Sensible Field Computing: Evaluating the Use of Mobile GIS Methods in Scientific Fieldwork

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Abstract

Traditional analogue field methods are increasingly becoming a limiting factor in the workflow of computerized research projects. At the same time, the potential of mobile GIS and other mobile computing methods to support better and more efficient scientific data collection is widely acknowledged. There seems, however, to be little scientific proof for the added value and successful continuation of these methods beyond the pilot stage. In particular, the diversity and unique mobility characteristics of fieldwork pose specific difficulties for the design, implementation, and support of these methods. This paper offers a simple ex ante/ex post evaluation framework to help researchers in estimating the added value of a mobile computing method. The application of this framework is exemplified with an archaeological case study and demonstrates that its use can result in a more comprehensive view of the potential and actual benefits of applying specific mobile computing methods in scientific fieldwork.

Introduction

A large body of literature addresses the essential role that fieldwork plays in the geo- and environmental sciences such as hydrology, geology, and biology (Cottingham et al., 2002). While these fieldwork projects have different objectives and apply different methods, they share the characteristic that the collection of raw data is still carried out in a traditional way, using pen and paper as the main recording instruments (Wagtendonk and de Reus, 2004). However, in response to the expanding availability and functionality of powerful hand held computers, Global Positioning System (GPS) receivers, mobile geographic information systems (GIS), and computing software, researchers are increasingly integrating or replacing their conventional field methods with (seeming) more efficient mobile computing methods.

The capabilities and functionality of hand-held computers, mobile GIS, and related mobile location technology for scientific purposes are acknowledged by many researchers (e.g., Pundt and Brinkkötter-Runde, 2000; Vivoni and Camilli, 2003; Karimi et al., 2004; Nusser et al., 2004; Tripcevich, 2004). The research literature, however, does not provide convincing proof that the application of mobile technology is very successful in the long term; neither does it quantify or estimate its added value. In fact, most publications covering this subject describe only pilots and experimental trials (e.g., Pascoe et al., 1998; Vivoni and Camilli, 2003), which are frequently presented as successful or at least promising. Furthermore, researchers are often dealing with the subject of computer-assisted fieldwork from a very technical perspective (e.g., Tsou, 2004; Montoya, 2003). More process-oriented points of view, e.g., using cost-benefit approaches and comparing existing and new methods are still rare. In short, critical reviews of the suitability of mobile GIS methods are occasional or absent. Authors such as Clarke (2004) and Nusser et al. (2004), however, propose to put the development of new models and methodological principles for the use of mobile GIS and mobile computing in scientific data collection on the research agenda. Missing in this respect, are sound methodological principles for the design and evaluation of mobile computing methods, prior to and after their application.

The main objective of this paper is to offer an ex ante/ex post evaluation framework for the application of a mobile GIS-based field method, exemplified with a case study concerning archaeological field surveying. This means that we evaluate beforehand (ex ante), on the basis of a detailed process analysis, the possible added value and possible drawbacks, of a new mobile GIS method for an archaeological field survey. Next, we evaluate (ex post) the impact of the applied mobile computing method on the research process in this case study, based on a consensus judgment with several users. The selected case study represents a typical category of scientific fieldwork that has a focus on efficient and effective data collection during archaeological surveying in Southern Italy.

Although this framework does not include a specific methodology for the design of a suitable mobile computing method, it contains several of the components necessary to plan such design. Nor does the framework offer a methodology for estimating the chances of a successful implementation and adoption of a new mobile computing method. These chances depend on many different factors, including technical, financial, organizational, and even psychological factors. Although we will discuss some of these factors, a systematic analysis of these factors is not in the scope of this paper.

To support the process analysis in the evaluation framework described above, we first need a better understanding of...
the relationship between principal fieldwork characteristics and the specific properties of computer assisted field methods that are supposed to generate an added value to the field process and the scientific workflow. This will be the subject of the first part of the paper, including a characterization of the most relevant mobile aspects of fieldwork and fieldworkers, in different disciplines. Next, we will present a case study, followed by the process analysis of the ex ante and ex post evaluation of the mobile computing method.

Scientific Fieldwork and Mobile GIS Field Computing

Fieldwork is considered, in most disciplines and particularly in geography, as a key element for understanding our world through direct experience and consequently “as a fundamental method for geographical education” (Gerber and Chuan, 2000). In addition to its role in scientific education, fieldwork is essential for the collection of scientific, location-specific data.

With scientific fieldwork we refer to the collection of information for scientific studies that is performed outside of the university or research institution setting, usually through the collection of scientific location specific data and/or the study and analysis of certain natural or social phenomena. We will concentrate especially on fieldwork in which the exact or approximate location of the subjects of study plays an important role. This implies the mapping of the location or geographical extent of the field data and storage of the data in a spatial database or a GIS.

It should be noted that in the last two decades, the objectives and scale of geo-scientific field campaigns went through considerable changes as a result of the developments and application of remote sensing data collection techniques. For example, with the use of the Earth observation satellites, we can now study several land surface characteristics (e.g., vegetation dynamics, soil moisture, geological structures) without even going into the field (Wagtendonk and De Jeu, 2005). There still remains a need, however, to conduct fieldwork to verify our remotely sensed data, measure locations not covered by remote sensing, or measure field characteristics such as stream flow velocity that cannot be measured from a distance. The combination of mobile GIS and location technology such as GPS, make these new field tasks possible in a more efficient and effective way, particularly in areas with poor map resources or homogeneous terrain with few reference points. An overview of different forms of integration between mobile GIS and remote sensing for different disciplines has been given by Gao (2002).

Aside from the changing role of fieldwork described above, it is important to realize that there are small but essential differences between scientific fieldwork and institutional fieldwork (e.g., for asset management) or fieldwork for commercial purposes. Possible differences include scientific data requirements, the complexity of the field methods, the need for analysis or interpretation on the spot, and the deployment of students instead of only professional fieldworkers. These differences have an impact on the design and requirements for both traditional and modern field methods.

In the central part of Figure 1 (presented in the grey boxes), we have summarized the most important limitations and requirements in scientific data collection. A comparative SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) is carried out between traditional field methods and mobile computing methods applied in scientific fieldwork, based on reported experiences of several authors (e.g., Beck, 2003; Buller, 2002; Leusen and Ryan, 2002; Montoya, 2003; Nußser et al., 2004; Nykänen, 2002; Pundt and Brinkkötter-Runde, 2000; Tripcevich, 2004; Tsou, 2004; Vivoni and Camilli, 2003) and some of our own experiences with mobile computing methods (Wagtendonk and de Reus, 2004; Wagendonk et al., 2004a; Wagendonk and De Jeu, 2005; Beinat et al., 2005). A SWOT analysis is a well-known, simple, and powerful tool in business research and can be used for auditing a product and its environment. The results from our SWOT analysis are also presented in Figure 1.

The scheme in Figure 1 makes clear that although mobile computing methods offer obvious advantages in efficiency and effectiveness of data collection, they also require relatively high personal and financial investments to develop, implement, and maintain. Even though researchers understand the advantages, they often lack the necessary resources for development and implementation of new methods, including knowledge and experience with mobile computing technology. They therefore risk interrupting the dataflow of the whole research process and the loss of invested resources in case of failure. To break through this vicious circle, they have to know beforehand what are the probable costs and benefits, and what are the likely chances for success or failure of implementation.

To what extent the necessary investments in mobile equipment, application development, data preparation, and organizational changes will be worthwhile depends on many factors, but in the first place is the purpose (e.g., directed to scientific data collection or directed to learning specific field measurement skills in a student centered approach) and characteristics of the fieldwork itself. Other factors that can have a direct impact on the potential for mobile computing methods include:

- the available financial resources for mobile equipment (short and long term),
- the importance of digital data used in the office workflow and the desired speed of data acquisition,
- the importance of exact field locations,
- the amount of repetitive field measurements,
- the importance of revisiting measurement locations,
- the importance of digital field analysis,
- the importance of objective data collection, direct error control and validation,
- available technical assistance for application development and assistance during fieldwork,
- motivation for application of mobile computing methods and technical knowledge of users, and
- the need for real-time information in the field.

Characteristics of Mobile Field Computing

It could be argued that the current trend of computerization of the field process resembles the automation process of office work that took place in the past decades. However, the process of scientific data collection in the field is in many respects incomparable with data related operations in the office or laboratory environment. Some important aspects that affect the design of mobile computing methods and applications were presented by Pascoe (1998) with the key characteristics of a mobile fieldworker:

1. “Dynamic User Configuration. The fieldworker wants to collect data whenever and wherever they like, whether they are standing, crawling, or walking.
2. Limited Attention Capacity. Data collection tasks are oriented around observing a subject. Depending upon the nature of the subject the user will have to pay varying amounts of attention to it. In most of these situations it is important that the user has to devote minimal time to interacting with the recording mechanism.
3. High-Speed Interaction. The subjects of some time-dependent observations can be highly animated or, more commonly,
have intense periods or ‘spurts’ of activity. During these spurts of activity they need to enter high volumes of data very quickly and accurately, or it will be lost forever.

4. Context dependency. The fieldworker’s activities are intimately associated with their context. For example, in recording an observation of a giraffe, its location or the location of the observation point will almost certainly be recorded too. In this way the data recorded is self-describing of the context from which it was derived. Further applications of the data often involve analyzing these context dependencies in some form, e.g., plotting giraffe observations on to a map.”

Which of these characteristics are applicable, and to what extent, depends on the specific fieldwork. The type of field research, its scientific objectives, the scale of the study area, and the field situation determine to a great extent the way the research is carried out (walking and crawling), and in what kind of organizational setting (number of teams and internal cooperation). In reality, this means that mobile methods have to be tailored to the unique fieldwork characteristics in order to be successful. As an example, design implications for a fieldwork process where researchers need almost constant visual contact with their object of study (limited attention capacity for the recording mechanism), could be certain indirect operating interface mechanisms, such as automatic completion of fields, automatic time and location stamping, audio controls (voice recognition), specially designed buttons on device or touch-sensitive screen, and different kinds of context based services (Ryan et al., 1999).

Case Study: Salento-Isthmus Archaeological Field Surveys, Italy

In 1999, the Archaeological Institute of Free University Amsterdam began the execution of archaeological field surveys on the Murge plateau in Southern Italy (Attema et al., 2003) as part of a larger archaeological project, the Salento-Isthmus project. The main research objective of the Salento-Isthmus project is to investigate the way that local communities shaped and interacted with the landscape in the first millennium BC, including the influence of Greek and Roman colonization starting in the late eighth century BC.

The specific goal of the field surveys is to collect data for this investigation by systematically surveying this archaeologically almost unexplored area. In spite of the considerable deployment of students, the fieldwork approach is purely scientific and lacks deliberate educational elements.
Fieldwork Process and Mobility Characteristics

The operational field process consists of a systematic survey of selected areas divided in survey units with small field teams of five persons. On the basis of aerial photographs and the local situation at hand, the surveyed terrain is divided as much as possible in regular, rectangular units of 50 m × 50 m that are surveyed by the team-members walking simultaneously five parallel transects (Figure 2) of approximately 2 m wide and 50 m long (covering in this way 20 percent of the surface of the whole unit), looking for and collecting all visible anthropogenic material (pre-classic to middle ages) lying on the ground surface.

Before or just after walking the unit, the team leader maps the unit on an aerial photograph and describes the environmental and physiographic characteristics of each separate unit in a special form, linked to the unit number on the aerial photograph. The unit characteristics are used to classify the landscape the unit is in, and to determine the possible visibility of the archaeological finds in each unit. For example, a unit with a high degree of stoniness and dense vegetation scores very low on the five-parameter visibility index. Depending on the score in the visibility index, the number of finds in each category are multiplied with different factors to be able to construct the final, weighted, finds density maps. After walking a unit, the finds are collected in numbered sample bags for later determination and classification in the sample database. In the case that field teams cross each other, -unit borders are compared with landmarks on the aerial photographs and corrected where necessary. This is usually only possible for clear landmarks. In those areas, accurate GPS-based mapping methods would be preferable (Leusen and Ryan, 2002).

With respect to mapping accuracy, it should be noted that the exact location of archaeological findings inside a unit is irrelevant for the survey method as a whole. The mapping of unit borders affects, however, the measured area of the units and therefore the artifact density calculations that are carried out in the post-processing phase. Correct unit mapping is especially difficult in hilly areas without clear landmarks. In those areas, accurate GPS-based mapping methods would be preferable (Leusen and Ryan, 2002). Accuracy requirements for the purpose of density mapping are, however, still rather limited as it is expected that the estimation of the five-parameter visibility index (stoniness, shadiness, vegetation cover, soil humidity, and amount of recent anthropogenic material) by different surveyors is a much larger source of uncertainty than the expected location errors in unit mapping (e.g., Wandsnider and Camilli, 1992; Bevan and Conolly, 2004). Therefore, some deviation of unit size and/or position can be considered acceptable by researchers in this kind of survey project. The aerial photographs used for archaeological field surveys on the Murge plateau in Southern Italy have an acquisition scale of 1:10 000 and are taken to the field as photocopies on the same scale. If we estimate a maximum field drawing accuracy of approximately 1 mm, this implies that the maximum accuracy of unit borders drawn in the field is around 10 m.

Location errors in the field drawings are corrected as much as possible in the postprocessing work in which previously drawn unit borders are compared with landmarks, such as roads, on the aerial photographs and corrected where necessary. This is usually only possible for locations that have been clearly used as a starting or ending point for the surveying. For example, in Figure 3 all unit borders can be corrected on the basis of surrounding roads.
and field borders. However, the exact location of borders between units, such as between units 12168 and 12169 in Figure 3, can only be determined by skilled survey teams in the field on the basis of counting steps (distance walked), estimating distances, or by comparing specific landmarks in the field with the aerial photograph.

If we assume that the post-processing work can improve the accuracy of the field maps to about 5 m, this would imply a maximum surface error of approximately 20 percent per unit, in the case of 50 m × 50 m units (underestimated as 45 m × 45 m or overestimated as 55 m × 55 m). This (non-cumulative) unit mapping accuracy is in line with comparable surveys (e.g., Martens, 2005).

Based on this rough estimation, we suggest that in order for any kind of automatic positioning technology to be of additional value for survey unit mapping, it should have a horizontal accuracy of 5 m or less. The different mobility characteristics discussed here have important design implications for the developed mobile GIS application and method, these will not, however, be discussed in this paper. For specific design considerations relevant for mobile GIS methods in archaeological survey we refer to Tripcevich (2004) and Leusen and Ryan (2002).

Ex ante Evaluation of Mobile GIS Method
To get a more comprehensive idea of the characteristics and the potential benefits of applying a new mobile computing method, we carried out a detailed process analysis. Figure 4 illustrates the workflow of the traditional archaeological field survey process, broken down into four basic process components: the preparatory planning and logistical activities at the research institution; the operational process during the fieldwork itself; the post-processing activities in the field lab; and the intelligence and analysis back in the office environment of the research institution.

We will use this scheme to discuss in a systematic way, where and how improvements to this process can be made. Additionally, we describe in Table 1 how different process components are carried out in the traditional method and how they can be executed using a mobile computing method. The added value of the new method is then assessed for each of the presented process components. The nature of the benefit is described in qualitative terms, such as efficiency, effectiveness, consistency, and accuracy. Where appropriate, we also add possible drawbacks to the use of the mobile computing method. The numbers in the far left column in Table 1 correspond to the process components in Figure 4.

The results in Table 1 make it clear that the described mobile field method has many potential advantages compared to the traditional method in different phases of the process, in principle leading to faster and better scientific output. This alone would justify the development and implementation of such a method. It is, however, still difficult to estimate the change and success of using such implementation only on the basis of the table. As previously discussed, the potential of a mobile computing method depends on many factors. Without going into detail, the main reasons in this case study in favor of the development and application of this new method were the scientific nature (quality requirements) of the survey, the specific mobility characteristics (previously described in the Characteristics of Mobile Field Computing), the important role of location, the intense use of digital spatial data in the research process, the repetitive character of the measurements, and finally, the motivation and need of the involved researchers for applying a new mobile computing method. Further, the proposed method followed closely the well established, existing method and was therefore expected to have relatively small impacts, and associated risks, on the existing research process.

Applied Mobile GIS Method
On the basis of the analysis presented here above and in close cooperation with the archaeologists of the Salento Isthmus project of the Free University Amsterdam, we designed, developed, and tested the new mobile computing method. The concept was piloted in 2004 and fully operational in 2005 and 2006.

Application Characteristics
The developed application consists of three distinct components: (a) orientation, (b) mapping, and (c) registration.

The “orientation component” consists of the combination of the mobile GIS (i.e., a PDA with common mobile GIS software) and a wireless GPS with an accuracy of approximately 5 m. The combination of GPS with mobile GIS serves for quick position determination in the terrain on the orthophotos. All GPS functionality is provided by the mobile GIS software.

The “mapping component” serves to map the perimeter of each unit in a consequent, effective, and efficient manner. To make spatial analysis possible, like density mapping, units have to be mapped in the form of topologically correct polygons. Originally, mapping was done by sketching the unit borders in the field on a paper copy of an orthoimage. A serial number was added for each mapped unit corresponding to the attribute information collected from each unit.

After the fieldwork, back in the office environment of the research institution, these borders were digitized and transformed to a GIS format and linked to the unit attribute tables on the basis of the unit numbers. For the current application, a map tool was developed to automatically draw geometrically correct polygons on the basis of GPS start and end position of the survey team leader. This process requires minimal user attention and speeds up the mapping considerably. As this method is less appropriate for irregular terrain, the application also provides a manual mapping option. In both methods vector points are used for labeling.
units and adding attribute information (adding the point initiates the unit form interface). The reason for this is that the manual mapping method does not always produce topologically correct, closed polygons in the field and can therefore not be used to add attribute information. Where necessary, closed polygons are created and corrected on the basis of the orthophoto during the post-processing process. Finally, points with attribute information are linked to the corresponding units in a point-in-polygon operation.

The “registration component” aims at collecting all relevant unit information in a consequent, effective, and efficient manner. To guarantee a good integration with the existing research process the digital entry form has been based directly on the original analogue form. Most of the parameters on this form are linked to lists of fixed variables which could therefore easily be transformed in pick lists or dropdown lists, see Figure 5. To support a clear and logical data-input, the digital form was organized in different tabs, see also Figure 5.

To ensure complete data entry, users cannot fill in certain information or end the data entry process without finishing the registration of certain key fields (conditional data entry). Other characteristics of the digital entry form are automatic time and location stamping for each unit, automatic registration of unit numbers, and a copy option of the last recorded unit data (this is a time saving option in areas where there is no, or little, variation between units).

The form contains a special tab to describe the samples taken in each unit. As the unit database on the PDA is linked to the sample database, filling in this field means simultaneously filling in the samples database. Furthermore, for each unit fixed day parameters are entered automatically on the basis of a set of session parameters, like project name and team members that have to be filled in after starting up the application. Finally, the application gives the option to produce an automatic day report.

**Preprocessing and Postprocessing Activities**

Preprocessing activities preceding the fieldwork consist mainly of collecting, processing, and georeferencing digital orthophotos. Daily preprocessing activities during the fieldwork include preparing and downloading updated unit layers to the PDAs, cleaning up memory cards, checking functionality of mobile devices, charging batteries, and so on.

The daily postprocessing activities in the field lab consisted of:

- error checking of the attribute database, error checking and on-screen enhancement of unit borders on the basis of the digital orthophotos and judgment by the responsible team leaders,
- integration of point (with attribute data) and polygon data and merging of completed GIS layers,
- addition and processing of digital sketch layers of encountered sites,
- preliminary density analysis of archaeological finds.
**Table 1. Comparison of Traditional Field Method with Possible Mobile Computing Method**

<table>
<thead>
<tr>
<th>Nr</th>
<th>Traditional Method</th>
<th>Mobile Computing Method</th>
<th>Added Value</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Acquisition of maps and orthophotos. Reproduction (copies) of field maps and unit forms.</td>
<td>GIS database preparation. Map transformations between coordinate systems, image compression. Preparation and transfer to mobile GIS data base</td>
<td>• Complete digital workflow  • Central GIS database  • Database suitable for GIS analysis</td>
<td>• Preparation phase more time consuming  • and specific GIS skills required</td>
</tr>
<tr>
<td>3</td>
<td>Survey plan/data collection strategy (where to survey) is based on analysis of landscape characteristics and known sites. Mapped units are drawn on a paper copy of an analogue orthophoto. Preparation field material (field forms, maps, etc.)</td>
<td>Survey plan is prepared in a similar way as in the traditional method but can be adapted during the fieldwork on the basis of daily updated unit map showing find densities. Field teams can bring updated field map on PDA and/or in printed form. Preparation mobile equipment (memory cleaning, battery charging)</td>
<td>• Completeness  • Coherence  • Effectiveness</td>
<td>• Map preparation requires GIS skills and/or support  • Daily technical preparation more complicated</td>
</tr>
<tr>
<td>4–5</td>
<td>Orientation in monotone agricultural fields or repeatedly, areas with lack of reference points, is difficult, time consuming and leads easily to confusion and errors.</td>
<td>Mobile GIS with GPS orientation makes quick orientation in difficult terrain possible, also for people with less orientation skills. This decreases the time the survey team has to wait for the team leader finishing the orientation and mapping tasks.</td>
<td>• Speed  • Spatial accuracy  • Flexibility (deployment fieldworkers)</td>
<td>• Dependence on mobile equipment and location technology</td>
</tr>
<tr>
<td>6–7</td>
<td>Unit mapping and site sketching on paper copies of aerial photographs</td>
<td>GPS assisted mapping in mobile GIS. Digital drawing on transflective PDA screen.</td>
<td>• Speed  • Spatial accuracy  • Relocation units &amp; sites (GIS location)  • Easy production of maps  • Attribute accuracy  • Completeness  • Coherence  • Daily up-dated field database: no omissions or duplications</td>
<td>• Limited map visibility with intense sunlight  • Limited map overview</td>
</tr>
<tr>
<td>6–8</td>
<td>Manual unit numbering on unit form and corresponding units sketched on orthophoto. Leads easily to numbering errors.</td>
<td>Automatic unit numbering in unit form linked to unit numbers on unit map prevents duplicate unit numbers, omitted unit numbers or not corresponding unit numbers between map and unit form</td>
<td>• Speed  • Completeness  • Attribute accuracy  • Consistency  • Database queries in field possible</td>
<td>• Risk for equipment, data storage or data trans-mission failures</td>
</tr>
<tr>
<td>8</td>
<td>Manual registration of unit parameters in analogue forms. Poor handwriting can lead to interpretation errors. In areas with similar units, the same information has to be filled in repeatedly which is time consuming and leads easily to mistakes.</td>
<td>Dropdown and/or pick lists for selecting appropriate unit and visibility characteristics. Copy unit information option in case of similar units. Automatic registration of time, location and specific session parameters per unit. Data entry order and obligatory or conditional fields make data collection by different teams more objective</td>
<td>• Speed  • Completeness  • Attribute accuracy  • Consistency  • Database queries in field possible</td>
<td>• Risk for equipment, data storage or data trans-mission failures</td>
</tr>
<tr>
<td>10–12</td>
<td>Paper administration unit forms, and transcription to database. Error checking database</td>
<td>Digital upload from PDA to PC</td>
<td>• Speed  • Elimination manual transcriptions and related errors  • Limited post-processing activities</td>
<td>• New digital data transfer risks</td>
</tr>
<tr>
<td>13–15</td>
<td>Manual digitizing in CAD program of sketched unit boundaries. Map editing and conversion to GIS. Link to unit attribute information via unit number</td>
<td>Digital upload of unit GIS layers and digital sketches. GIS map editing. Merge with unit attributes using point in polygon operation.</td>
<td>• Speed  • Strong decrease post-processing activities  • Objectivity (map editing controlled by team leader)  • Flexibility</td>
<td>• GIS skills/support required</td>
</tr>
<tr>
<td>16</td>
<td>GIS (density) analysis in office environment in the Netherlands</td>
<td>GIS (density) analysis during fieldwork leading to progressive insight study area and possible adaptations to survey strategy and additional field checks</td>
<td>• Speed  • Completeness  • Effectiveness  • Student learning and motivation</td>
<td></td>
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</tbody>
</table>
• cartographical preparation and printing of field maps for data collection strategy, and
• preparation of updated survey data layers for daily download to PDAs.

Data and Communication Aspects
Data sets can be divided into spatial source data (orthophotos, 1997; Servizio Cartografico Regione Puglia, acquisition scale 1:10 000, 2 m resolution) used as backdrop images for orientation and mapping purposes, and the final unit data (vector format), i.e., the geographic delineation of unit shapes and associated attribute data. Additional datasets like topography, land-use, and elevation are used for preparation and postprocessing purposes, but not in the field on the handheld computer. A 10 percent compression was applied to the orthophotos to make fast zooming and panning on the mobile device possible.

Usually two to four field teams operate in the same study area. The survey project leader coordinates the different teams, and each team is coordinated separately by a team leader. Team leaders discuss on a daily basis the survey strategy with the survey project leader and stay in touch by mobile phone. Collected data is uploaded at the end of the day to the digital GIS database in the field station and integrated and processed by the GIS specialist. The use of wireless data exchange and communication infrastructures were not considered because of the limited need for this kind of functionality and because of the remoteness and hilliness of the area, that results in a rather poor coverage of telecom networks, especially outside the villages.

Ex post Evaluation of Mobile GIS Method
As the introduction of new computer-assisted data collection methods impacts several components of the research process; the final evaluation of a new method should take all these components into account in an aggregated assessment. An evaluation of the different components of the field method was made by systematically interviewing team leaders experienced with both the old and new methods. This involved structured (open-ended) oral interviews with two team leaders shortly after the 2005 campaign and three different team leaders shortly after the 2006 campaign. Interviews were structured on the basis of the different process stages and the different components of the methodology within these stages. Small improvements were made to the application and methodology between the field campaigns of 2005 and 2006, but these were not considered structural changes. Evaluation results of 2005 and 2006 could therefore be aggregated. Interviews with (student) team leaders and other team members not experienced with the old method were excluded from the evaluation. All conducted interviews were summarized in two evaluation reports, one for 2005 and one for 2006, which were discussed with the field leaders and the field campaign leader, among others, in a special seminar dedicated to Mediterranean field surveys (personal communication, Free University Amsterdam, 10 February 2006).

Based on the interview-based evaluation reports, we summarize (see Table 2) the consensus judgment on the impact of the new method on eight evaluation axes. Most of these impacts are difficult to quantify, so we have judged them using an ordinal scale, categorized in different quality indicators, and for different process components. The table does not contain symbols for negative impacts, as these were not observed in this case study or compensated by other positive impacts. Where quantification of impacts was possible, we have added them after the following qualitative evaluation table.

In the “preparation phase” of the fieldwork, some positive impacts are identified, mainly related to the fact that the preparation, organization, analysis and storage of field data can all take place on one computer, reducing the need for photocopies and paper administration. In terms of mobility, data exchange and so on, this has considerable advantages, but at the same time the digital organization at the research institution and at the field base station can imply other risks if data bases are not well organized or managed.

In the “execution phase” we see a clear positive effect in terms of efficiency improvement (component A), mainly as a result of faster orientation and field mapping. Also the digital data entry speed increases because of the tailored interface design and (partly) automatic input assistance. This efficiency is further improved by the fact that the method simplifies the operational tasks of the team leader. This makes it possible to promote fieldworkers with less orientation and mapping skills to the role of team leader, which eventually increases the field activities resulting in faster data collection. Logically, this has also a positive effect on...
The flexibility of the organization of the fieldwork (component G). Further, the program logic, GPS support and the user interface helps fieldworkers to collect more spatially accurate and consistent data, without omissions or redundancy, effecting positively the effectiveness and data quality in components B and C. At the same time the storage of unit data in a queryable GIS database linked to GPS locations positively affects the repeatability and verifiability of research results (component D). Last but not least, the motivation and commitment of fieldworkers is clearly positively effected, confirmed by pre- and post-evaluations with all the involved fieldworkers. Fieldworkers see clearly the benefits of the mobile computing method and see the method also as an opportunity in learning several technical field method skills, such as the use of mobile GIS, GPS, and mobile computing in general.

The largest benefits of the new method, however, can be seen in the “postprocessing phase.” In terms of efficiency, considerable time previously spent in transcribing analogue data to a digital format, can now be spent on database cleaning and map editing during the fieldwork campaign. As this postprocessing work can now be done directly after returning from the field, it gives the possibility for the team leaders to check the quality of their recordings on a daily basis and assist the GIS specialist in the data and map editing, positively increasing the effectiveness of the process (B) and quality of the produced results (C), especially in terms of reliability. In the old situation, the postprocessing work was often undertaken after the fieldwork campaign, back in the office environment in the Netherlands. In the case that the team leaders were involved, their feedback was less reliable as their memory of exact unit characteristics would be affected. Another positive effect of the digital GIS data collection is that, the relatively simple GIS editing process (effecting components B and G) can all be done on one PC using one GIS software program, making data transitions between CAD and GIS superfluous. Fieldworkers already trained in the use of mobile GIS can be trained relatively easily in executing the GIS editing tasks on the PC in the field station. Clearly, the removal of postprocessing tasks (transcription analogue data to digital database) and the fast computer postprocessing generates time which can now be spend on more intelligent and motivating tasks (thus a strong impact on the back office processes in the intelligence/data analysis phase), effecting also the motivation of fieldworkers in this phase of the process (component H). Another positive side-effect on the execution phase results from the fact that fieldworkers can now be daily-supplied with updated databases and field maps on their PDAs, giving a better overview of the completed work and preventing redundancy in overlapping study areas between field teams. A positive effect for the preparation phase is that updated field maps are used on a daily basis after the fieldwork in the field camp for discussing progress and survey strategy with all survey team members.

In the “intelligence/data analysis phase” the biggest impact follows from the fact that processed and checked data is already available during the fieldwork, making first data interpretations and data analysis, like density mapping, possible already during the field campaign. An example of an artifact density map is shown in Figure 6. The results of this kind of analysis can create further insight into the artifact finds distribution in the study area and give occasion to reflect on the best survey strategies. The earlier production of analysis results can in principle also lead to faster dissemination of research results. In fact, the speed of data collection and processing poses questions to current research strategies, which are still based on the interpretation of artifacts by specialists. Because of the increased speed in which initial results become available, the existing practice of publishing preliminary results based on rough interpretations of material has become even more interesting and the problem of delay in detailed artifact interpretation has become accentuated. For archaeologists working in areas where it is not allowed to remove artifacts from their original position, as discussed by Tripcevich (2004), the increase of onsite analysis potential would probably be very welcome. Finally, the availability of processed data and analysis possibilities increases the learning possibilities of students and therefore their motivation and commitment during the fieldwork.
A number of the impacts described here can be quantified. Unfortunately, it is often difficult to find relevant material for comparison between traditional and new field practices. One of the reasons for this is that comparisons between different years cannot be made, because of differences in study areas leading to considerably lower or higher numbers of surveyed fields. Another reason is that it is very impractical to have operational field teams using different field methods simultaneously. However, in the first pilot year of the new application, only one team was equipped with the new method and the other teams with the old method, making quantitative comparison possible. In Table 3, the quantitative results of 2004 are presented. The figures are based on the results of one field team during a fieldwork of approximately four weeks, resulting in circa 500 mapped units per team.

Table 3 shows only a minor increase in the number of mapped fields during the fieldwork, but it shows also the almost complete elimination of the time involved in database input (from paper field forms). Also, the reduction in digitizing work is considerable, work that is in the new method carried out during the fieldwork on a daily basis. Finally, a part of the GIS analysis in the new method is already carried out during the fieldwork. Considering the fact that this comparison is based on the year of implementation when only a part of the current functionality was in operation, these figures are conservative. We expect a higher number of mapped fields in the execution phase compared to the traditional method, as a result of improved GPS orientation (not yet functional in 2004) and mobile GIS mapping functionality. The figures in this table confirm earlier experiences (Wagendonk et al., 2004b) that quantitative benefits are initially found mainly in the reduction of postprocessing work. After fieldworkers got used to working with the new method and often after additional improvements, also the time gains during execution tend to increase, especially in the case of professional fieldworkers.

As in any implementation of a newly developed method there are also some drawbacks to mention, often related to technical issues. Some of these drawbacks are represented in the “weaknesses of mobile computing methods” box in Figure 1. However, none of these issues have seemed to have a lasting effect on the data collection process, and therefore they are not discussed here.

A drawback of the evaluation method presented in this paper could be the fact that the execution of a good evaluation is a labor and time intensive task, requiring thorough knowledge and/or analysis of the field and scientific processes involved. However, as the field process is often such a central and determining element in the whole research cycle, gathering more process knowledge can in any case be considered beneficial for the improvement of the field processes, even if it is decided that mobile field methods are not applicable or don’t have sufficient added value.

**Summary and Conclusions**

The potential of mobile GIS methods for the improvement of scientific data collection is widely recognized and many examples of trials and pilots of such methods are described in the research literature. However, despite the apparent consensus on their potential, implementing mobile computing methods is less straightforward than it seems, i.e., there is not a simple translation from analogue method to digital method. The specific mobility characteristics of different fieldwork activities and several technical, organizational, and financial factors strongly affect the successful implementation of such methods. Furthermore, the implementation of new data collection methods impacts the workflow of the research process in several ways, as scientific data collection is a principal component of the research process. In other words, implementing new data collection methods involves existing research practices and needs careful consideration, implementation, and evaluation. However, surprisingly few authors accompany their research results regarding the implementation of mobile computing methods with systematic analyses of achieved success or failure. Neither do authors describe the decision process they went through in developing and applying mobile computing methods in their research.

In this paper, we have therefore proposed an *ex ante* and *ex post* evaluation framework to help researchers in estimating the added value of mobile computing methods before and after their application. This framework offers a strong foundation for decisions concerning the implementation of mobile computing methods, well integrated in the whole research process. A case study of archaeological surveying is used to illustrate the use and outcome of this framework.

To support the use and understanding of this framework, we started this paper with an overview of shared knowledge concerning advantages and disadvantages, in the form of a SWOT analysis, of both traditional and mobile field computing methods, based on the work of several authors.

The *ex ante* evaluation is based on a process analysis of the existing field method, combined with knowledge of technological possibilities and specific mobility characteristics of the fieldwork. This paper shows that by carrying out a process analysis of the fieldwork in relation to the whole research process, the added value of mobile field computing...
can be assessed in a systematic and complete way. In the case study, the ex ante evaluation results in a strong expectation of benefits from applying mobile field methods.

After the actual development and implementation of the proposed method in the case study the ex post evaluation was carried out, based on a consensus judgment with several users, experienced with both the old and the new methods. The results of this evaluation confirm the expectations that followed from the ex ante evaluation, which has therefore at least an indicative value. The ex post evaluation framework shows how an evaluation of a new mobile computing method is carried out that takes into account different research process phases and qualitative process indicators. In the case of the archaeological case study, it shows that the applied method has particularly strong impacts on the effectiveness and verifiability of data collection in the execution phase and on the efficiency of the field postprocessing phase. This is the result of the elimination of analogue data from the workflow, removing several laborious postprocessing tasks. In other words, it reduces friction from the workflow, freeing up time that can now be used for more intelligent tasks, like error control and data analysis. The removal of tedious tasks in the field and during the postprocessing stage also contributes to the motivation and the involvement of the fieldworkers in the research process. For the organization, the mobile computing method means more flexibility in the composition of field teams and a better deployment of skills and work power. Even more important, it leads to a shift from merely data collection to data analysis during the field campaign. As a whole, we conclude that the mobile computing method leads to a more efficient, consistent data collection, resulting in a faster and higher quality of scientific output.

Finally, our research demonstrated clearly the benefits of using the ex ante/ex post evaluation framework for planning and evaluating computing methods in scientific fieldwork. The ex ante evaluation in this paper showed that a better overview of the potential benefits (and drawbacks) of a mobile computing method can be formed if the method is analyzed in relation to the whole research workflow. This gives a stronger foundation for the decision to implement such methods, and also provides important indications for the design of such methods. Furthermore, it can create important support in the organization for the approval of development plans. The ex post evaluation on the other hand, confirms in an objective way the expectations from the ex ante evaluation and provides a more complete picture of the identified benefits and insight in relation to the work process. It also identifies new potential benefits and opportunities that are not yet fully exploited.

The scientific data collection process is an essential process for research. When it comes to improvement, there is obviously much at stake. Investments have to be made and risks have to be taken. The evaluation framework presented in this research is a powerful tool to support such decisions. The evaluation framework is a good starting point for the disciplines where mobile computing methods are considered for scientific data collection. The framework is also useful for the evaluation and further improvement of already applied mobile computing methods.

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