

GIS, SINKS, FILL, and Disappearing Wetlands: Unintended Consequences in Algorithm Development and Use

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ABSTRACT

Geographic Information Systems (GIS) software has become an important computational tool in several fields. GIS software ranges from command line processors, with maximal control over internal model decisions, to GUI versions with point-and-click access to pre-set modules. Based on the output from this software, some GIS users make important decisions to plan and manage landscapes (e.g., cities, parks, forests) with real consequences for the managed ecosystems. We discuss a programming decision in a GIS algorithm originally used to discern flow direction in hydrological modeling: a first step in mapping streams and rivers. Topographic depressions (“sinks”) are “filled” in the algorithm to map water flow downstream; otherwise, the GIS algorithm cannot solve the flow direction. Unfortunately, sinks are often “isolated” wetlands which provide essential habitat for many species not commonly found elsewhere. Thus the algorithmic filling of sinks can make these wetlands “disappear” in GIS output and land-use decisions based on this output.

This algorithmic detail may have potentially devastating real-world consequences for numerous wetlands because land-use plans made in ignorance cannot adequately conserve these unique habitats and the vital ecosystem services that wetlands provide. These consequences were not anticipated by the programmers who originally implemented the flow direction algorithm and may not be known to GIS users. We offer several strategies to reduce the impact of these consequences for GIS programmers, users, and policy makers who depend on GIS data when making decisions.

Categories and Subject Descriptors

K.4.1 [Computers and Society]: Public Policy Issues – *ethics*.

General Terms

Algorithms, Documentation

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Keywords

Geographic Information Systems, GIS, land ethic, ecological ethics, hydrologic model, wetlands, algorithm, assumptions log.

1. INTRODUCTION

Geographic Information Systems (GIS) software (e.g., the prevalent ESRI products ARC/INFO, ArcView, and ArcGIS) have become a *de facto* standard for anyone who models spatial systems using digitized maps, topological data, and remote sensing data. GIS computational tools continue to increase in popularity (Figure 1), and are likely to remain a major tool for spatial modeling and its applications to urban and natural resource planning and management. In addition, the improved spatial resolution afforded by new satellite technologies will enable more detailed models of spatial patterns and processes. However, GIS capabilities have not developed without criticism [19], some of which are related to modeling decisions: these issues will remain regardless of improvements in data resolution [10].

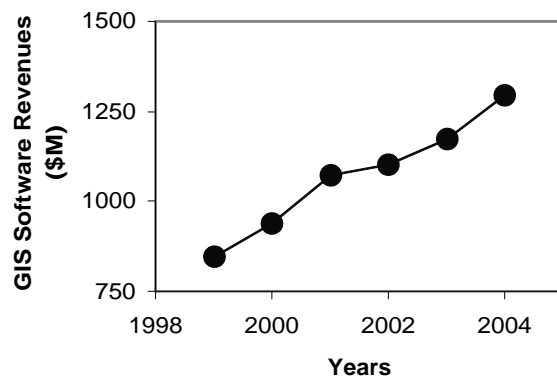


Figure 1. Estimated annual GIS software revenues, in millions of \$US, unadjusted for inflation. Values for 2004 are projected, and all data were obtained from DaraTech, Inc. (<http://www.daratech.com>).

When faced with uncertainties regarding decisions, disciplines should be guided by ethical standards and GIS users are no exception [16,23]. Despite the fact that GIS is explicitly focused on spatial systems that include non-human entities (i.e., ecosystems, including diverse species), the code of ethics for GIS focuses only on human interactions [23]. Standards for ethical interactions between humans are essential, but it is striking that a discipline that focuses on ecosystems and landscapes has not also

incorporated into its code the long-standing and vital principle of a land ethic [9]. A land ethic “simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land” [9]. A land ethic has recently been expanded into the relatively new sub-discipline of ecological ethics [14].

Many GIS users (e.g., regional planners and public lands managers) employ daily a strong ecological ethic that may not be explicit in an organization’s code of ethics. GIS users and their organizations make important decisions, based on GIS output, that have significant consequences for many people and landscapes, including the ecosystem services [3] provided by ecosystems within a landscape. It should be all the more important to GIS users and their organizations to discover any hidden or overt decisions in GIS software that might be affecting policies and implementation plans based on GIS output. An important example is provided by the decisions regarding the recognition, definition, and protection of wetlands.

Landscapes are composed of terrestrial (e.g., forests, prairies) and aquatic (e.g., rivers, lakes) ecosystems, and are most simply visualized in those terms. More difficult to categorize are wetlands, which are transitional between terrestrial and aquatic ecosystems, and may vary through the seasons or years in their fit to either dry or wet conditions [15]. Riverine wetlands are clearly associated with perpetually-flowing, navigable waters, and so are protected under the U.S. Clean Water Act. However, many other diverse wetlands (variously dubbed depressional wetlands, vernal pools, temporary ponds, prairie potholes, and ephemeral or seasonal wetlands) may only receive or discharge waters to rivers occasionally, if ever. These wetlands (hereafter referred to as “isolated” wetlands) provide important ecological services such as flood mitigation, groundwater recharge, nutrient processing, and habitat for unique flora and fauna [8,20,26]. However, many (~90% in some U.S. states) wetlands have already disappeared due to human land use [2] and protection of remaining isolated wetlands under U.S. law has been challenged [24,25]. Among all landscape components modeled using GIS, isolated wetlands may rank as one of the most numerous and most controversial: therefore, GIS-based decisions need to be well-founded.

To what extent is our GIS-based understanding (and thus protection) of isolated wetlands affected by decisions in GIS algorithms? To answer this question, we focus on a decision in ESRI GIS software in which landscape depressions (a.k.a. “sinks”) in hydrological models are “filled in” virtually to “correct” the flow of rivers and streams in the virtual landscape. A sink is a topographic location (e.g., a 30 m² cell in a Digital Elevation Model, or DEM) that is at a lower elevation than all neighboring cells. Note that this definition of a topographic sink is wholly consistent with the definition of an isolated wetland [8]. Also, we should make it clear that much wetland loss occurred before the advent of GIS [2]. We emphasize here the potential effects of GIS on current and future conservation of the few remaining wetlands.

2. USING GIS TO MODEL HYDROLOGY AND AN UNINTENDED SIDE EFFECT

Hydrologic models in GIS often use elevation data to model the locations of streams and rivers, and typically begin by modeling

flow direction across a digital landscape and make two basic assumptions regarding rivers and streams in the landscape:

- (a) Rivers are fractal systems [18,22]. Fractal geometry accurately models the irregular textures and branches of many natural patterns [11], as opposed to Euclidean geometry that best describes the smooth surfaces and continuous edges of human-engineered objects. As fractal systems, rivers are then assumed to demonstrate self-similarity at different scales of hierarchical branching forms and to be space-filling (i.e., all of a surface is ultimately drained). It is this second assumption of fractal patterns that is especially important for wetlands, because it implies that no isolated wetlands exist.
- (b) “Sinks in elevation data are most commonly due to errors in the data. These errors are often due to sampling effects and the rounding of elevations to integer numbers. Naturally-occurring sinks in elevation data with a cell size of 10 meters or larger are rare (Mark, 1988 [*sic*; 12]) except for glacial or karst areas, and generally can be considered errors.” (ARC/INFO Documentation).

Before a hydrologic model can be generated, a digital elevation model (DEM) must be “corrected” to remove problems identifying unassigned flow direction. If flow enters a cell lower in elevation than its neighbors (i.e., a sink), then the GIS flow direction algorithm cannot discern where water would flow thereafter. It is important to note that sinks occur on the land between stream channels, and do not necessarily occur only in streams (i.e., a map of flow directions is not synonymous with a map of streams). The hydrologic model programming deals with sinks by identifying them and “filling” them in the DEM, using the SINKS and FILL routines in ARC/INFO or by following menu sequences in ArcView or ArcGIS. A comparable correction can also occur within the flow direction routine, because one-cell sinks “are considered noise.” While users of ARC/INFO (command-line programming) are more likely to fully understand the assumptions of the SINKS and FILL routines because they must read command documentation, users of ArcView or ArcGIS invoke SINKS and FILL routines through higher-level command structure in drop-down menus, and need not read documentation. Once isolated sinks are “corrected,” flow direction modeling can occur without the logic dilemmas posed by sinks. It is possible to generate flow directions without invoking SINKS and FILL, but resulting models of streams are obviously in error compared to traditional maps because streams are fragmentary and/or do not match known stream locations. Thus, most hydrological models will fill sinks.

This algorithm is perfectly satisfactory for the simple purpose of identifying water flow directions, assuming available water exceeds soil and basin retention capacities + evapotranspiration rates, and that this assumption remains a constant, as in a river. However, nature is not always that simple, and difficulties ensue when the above process is used to model natural landscapes because:

- (a) Natural systems are not purely fractal [5] or constant. Therefore, assuming fractal geometry (and its corollary of space-filling) applies a fixed approximation. In reality, numerous isolated wetlands are partly drained to rivers only occasionally, if at all, and otherwise dry by

evapotranspiration. Mapping those wetlands as part of permanent drainage networks falsely “fills” and then “drains” them in GIS models and ignores their role as wetland habitats and flood-control systems unique to rivers or terrestrial ecosystems.

- (b) Numerous sinks $\geq 10 \text{ m} \times 10 \text{ m}$ (i.e., 100 m^2) exist as real-world entities, called isolated wetlands. For example, $> 1,000$ former isolated wetlands (average size = $5,000 - 10,000 \text{ m}^2$ depending on the model used) were identified by using sinks in one Illinois county now dominated by agriculture [13]. These wetlands were within a glaciated region, but this is also true for wetlands within the 30% of the Earth’s land surface that was glaciated during the Pleistocene [4]. In addition, many more wetlands also exist in unglaciated karst regions of the world (e.g., Florida). To assume that isolated wetlands $> 100 \text{ m}^2$ can be considered topographical errors is to ignore many large isolated wetlands in hydrologic models of land surfaces and further enable or promote wetland losses. In addition, at least one-third of Earth’s land surface is a significant exception to the advice that sinks can be considered errors.

Thus, the decision to “fill” sinks in a digital elevation model of a landscape equates to the decision to obliterate depressional wetlands in that modeled version of reality (Figure 2). For some uses of these hydrological models, that decision may not have significant consequences. However, if the resulting GIS stream layer is used in subsequent land-use and natural resource management decisions, then those decisions may contribute to significant wetlands loss, species extinctions, and increasingly disastrous flooding. How can wetlands be conserved, protected and managed if they are not known to exist? The phrase “disappearing wetlands” in the title of this paper is, therefore, doubly appropriate: because of the algorithmic decision to “fill” isolated wetlands, those wetlands can disappear from GIS output. When the isolated wetlands disappear from GIS output, policy decisions based on that output may result in the physical disappearance of those wetlands as well.

The increasing importance of GIS in land-use planning and natural resource management sets up a potential for many such scenarios. In addition, financial support for labor-intensive field verification of GIS models is commonly limited, so organizations (e.g., state agencies) may rely more heavily on GIS models: each GIS programming decision becomes increasingly significant if field verification is absent.

In the case of isolated wetlands and the species inhabiting them, this influence could be catastrophic on top of historical losses of the majority of wetlands [2, 6,13,20].

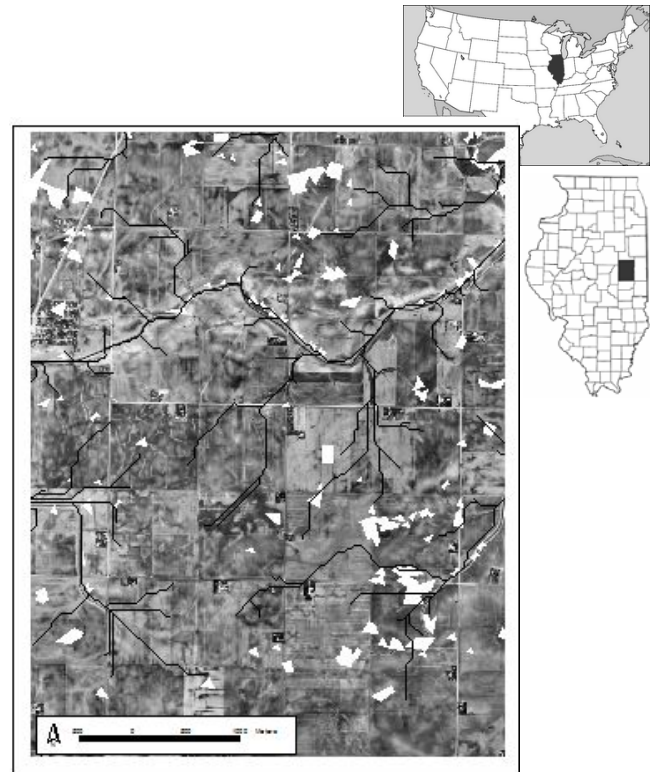


Figure 2. An example of the potential impact of hydrological modeling in GIS on isolated wetlands. Sinks (white polygons) and streams (black lines) are overlaid on an aerial photograph of bare fields (Foosland NE quarter quadrangle of Champaign County, Illinois, USA). Unlike most GIS hydrological modeling, sinks were identified (and saved as a data layer) prior to “filling” in preparation for hydrological modeling of flow directions, and streams were based on those flow directions. Typical GIS hydrological modeling would not save the sinks before mapping of streams, and most GIS users and consumers would not visualize the sinks, some of which represent isolated wetlands. Insets show Illinois within the U.S.A. and Champaign County within Illinois.

3. EXAMINING FOUR STAKEHOLDERS IN GIS HYDROLOGICAL MODELING

This mismatch between the *model* of the landscape and the physical *reality* of the landscape causes different, important problems for each of four groups of GIS stakeholders:

1. GIS programmers. We define GIS programmers as those ARC/INFO users who are relatively more sophisticated about the inner workings of GIS and ARC/INFO. GIS programmers may also develop macros, routines, and interfaces for ArcView and ArcGIS users.
2. ArcView and ArcGIS users. We define ArcView and ArcGIS users as relatively less sophisticated users who depend on menu-driven, point and click interfaces to process GIS data.
3. Consumers of the information GIS programmers and ArcView and ArcGIS users produce. We define consumers as end users who are unaware of algorithmic assumptions and decisions and rely on GIS information produced by the

other two groups of people. For example, a GIS technician may develop maps to be viewed by managers, who use the maps in forming policies and management decisions.

4. Isolated wetlands. We define this set of stakeholders as the distinctive sets of species and their habitats collectively recognized as these ecosystems.

Each group is affected by the model-reality mismatch as follows:

1. GIS Programmers. The ARC/INFO command line format requires users to specify detailed code. These users presumably learn the details of the ARC/INFO code at a low level of detail via access to the documentation for the SINKS and FILL commands, including the appropriate caveats about the limitations of those functions. Thus GIS programmers are likely be aware of the limitations, and should be aware of problems that might be caused by that mismatch. However, GIS programmers developing a new application that might conveniently use SINKS and FILL are confronted with the following choice: either use the SINKS and FILL commands with their inherent limitations, modify SINKS and FILL to better take into account the problem, or write completely new routines (perhaps based on a new model; e.g., [7,17]. Not surprisingly, GIS programmers typically use the existing SINKS and FILL routines to build new applications.
2. ArcView and ArcGIS Users: These users access GIS data and functionality using pull down menus and packaged modules developed by GIS programmers. These menus and modules enable more users (those without the sophisticated knowledge of GIS and programming required of GIS programmers) easy access to the useful functions and data available through GIS. However, these relatively less sophisticated users are likely to have a less detailed understanding of the assumptions and limitations of the algorithms implemented in a pull down menu. This group generates many of the GIS products for End Users.
3. End Users. These are people who don't know and/or don't care about *how* GIS helps develop necessary information, but who are intensely interested in the information developed. For example, people using ArcView or ArcGIS (group #2) can develop a hydrological model of a landscape (e.g., a forest) and plan for hydrological modifications (e.g., roads, drainage, dams) from the comforts of their office (assuming little/no field verification occurs). Resulting plans (and the known and unknown assumptions about the reality of the terrain) will then be used as the basis of actual construction work. It is quite likely that managers and contractors will all work from the resulting plan, and will not realize that the plan is based on a *model* replete with assumptions.
4. Isolated Wetlands. These ecosystems must suffer the consequences of decisions by the human stakeholder groups 1-3. Some isolated wetlands persist as fragmentary residuals of former ecosystems, as when they are bisected by a road, or converted to retention ponds. In these cases, some species may persist, while others perish or leave. Other isolated wetlands (and the species inhabiting them) are obliterated entirely under urban development or agriculture. Of course, isolated wetlands have no voice in decision processes, though the loss of ecosystem services [3] (e.g., flood control) may eventually impact other stakeholders after the wetlands are lost.

At this point, we want to emphasize an important distinction between the human stakeholder groups: of the three, the GIS programmers are the most likely to understand the weaknesses of the SINKS and FILL commands. However, they are also the least likely of the three groups to know in detail how the other two groups will eventually interpret the GIS data processed, output, and used by the other two groups. *This difference between knowledge of the algorithmic details and knowledge of the eventual consequences of those details is a critical aspect of the problem.*

We do not wish to imply that the groups above set out to harm wetlands. On the contrary, we expect that GIS developers expected better management of all lands with increasingly efficient oversight. Indeed, the use of GIS is expected to facilitate decisions based on more accurate and precise information than would be practical without GIS. However, through the partitioning of GIS expertise and decision-making described above, the consequences of some GIS software choices may result in irreparable harm for the fourth stakeholder group: isolated wetlands. Especially in the absence of field verification, GIS output becomes a "reality" more important than the actual physical contours of the landscape. Given that a GIS "reality" is relatively inexpensive to produce, and field work is more expensive, limited budgets will dictate that decisions be made based primarily on GIS output. But that fiscal efficiency bears an external cost resulting from a simplistic model of a complex natural system: entire ecosystems (including endangered species) may be erased.

Typically, stakeholders in an ethical analysis are humans. However, by expanding GIS ethics to include ecological ethics, we also identify small wetlands as a fourth stakeholder group. In turn, wetland loss affects people because of the loss of ecosystem services [3,8,20,26]. The vast majority of wetlands that once existed in the U.S. have already been lost [2], in part because value systems did not include them. Unfortunately, the somewhat obscure details of a particular GIS algorithm have become an obstacle for the people and organizations trying to maintain existing wetlands and trying to restore some of the wetlands already lost. GIS-based understanding (and thus protection) of isolated wetlands is heavily affected by decisions in GIS algorithms; decisions that appear to be unrecognized and with consequences that were surely unintended.

4. POSSIBLE REMEDIES TO THE MODELING PROBLEM

How should the problem described above be fixed, and who should fix it? A relevant principle in professional ethics is that a person with more power in a situation has increased responsibilities in that situation [1]. In this case, GIS programmers are in a position of power. They know the GIS algorithms and their limitations better than anyone, and they are the people who make the power of the algorithms conveniently available to other users. The locus of responsibility and the power to change reside mostly with the GIS programmers.

There are different ways GIS programmers could approach this problem. Without any additional programming, GIS programmers

could try to educate users about the limitations of some of the algorithms. This might be effective, but our experience suggests that people will use tools that are most convenient, and will often ignore software instructions, users' manuals, and software documentation.

Another approach would be to produce output that more accurately reflects the actions undertaken to produce the model. One possible fix would be an Assumptions Log with a map output that progressively records assumptions accrued during GIS modeling and that is saved with model output. For example: a hydrological model should keep a database of the number, sizes and coordinates of sinks that were filled, and depict the "filled" sinks as a GIS map. With this information available, users would at least have the potential of recognizing that wetlands may have been ignored in the model. Once identified, these wetlands could be included in the model and might be protected in subsequent decisions and policies. Such an approach could be generalized to illuminate other decisions with ethical importance that are made in GIS, and it is also likely to help End Users better understand that GIS products are no more than models of real ecosystems and landscapes.

We think an approach that is more likely to be the most effective (but the most expensive) is to change the assumptions in the current modeling algorithms to avoid assumptions that "fill" isolated wetlands. This approach will require some non-trivial revisions to the SINKS and FILL commands (see [7,17]) and perhaps several other commands that interact with those two. Despite the expense and protracted distribution likely for this strategy, we think it may be the best ultimate solution (though an assumptions log would also continue to be valuable). It is our judgment that the potential harm to the wetlands counterbalances the costs of these revisions, and that all three suggestions should be followed until this third option is operational.

In addition to GIS programmers, we contend that GIS users also bear responsibility to be sensitive to the possible detrimental effects of using GUI data products without sufficient ground truthing. Organizations (e.g., U.S. Geological Survey) that provide GIS data layers and products (e.g., maps, data bases) that include hydrological models described above should carefully examine the assumptions of the model, including ramifications and limits on the ethical use of models given those assumptions, and should prominently list those assumptions and ramifications in metadata associated with data and products. Web-based access to GIS data and products accelerates the transfer of valuable GIS outcomes, but also enables widespread ignorance and/or misuse of inappropriate assumptions, and only furthers the undervaluation and obliteration of isolated wetlands. More complete information about the limits of these data products might prevent some of the inappropriate decisions that will lead to significant ecological harm in the long run.

Finally, we recommend that GIS ethics codes (e.g., [23]) incorporate an ecological ethic [14] to explicitly acknowledge that the ecosystems represented in GIS products are also stakeholders in decisions based on those GIS products. Full consideration of the ramifications of GIS analyses will help avoid future dislinkages between programming decisions and end-user decisions as described here, and will help avoid the unintentional

extirpations of wetlands and the species that live in them.

5. CONCLUSIONS

GIS has revolutionized the manner in which we visualize, understand, and manage our physical world. GIS programmers and users can produce, interlace, and summarize multiple complex data layers in maps that cogently display complex spatial information for interpretation and application of that understanding. But GIS remains no more than a model of spatial patterns, with all the assumptions, internal decisions, and limitations inherent in a model of the physical world [21]. As with any model, the internal decisions and assumptions are important, especially when the model can be the primary resource for subsequent decisions affecting entire ecosystems.

GIS programmers and users have an ethical responsibility to understand, record, and convey those assumptions and programming decisions to end users who may have little technical appreciation for GIS modeling steps. In addition, that ethical responsibility should transcend exclusively human-oriented ethical standards by incorporating ecological ethics: outcomes of GIS programming and use have important consequences for entire species and ecosystems in this life support system we call Earth. Isolated wetlands are sensitive systems threatened by an algorithm commonly used in GIS, in addition to other pressures. GIS programming should not contribute to further loss of isolated wetlands: programmers and users have the responsibility and power to resolve the problems presented here, and to more wisely use GIS for more effective decisions regarding isolated wetlands.

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