor sites would be about 1,500 rem (DOE 1987). This collective dose is not spread evenly across the population. The various feasible routes tend to converge near the disposal site, leading to higher exposures for the population along the latter segments of a route.

The International Atomic Energy Agency (IAEA) estimates that the cost of a standard unit of dose (100 rem) is about $5,000 (IAEA 1986).

The estimated cost of radiation exposure to the public during the transport of radioactive waste from 80 reactor sites is therefore about $75,000 ($5,000 per standard unit of dose X 15 doses). The GIS output would reduce this expected cost by 3.75 percent, for an expected effectiveness benefit of about $2,800. Note that the $2,800 estimate is of the gross benefits of the application. To determine if GIS is a cost-effective approach for reducing risk, it would be necessary to compare the cost of running the application against the expected benefits.

Case Study—Pavement Management Program

A pavement-management program involves keeping an inventory of the existing condition of the roads included in the program, identifying the improvements needed, assigning priorities to these, and scheduling and carrying out improvements subject to a budget constraint. The Wisconsin pavement-management decision support system (PMDSS) was designed to provide computer support to the pavement managers (WDOT 1990).

A traditional pavement management system uses county, route, and log mile data for location information, but not geographic coordinates. The Wisconsin PMDSS has developed a conversion table to relate county, route, and log mile to geographic coordinates, to take advantage of GIS capabilities. The principal use of the GIS is to integrate data from various databases with different location reference systems, and to produce graphic product displays.

The pavement-management database includes information from a variety of other data files. The GIS provides a geographic coordinates location key that permits the easy integration of this information into the PMDSS structure. Without the GIS location key, the GIS staff would have had to manually collate the information into the PMDSS. Prior to the use of GIS, this is exactly what the WDOT did for a study comparing highway improvements with safety. In the absence of a GIS, they would have done the same type of manually collating for the PMDSS as well.

The WDOT estimates that manual collating would take about half a year of work and cost about $12,000. The GIS accomplishes the same task automatically and at trivial expense. The value of the GIS efficiency benefit is the avoidance of the $12,000 annual cost.

The graphic outputs of the application could not be produced without the GIS. The value of the graphic outputs represents effectiveness benefits. The only users of the graphic outputs are pavement managers in the WDOT. The graphic outputs have three effects on the users:

1) To improve quality control.
2) To provide better information about pavement sections needing detailed analysis.
3) To improve communications with local highway departments.

Benefits from Improved Quality Control

The graphic GIS outputs greatly improve quality control. Data errors that would remain hidden in long tables and columns of figures stand out plainly on the GIS graphic outputs. The GIS outputs have permitted the WDOT to make significant improvements in the quality of the data in the PMDSS. WDOT has identified and corrected an error rate that was as high as 5 to 10 percent.

The increased accuracy has resulted in changes in the annual pavement-management plan. The WDOT renovates about 900 miles of roadway each year. The purpose of the pavement-management plan is to make sure that WDOT renovates the 900 one-mile segments most in need of renovation. The GIS outputs enable pavement managers to identify highway segments badly in need of renovation that had been overlooked in the previous manual process. The increased accuracy due to the GIS results in the replacement of about 10 such miles of highway in the plan each year.

The GIS benefits are equal to the increase in the total value of the 900 miles of renovation. The total value increases because 10 miles of lesser valued renovation are replaced by 10 miles of more highly valued renovation. To directly measure the GIS benefits, it is necessary to know three things:

1) The value of a typical mile of highway renovation.
2) The typical variation in the value of renovation.
3) The value of renovation for the typical mile segment discovered by the GIS that had been overlooked by the manual process.

None of this information is known, but it is possible to make reasonable estimates. The value of a typical mile of highway renovation can be estimated based on total WDOT expenditures for renovation. This yields a conservative estimate of $350,000 per mile of renovation. WDOT officials believe that a 50 percent variation in the value of renovation is a reasonable estimate. This means that the value of the various road segments ranges from a low of about $230,000 to a high of about $470,000.

It is reasonable to expect that the 10 miles that are replaced from the original plan fall at the low end of the value range. It is also reasonable to expect that the overlooked segments that replace them are not the most highly valued segments; that is, it is more likely that average to lower valued segments would have been overlooked. WDOT officials believe that the overlooked segments on average are about 20 percent below the average value; that is, the overlooked segments have an average value of about $280,000.

The GIS benefits are measured as the increase in the total value of the 900 renovated miles. This increase is estimated to be $500,000 [($280,000 − $230,000) × 10].

Benefits from Better Analysis

The GIS graphic outputs help pavement managers to identify segments of roadway that deserve additional study. Prior to the use of GIS, it took about 40 hours to do the research necessary to answer a question about one segment. With the GIS, the needed information is available at the touch of a button. The GIS, therefore, enables the additional research to be done at much lower cost. In fact, prior to the use of GIS, pavement managers seldom did the additional research, and so made their decisions without the benefit of this information. The GIS effectiveness benefits are equal to the value of the new information.

The fact that pavement managers generally chose not to do additional research suggests that the value of the additional information was generally less than the cost of gathering it. The cost of 40 hours of research is about $475. Since pavement managers sometimes did do the manual research, this suggests that the value of the additional information is sometimes greater than $475, but not often. WDOT officials believe that $200 is a reasonable estimate of the average value of the additional information.

Only a small number (about 10 percent, or 90 miles) of the segments can benefit from additional study. The value of the GIS effectiveness benefit, therefore, is estimated as $18,000 ($200 per one-mile segment × 90 segments).

Benefits from Better Communication

Personnel from local highway departments meet with state DOT officials, at which time GIS-produced maps are used to help explain how the state pavement-management plan relates to local areas. These meetings involve considerable discussion, debate and negotiations, as this is the principal forum in which local concerns are incorporated into the plan.

The use of GIS outputs has not changed the amount of time and effort invested in these meetings. However, it has led to a positive change in the focus of the arguments. Prior to the use of GIS, much time was spent arguing about the accuracy of the data underlying the plan. Since the use of GIS, there has been general acceptance that the data are accurate, and the discussions have been much more directed toward questions of policy.

This change in the focus of the discussions almost certainly makes the meetings more enjoyable for most participants. However, it is less clear if the change yields any objectively measurable benefits. It is tempting to measure the GIS benefits as the value of the time saved on discussions of data accuracy. The fact that the meeting participants voluntarily chose to invest the time saved in discussion of data accuracy to discussion of other topics suggests that they believed those discussions to be worth at least as much as the value of their time.

The true measure of the value of the additional discussion, however, depends on what effect it has on decisions reached in the meetings and modifications to the pavement-management plan. This effect is not known, and it did not prove possible to make a reasonable estimate of it. The benefits of improved communication are probably positive, but have not been measured.

Summary and Conclusions

All too often, cost-benefit studies of GIS technology have done a good job of measuring efficiency benefits, but a poor job of measuring effectiveness benefits. This has the effect of concentrating attention on how a GIS can help to reduce the cost of an organization's existing applications. It suggests that expenditures on GIS technology are justified only when they will result in large efficiency benefits. This is a serious mistake. For many organizations, the real value of a GIS is not that it helps them do their work cheaper, but that it helps them do their work better. GIS technology has the potential to fundamentally change the functioning of many organizations. Measuring benefits only with an efficiency yardstick tends to slow down the adoption of GIS and to delay the realization of effectiveness benefits.

The solution to this shortsightedness is to do a better job of recognizing and measuring effectiveness benefits. When effectiveness benefits are not objectively measured, it is easy to dismiss them as intangible. When they are measured, it is clear that they are just as real as efficiency benefits.

The USGS case studies demonstrate a practical technique for measuring effectiveness benefits. The key is to identify how the GIS outputs are different from the previous manual outputs, and how those differences affect the users of the GIS outputs. Measuring the value of a single effect on a single user is a difficult task, but it is usually a feasible task. The case studies demonstrate that, by narrowing the focus to the point where pertinent questions can be asked about the value, it is usually possible to reasonably measure benefits that previously had appeared to be nonquantifiable.

The Oak Ridge National Laboratory case study shows that existing documents can be adapted to yield inferences about benefits, even when those documents do not explicitly address benefits themselves. The Wisconsin Department Of Transportation case study shows that the lack of hard data is not an insurmountable obstacle. Common sense assumptions and informed estimates can be used to reasonably measure the general level of benefits. The Wisconsin DOT case study also shows that it will not always be possible to measure every effectiveness benefit. The point is not that the USGS technique provides an infallible method for measuring effectiveness benefits—because it doesn't. What the USGS technique does do is provide a practical alternative to simply writing off effectiveness benefits as intangible. Better measurement of effectiveness benefits provides a better understanding of where and how GIS technology is useful, so that organizations can invest their GIS dollars wisely and well.

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