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Integration of near-surface monitoring information using ArcGIS at the Illinois Basin – Decatur Project, USA

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Abstract

The Illinois Basin – Decatur Project (IBDP) is a large-scale carbon capture and storage (CCS) demonstration injecting 1 million metric tons (1.1 million tons) of carbon dioxide into a deep saline reservoir over a period of 3 years. Near-surface site characterization and monitoring was initiated in 2008, and it includes multiple data streams that need to be periodically compiled, organized, and assessed throughout all phases of the project. A database of over 150 spatial data layers from external sources and project partners was compiled for the project using Esri's ArcGIS software. The database is used to integrate IBDP near-surface monitoring measurements into an accessible and flexible spatially-referenced framework. The geographic information systems (GIS) map database enables a wide range of information visualization and exploration. Although some limitations do exist (e.g., data management overhead, a selectively-optimized environment for temporal data representation), the IBDP GIS-based data management solution works well for map-based information visualization, as well as spatial data exploration and analysis. In particular, the automation of routine spatial analytical tasks has resulted in significant time savings when applied to mapping and analysis of near-surface field monitoring data (e.g., soil fluxes) and is an example of how a GIS framework can be applied to other data streams at IBDP and other CCS projects.

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Keywords: Illinois Basin, IBDP, CCS, geologic carbon storage, MVA, near-surface monitoring, soil CO_2 flux, GIS, spatial data management, analysis, mapping, automation.

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1. Introduction

The Illinois Basin–Decatur Project (IBDP) is a large-scale Carbon Capture and Storage (CCS) demonstration injecting 1 million metric tons (1.1 million tons) of carbon dioxide (CO_2) into the subsurface over 3 years at a rate of 1,000 metric tons (1,102 tons) per day. Near-surface site characterization and monitoring began in 2008 to establish pre-injection baseline conditions, and injection of CO_2 into the Mt. Simon Sandstone began in November 2011. Monitoring, verification, and accounting (MVA) goals at IBDP include demonstrating that project activities are protective of human health and the environment. Both deep subsurface and near-surface zones are being monitored throughout all phases of the project (i.e., the pre-injection, injection, and post-injection phases).

In general, display and management of subsurface information is often accomplished by use of commercial modeling packages tailored for viewing and interpreting geologic information, such as drilling and core descriptions, geophysical logs, seismic data, or 3-dimensional subsurface models. However, for surficial and near-surficial information, geographic information systems (GIS) are better-suited to capture and analyze spatial relationships between data elements, and GIS software can be a more flexible data management environment due to the wider availability of standard-format data, spatial analytical tools, and software customization options. Spatial datasets (often referred to as data *layers* or map layers) from numerous sources have been compiled and organized in a spatial database and GIS map framework in support of IBDP near-surface monitoring activities.

The goals in establishing a GIS map and database project for IBDP were to develop an integrated framework to: (1) efficiently manage spatially-related project data, (2) import data from external sources and project partners, (3) document land surface changes and site activities over the life of the demonstration, and (4) integrate IBDP near-surface monitoring measurements into an accessible and flexible spatially referenced framework. Presented here is a discussion of our working GIS solution and the challenges and benefits of its implementation using ArcGIS [1] software for the IBDP site in Decatur, Illinois.

2. Project background

Geographic information systems software has played a central role in regional geological mapping and carbon storage resource assessments by the Midwest Geological Sequestration Consortium (MGSC) for more than 10 years, based on a strong history of GIS use and available data at the State Geological Surveys of Illinois, Indiana, and Kentucky [2, 3, 4].

Under the U.S. Department of Energy – National Energy Technology Laboratory's (DOE) Regional Carbon Sequestration Partnership (RCSP) program, early carbon sequestration studies from 2003–2005 by the MGSC performed regional mapping and assessment of geologic reservoirs for potential subsurface storage of CO_2 [5]. Geospatial datasets (e.g., map layers of reservoir extent, thickness, depth, and other properties) were compiled from both new and existing information, and used in volumetric equations to map and quantify CO_2 storage resource estimations and differentiate areas with greater or lesser storage potential. The use of GIS for organizing and automating the resource calculations provided the means for a powerful combination and manipulation of data, and offered flexibility to incorporate changing parameters as our understanding of the data and storage reservoir characteristics evolved.

Closely following MGSC's regional assessment work, several small-scale sequestration pilot projects [6, 7, 8] illuminated the need for integration of regional geological maps and data with more localized spatial data from a variety of external sources, for the purposes of (1) initial screening of site characteristics and selection of optimal CO_2-injection test locations, and (2) proximity analysis of sensitive features per environmental reporting requirements [9] after a candidate site was located. The pilot projects often required quick access to broad compilations of best-available data; early project time spent on spatial data organization and management resulted in readily accessible data for analysis, mapping, and reporting—and enabled rapid response to changing project needs.

To achieve our goals for near-surface spatial data management at IBDP, we sought to leverage past work and have a standardized GIS framework that integrated previous geological assessments and environmental data compilations with new MVA field measurements and monitoring analysis. Likewise, we expected to build upon our experience with GIS automation and programming, and apply these techniques to repetitive spatial data processing, analytical, and map creation tasks.

3. Methods

The IBDP study site is approximately 0.65 km^2 (0.25 mi^2), located in Decatur, Illinois, (Fig. 1) at the Archer Daniels Midland Company (ADM). Near-surface site characterization and baseline monitoring was initiated in 2008 and will continue throughout the life of the project through the post-injection monitoring period scheduled to end in late 2017. Near-surface MVA efforts focus on net CO_2 flux monitoring, soil flux monitoring, soil gas monitoring, and shallow groundwater monitoring. As these are ongoing monitoring efforts, data are continually added to the spatial data repository.

The foundation for IBDP geospatial data was a compilation of geological, environmental, and infrastructural datasets—to which we added custom data layers relevant to the IBDP site. Currently, a suite of over 150 spatial data layers from federal, state, and local sources has been compiled and organized to support IBDP activities. The collection of georeferenced imagery and data layers is herein referred to as the IBDP map database. A brief overview of the primary data layers in the map database is provided, with sources noted.

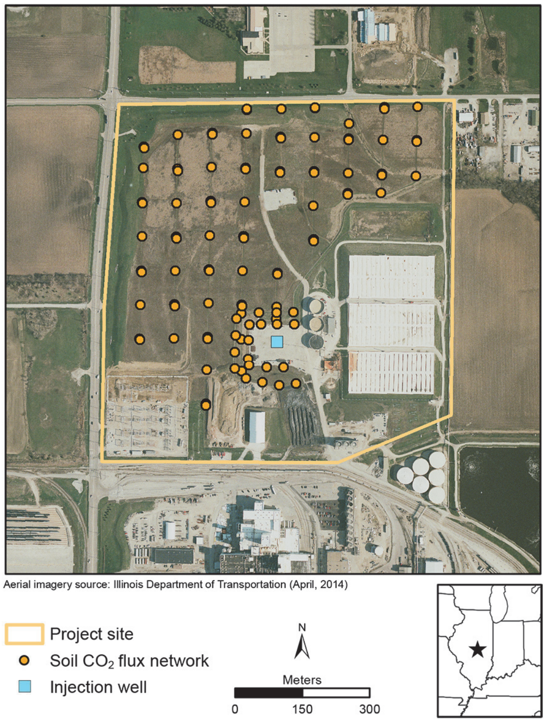

Fig. 1. Illinois Basin – Decatur Project (IBDP) study site with selected near-surface monitoring locations.

3.1. Geology and land surface information

Data layers describing the character of the ground surface relate directly to monitoring infrastructure installation, as well as analysis of measurements taken. Examples of near-surface geospatial data compiled for the IBDP map database are surficial geology [10], soils [11], and land cover [12, 13]. Selected subsurface data layers are also pertinent to near-surface monitoring, and include information about existing wells, borings and other subsurface penetrations such as mined areas [14, 15]. Most agencies provide their spatial datasets as individual downloads (e.g., GIS shapefile format), yet an increasing number offer direct connection to streaming map services [16, 17]. Although active map services work well at providing up-to-date data layers to GIS users, some services are geared more toward visualization rather than use or manipulation of the data—and supplemental data downloads may be required for more advanced spatial processing tasks.

Additional land surface layers compiled for the IBDP map database include satellite imagery, aerial imagery, and historical aerial photos (selected areas and dates are available, e.g., [18, 19]). Digital, georeferenced, topographic maps [20, 21] are a familiar information base to have available, and surface elevation data from the topographic maps are supplemented by high-resolution Light Detection and Ranging (LiDAR) digital surface and terrain models [22, 23]. To provide even further IBDP site-specific detail, custom high-resolution color aerial imagery is acquired bi-annually from the Illinois Department of Transportation.

3.2. Site and local infrastructure information

In addition to aerial imagery, IBDP map layers include existing infrastructure such as roads [1, 24] and locations of municipal services or utility lines (if available), as well as locational reference systems such as gridlines for the Public Land Survey System [25]. Although public and municipal utilities data are not used frequently for IBDP monitoring, they are valuable additions to the map database. In particular, they have been helpful during the siting and drilling of shallow groundwater monitoring wells, or to identify any potential interference with planned monitoring efforts at the site.

IBDP site-specific map layers were created from Global Positioning System (GPS) coordinates of all field monitoring locations with varying positional accuracies (e.g., spot measurements with handheld GPS devices to high-accuracy surveying). The GPS points were typically collected in Universal Transverse Mercator (UTM) Zone 16 or Geographic coordinate systems (1983 North American Datum) and include such elements as: shallow groundwater monitoring wells, soil gas sampling locations, soil CO_2 flux monitoring network stations, and electrical earth resistivity lines of transit. Other site infrastructure map layers delineate footprints of ADM's industrial installations such as CO_2 pipeline to the injection well, and assorted site construction and engineering plans. Similarly, agricultural field drainage tile locations have been provided by project partners, and are incorporated into the IBDP map database.

3.3. Data management

Except for connections to external map services, most spatial data for IBDP near-surface MVA activities reside on networked storage drives, in a mixed variety of formats:

- **Vector data** are stored as layers in ArcSDE (Spatial Database Engine) or Esri File Geodatabases (FGDB), or as individual shapefiles;
- **Imagery and raster data** are stored as georeferenced TIFF files, FGDB raster layers, or Esri grids;
- **Tabular data** reside in Oracle or Microsoft (MS) Access database(s) or as separate MS Excel tables. Tabular data can be spatially-enabled via X, Y coordinates, or joined via common identifiers to existing spatial data layers.

The format of specific data layers is generally based on the project task and timeframe under which the dataset was obtained or created. For example, ArcSDE layers and Oracle tabular data are often treated as "final" datasets or institutional archives, whereas shapefiles and FGDBs have less management overhead—lending themselves better to "working," or in-progress, data—and are generally easier to revise or update (e.g., such as with re-visitation and verification of handheld GPS-collected coordinates, or the mapping of temporary locations for proposed field installations). In some cases, loading and displaying numerous files of large size (e.g., full-resolution TIFF aerial images) can consume available program memory; it is more efficient to access the suite of IBDP site imagery as raster datasets stored in Esri's native FGDB format, in which data tiling and compression is optimized/managed by the software.

For internal distribution of IBDP data, a standardized suite of symbolized spatial data layers is provided to project scientists in a compact tool (a master ArcGIS map document and/or separate layer files), with the focus being on immediate data use and exploration rather than data searching, importing, and formatting of the individual raw data layers.

4. Results

Uses of the IBDP map database fall into the typical categories of information visualization, data exploration and analysis, and automation of spatial data processing tasks.

4.1. Information visualization

A fundamental use of the map database is for information visualization. Various maps are created for communicating and reporting project progress to many audiences ranging from internal project staff and scientists to external funding agencies and the general public.

For IBDP site maps and graphics, aerial imagery is leveraged highly and is often used as a common, visually familiar base upon which to display additional spatial information (see also Fig. 1). Digital and paper maps using high-resolution aerial imagery support internal communication of site activities, scheduling and field work logistics, and the planning of new field installations. In addition, the regularly updated series of aerial images, when added to historical photos or satellite imagery, are an important means of documenting land surface changes and site activities over the life of the IBDP demonstration. By saving each season's imagery explicitly in the map database, on-screen visual comparison or swiping (partially toggling imagery on/off in a sweeping motion across the screen) between two different dates is easily achieved without having to specially prepare two different (physical) maps.

Although information visualization underlies practically all components of spatial data use and mapping, some other targeted uses of the IBDP map database have been identified and are highlighted as follows.

4.2. Data integration and analysis

4.2.1. Proximity analysis

The GIS framework enables analyses such as the distance to, or buffered radii around, existing wells and borings—spatial inquiries which are necessary for pre-injection site characterization and injection well permitting requirements.

One such example involves the area of review (AoR) around the proposed injection well, which is used to spatially select and compile locations and depths of known wells/borings or other subsurface penetrations (e.g., coal mines) with respect to the estimated area of the modeled CO_2 plume after injection. Well data inside the modeled plume outline can be gathered and submitted to permitting agencies, and/or spatial statistics can be used to summarize well information per area of interest, such as minimum, maximum, and average well depth, or total number of wells per specific geologic formation.

In other cases, maps showing existing field infrastructure are consulted before the installation of additional monitoring equipment, for example, with respect to the locations and proximity of existing IBDP soil gas and CO_2 flux monitoring stations as well as pre-IBDP agricultural field drainage tiles; the maps and distance measurements, thus, are instrumental to planning an optimized equipment-spacing scheme and avoiding monitoring interference and potential equipment damage.

4.2.2. Interpolation and automation: soil flux mapping case example

A powerful use of the GIS database and software involves the integration of tabular measurements with spatial data, coupled with spatial interpolation and visualization of MVA field measurements. For long-term monitoring at IBDP, repetitive data processing and analysis tasks were the basis for developing a standardized set of procedures which could then be automated. Automation of spatial interpolation, data visualization, and map creation will be discussed in the following example.

Near-surface site characterization and monitoring at the IBDP site began in 2008 and represents multiple data streams that need to be periodically compiled and assessed, including soil gas samples that are collected annually to semi-annually, shallow groundwater samples collected monthly, and soil flux measurements collected weekly. In the case of soil flux monitoring, parameters such as CO_2 flux rate, soil moisture, and soil temperature are measured and collected weekly from 107 monitoring stations through spring, summer, and fall seasons [26]. To track conditions and look at temporal variations, data visualizations and maps were desired over the full time range of measurements.

The challenge was the sheer volume of data. Weekly sampling events have been collected since 2009, and for a single parameter alone (e.g., soil CO_2 flux), the end result was over 100 maps (and consideration of additional parameters serves to multiply this number). Manually creating each individual map may have been a reasonable task for yearly averaged data, but would not have been ideal, or efficient, for the weekly measurements or monthly averages; thus, the solution was to automate both the sequential and repetitive tasks of spatial data interpolation and map creation. The initial exploratory map series produced for IBDP were soil CO_2 flux, soil moisture, and soil temperature, and the general workflow from field data collection to mapped result is outlined in Table 1.

Table 1. General steps in the soil flux data collection and mapping workflow. Tasks notated with (+) have been automated using ArcGIS software.

1) Data collection:

- Collect data in field from 107 soil flux monitoring stations.
- Post-process, review, and correct data.
- Import to project database (MS Access):
    - Calculate monthly/seasonal/yearly averages.
    - Join tabular data to monitoring station location X, Y coordinates for GIS processing.

2) GIS processing:

- Spatially enable the tabular data containing X, Y coordinates.
- +Select data for sample weeks or time-period-averages of interest.
- +Grid and interpolate measured parameter(s) using Inverse Distance Weighted method.
- +Classify data ranges and visually symbolize contoured raster data.
- +Create map layout and export map results per time period as PDF file.

Before spatial data processing and automation could begin, certain elements had to be set up beforehand in the input database table structure. As flux network measurements are often collected in the field over a 2-day period, an *EventNumber* was assigned to the data by collection date, to allow for more than 1 day of collection per individual sampling "event," or week. In addition, a standardized naming/ordering scheme for data groupings (using "time-stamp" combinations and concatenations of *Year, SeasonName*, *MonthNumber*, and *EventNumber*) allowed for input database values to be used directly by the automation logic; the time-stamp values cycle through the program code as string variables, to be used several times in naming time-correlative elements: source data points, gridded-data raster layers, and output maps.

Next, using the ModelBuilder graphical programming module of ArcGIS, spatial data processing tools for *gridding* and *interpolating* the input data points were combined with *classification* of data interval ranges and color-ramps for optimal map *symbolization* (Fig. 2). Logically looping through the data processing tasks for each time-stamp resulted in both the source point data and the contoured raster layer, which could be viewed and explored on-screen along with the remainder of the time interval series of data.

As the software functions for exporting on-screen map results (to graphical output file) were not available to the ModelBuilder environment, a separate Python [27] programming language script was used to loop through time-stamped point and raster data *selection*, specific map *rendering*, and *naming* plus *exporting* of the desired maps to individual output PDF files for review and reporting (Fig. 3). The resultant series of maps can be animated, or presented as a sequence, to give quick visual representation to a large volume of data and further illustrate spatio-temporal variability in measured soil flux parameters at the IBDP site. In the case of soil CO_2 flux, the map sequence (Fig. 4) shows that there was significant variability before injection in November 2011, and that all observed variability during injection was consistent with the variability observed before injection began (for additional discussion see Carman et al. [26] in this volume). The exploratory maps also show that the highest average CO_2 fluxes were apparent in June 2009 and July 2011 (note: the number of weeks sampled per month may vary).

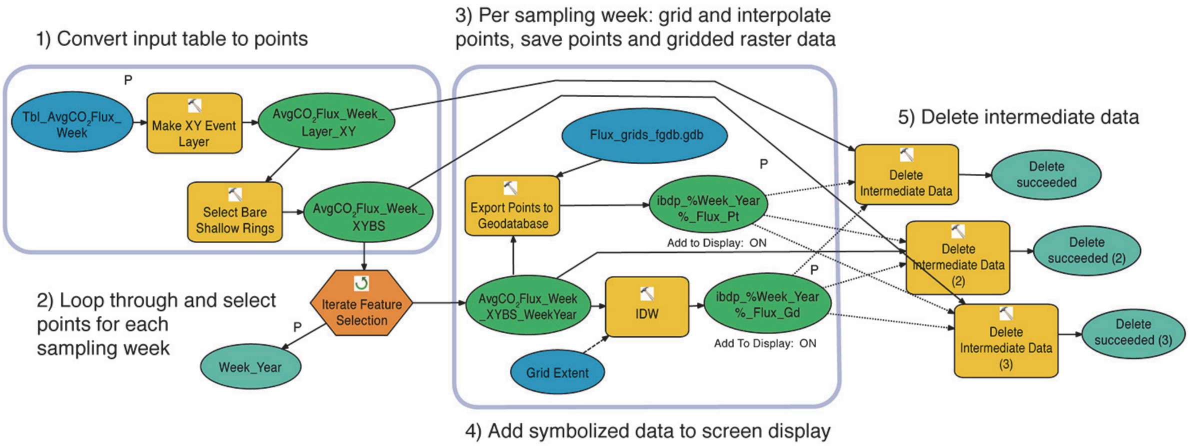

Fig. 2. GIS processing workflow: automation of gridding and interpolation of soil flux data using Esri's ModelBuilder (graphical programming interface) module for ArcGIS.

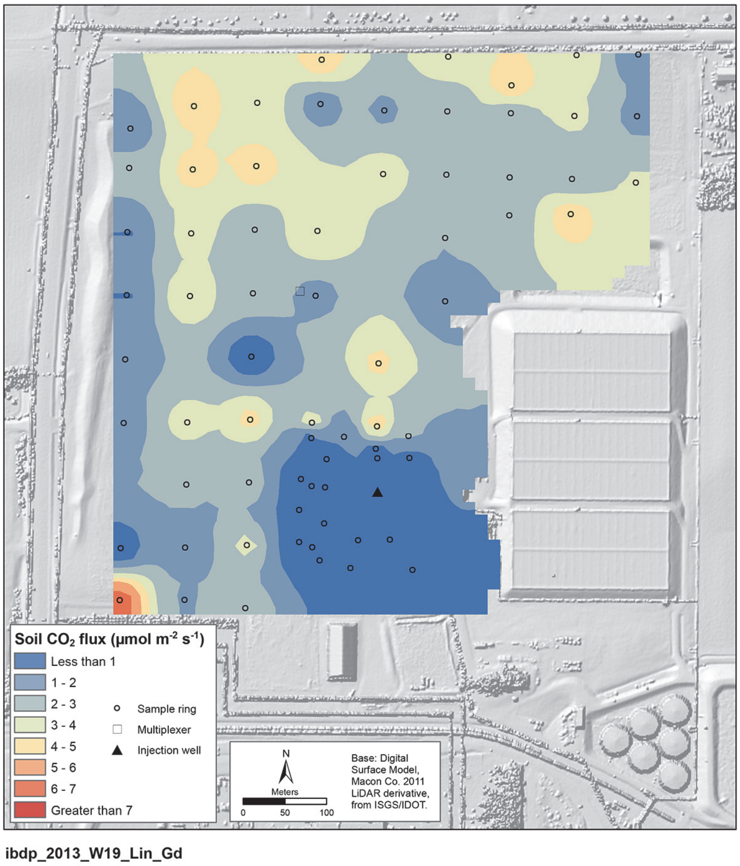

Fig. 3. Partial result from Python programming language script: single map of contoured soil CO_2 flux data at the IBDP site for sampling week 19 (May 8–10), 2013.

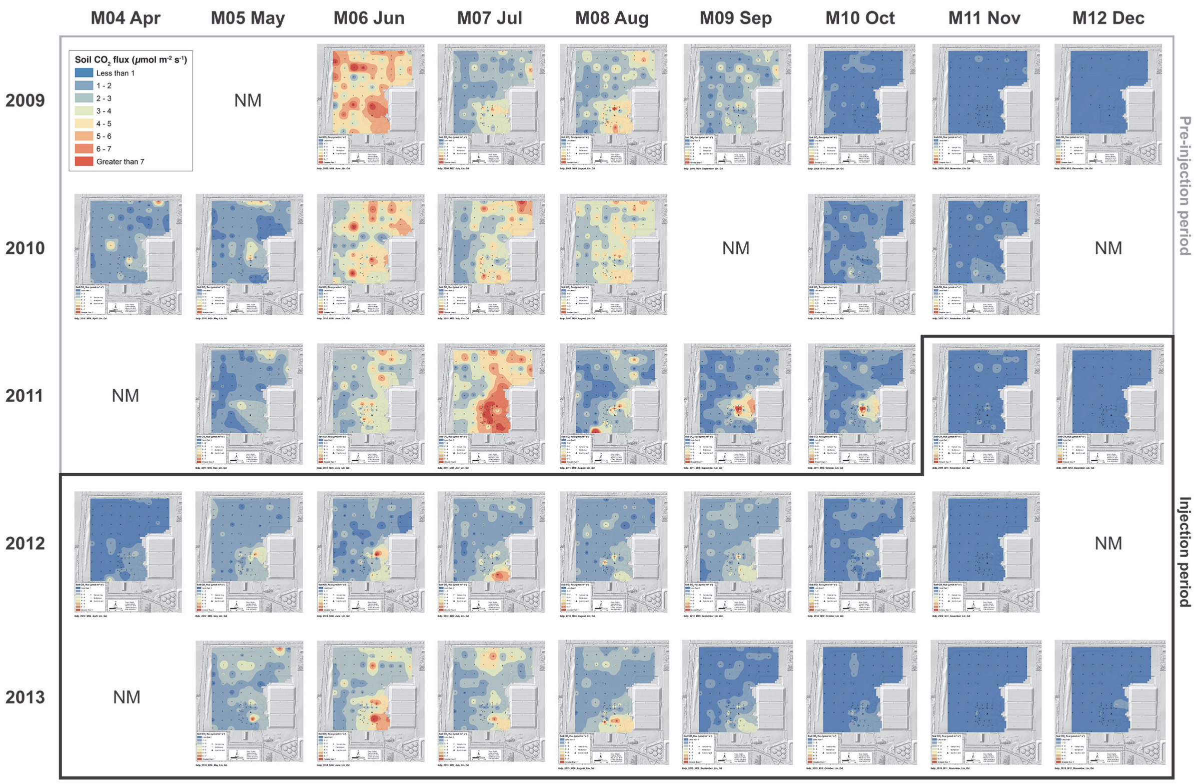

Fig. 4. Sequence of 38 exploratory maps showing monthly soil CO_2 flux variability (June 2009 through December 2013 timeframe). A similar sequence of *weekly* detail was based on 106 individual maps (not shown due to space limitations). The systematic map analyses were only feasible via the automation of data interpolation and map creation tasks in the GIS software. The black dividing line in the map sequence separates pre-injection and injection periods and denotes the start of CO_2 injection in November 2011. NM = not measured.

Although the GIS automation procedures were initially developed to tackle and loop through the large number of weekly or monthly soil flux maps in one batch, the programs can now be further customized to automate data verification and reporting tasks in concert with field data collection and post-processing efforts, for example, allowing options for less GIS-experienced staff to choose one week of interest from the input data table and automatically output a single PDF map file for any measured parameter.

The immediate benefit of our customized automation routine is that weeks of effort have been saved by not having to manually create hundreds of individual raster data layers and associated maps to view the series of results—and we estimate that much time was saved even when allowing for database and program development. Program flexibility and re-usability allow us the option to easily make changes or updates to the data/map design (e.g., different colors or values for contour ranges, new base layers, etc.) and observe results for the entire series in short order. In addition, the automation framework can be adapted for the display of other datasets (e.g., shallow groundwater, soil gas composition), potentially extending the time-savings benefit if visual data exploration is performed for additional selected measurement parameters.

5. Discussion

The challenges of managing the IBDP map database lie mainly in keeping existing data current, finding additional data sources to address ongoing research questions about the site, and addressing technical issues such as establishing and maintaining shared data and networked connections. At times, issues arise due to factors external to the GIS software. For instance, institutional server migrations (or staff, inadvertently) may alter file-system paths to networked data, or software upgrades may yield changes that affect data connections in ArcGIS (e.g., MS Access database differences between *Access 2002–2003*'s .mdb and *Access 2007*'s .accdb file types)—potential data disconnections which are also situations to be aware of, or attempt to plan for, when automating data processing tasks. To this end, the map database requires active management by a designated person in order to maintain consistency and up-to-date data, and to respond to staff needs.

In addition to ongoing data maintenance and upkeep, an important (yet sometimes overlooked) facet of GIS work is data organization for the purpose of distribution. In some ways, project-based GIS work mirrors an institutional database setting, and data sharing and availability to project staff are best planned for in advance; in our case, this meant consideration of staff involved, their use of the data, and potentially varied levels of software experience and/or data knowledge. In this context, the ArcGIS layer files provided to project staff offer two immediate benefits to any user: (1) stored connections to potentially numerous, grouped, datasets at once, and (2) pre-symbolized, or rendered, data layers. Although the full list of our IBDP layers in the master map document (.mxd file) can be daunting to an unfamiliar user, topical data groupings (e.g., Base/Location, Infrastructure, Geology, MVA, Aerial Imagery, Topographic/Elevation, etc.) help to keep things organized and focused; it is these data groupings that are saved separately as layer (.lyr) files, which bundle the visual symbolization and data connection information into easily transferrable data pointers for staff to selectively use and/or combine as needed.

As shown in our soil flux mapping case example, pre-processing of field-collected data was necessary before integration with the GIS workflow; tabular database queries and data manipulation are often best (or most efficiently) managed separately in the database software itself, and as such, may require database expertise. Experience with GIS, however, is necessary for performing advanced spatial operations or task automation and is strongly recommended for spatial data administration and providing user-support. For less-experienced staff, basic training in ArcGIS software has been helpful for general use of the IBDP map database, and staff have given feedback that brief intro sessions have been sufficient to meet basic data visualization needs.

Some limitations we have encountered using GIS, in general, for the management of near-surface monitoring data are that the scale of high-resolution georeferenced imagery is often equal to, or greater than, the accuracy of handheld GPS systems—which may require that high-value locations be professionally surveyed. The aerial images have proven very useful to the project, but as with any spatial dataset, positional accuracy must be properly documented and the appropriate scale of use must be well understood. Using GIS to combine data from varied scales and sources (e.g., national, state, municipal) with site-specific project information may illuminate spatial limitations inherent in natively smaller-scale data layers. In other words, regional data layers can add valuable information and context to project-level data, but may not be sufficiently detailed for site-specific decisions.

Computer-aided Design (CAD) files, commonly used by industry for infrastructure management or engineering studies, may sometimes lose their spatial coordinate system information upon translation to GIS formats, and thus may potentially need spatial "warping" to be referenced in the GIS framework; again, this is a potential source of locational inaccuracy, but the contextual benefit of having this information in the GIS relative to other project data layers may still prove valuable for certain applications.

Many MVA projects focus on display and management of subsurface information, using modeling or other down-hole visualization software packages. Oftentimes, it is easier to add open-format GIS layers (e.g., shapefiles), or images, into subsurface modeling software than it is to add modeling results to GIS software (via intermediate text files, or manipulation of customized data formats, etc.) The series of soil flux measurement visualizations, however, were only feasible via the automation of data interpolation and map creation tasks using GIS software. The systematic mapping and analysis of soil flux parameters are an essential component of near-surface MVA efforts at the IBDP site, and this work has greatly benefitted from data organization and integration within the IBDP map database.

Although the use of GIS for CCS studies has largely been focused on mapping, screening, and disseminating assessment results and data on regional scales [28, 29], our work at the IBDP site, along with that of others [30, 31], illustrates the flexibility of GIS for managing spatial data to support localized CCS and MVA projects, as well. Our IBDP work is unique in its comprehensiveness and integration of a vast array of spatial datasets pertinent to the demonstration site's near-surface characterization, fieldwork operations, and long-term monitoring. We are continuously adding to and integrating our CCS project datasets and monitoring observations, and expect to have a robust data visualization and interpretation framework built upon the IBDP map database.

6. Conclusions

Considering the goals for implementing the IBDP map database, ArcGIS software works well for map-based information visualization, and spatial data exploration and analysis. As shown in the soil flux mapping example, the automation of routine (or otherwise time-intensive) spatial data processing tasks has resulted in significant time savings and flexibility when creating hundreds of data layers and maps used to visualize the entire series of monitoring measurements at the IBDP site. The automation framework can be adapted to include other spatially distributed data streams such as shallow groundwater and soil gas composition measurements. As well, the flexibility of automated routines for data analysis and mapping allows them to be adapted and tailored for less GIS-experienced staff—allowing for a wider variety of users to reap the benefits of GIS in their IBDP work. The IBDP map database serves as a standardized, common, starting point for all project staff—a gateway to the project's spatial data through which staff are then free to customize and add to, based on their own GIS usage needs.

We find there are not many alternatives to using GIS for the management of near-surface monitoring network spatial information—especially when high importance is placed on incorporating data and results from previous mapping studies, or the flexibility to use maps and spatial data provided by multiple external sources is required. Although some technical or practical limitations exist to using ArcGIS software for near-surface monitoring information management, these limitations tend to be generally known entities, and workarounds can be planned for or developed.

Overall, the IBDP map database offers a highly flexible working solution that integrates multiple datasets into a common GIS framework. It is a robust platform used for data visualization and exploration, upon which additional spatial analytical workflows are being added, such as exploring spatial patterns along with potential correlations between monitored soil flux parameters and other near-surface spatial data layers. We will continue using ArcGIS as a tool for managing and integrating spatial information for post-injection monitoring at the IBDP site. In the future, we plan to leverage IBDP spatial data layers, and knowledge gained in implementing the IBDP map database, for additional related CCS and near-surface MVA activities such as the Industrial Carbon Capture and Storage project in Decatur, Illinois.

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References

[1] Esri. ArcGIS 10.1, Redlands, CA; also contains Esri Data and Maps for ArcGIS; 2012.
[2] Illinois Geospatial Data Clearinghouse, hosted by the Illinois State Geological Survey, http://crystal.isgs.uiuc.edu/nsdihome/.
[3] Indiana Geological Survey, Maps and data, http://igs.indiana.edu/.
[4] Kentucky Geological Survey (KGS), KGS databases, maps, and publications, http://www.uky.edu/KGS/.
[5] Finley, R (principal investigator). An assessment of geological carbon sequestration options in the Illinois Basin, Final report to U.S. Department of Energy October 1, 2003–September 30, 2005; 2005, available from: http://sequestration.org/publish/phase1_final_rpt.pdf.
[6] Frailey SM, Morse DG, Krapac IG, McKaskle RW. Sequestration and enhanced coal bed methane: Tanquary Farms test site, Wabash County, Illinois, Monson CC (ed.), Illinois State Geological Survey Open File Series 2012-2; 2012, available from: http://www.isgs.uiuc.edu/publications/ofs2012-2.
[7] Frailey SM, Parris TM, Damico JR, Okwen RT, McKaskle RW. CO_2 storage and enhanced oil recovery; Sugar Creek Oil Field test site, Hopkins County, Kentucky, Monson CC, Goodwin JH (eds.): Illinois State Geological Survey Open File Series 2012-4; 2012, available from: http://www.isgs.uiuc.edu/publications/ofs2012-4.

[8] Frailey SM, Krapac IG, Damico JR, Okwen RT, McKaskle RW. CO_2 storage and enhanced oil recovery: Bald Unit test site, Mumford Hills Oil Field, Posey County, Indiana, Goodwin JH, Monson CC (eds.): Illinois State Geological Survey Open File Series 2012-5; 2012, available from: http://www.isgs.uiuc.edu/publications/ofs2012-5.
[9] US Environmental Protection Agency. Region 5 Enforcement and Compliance, National Environmental Policy Act (NEPA) Enforcement, http://www.epa.gov/region5/enforcement/nepa.html, website accessed July 2014.
[10] Illinois State Geological Survey. Surficial geology and elevation data, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/st-geolq.html.
[11] US Department of Agriculture—Natural Resources Conservation Service (NRCS). Soil survey geographic database (SSURGO) for Macon County, Illinois; 2008, available from the NRCS Geospatial Data Gateway, http://datagateway.nrcs.usda.gov/GDGHome.aspx.
[12] US Geological Survey, Multi-Resolution Land Characteristics Consortium. National land cover database 2011, http://www.mrlc.gov/nlcd11_data.php.
[13] US Department of Agriculture—National Agricultural Statistics Service. Cropland data layer: Illinois 2007, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/landcover/nass07.html.
[14] Illinois State Geological Survey. Location points from the ISGS wells and borings database, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/st-geolb.html.
[15] Illinois State Geological Survey. Illinois coal resource shapefiles, http://isgs.illinois.edu/research/coal/shapefiles.
[16] US Department of Agriculture—National Agricultural Statistics Service. Cropland data layers 1997–2013, Cropland data web map service (WMS), WMS server: http://129.174.131.7/cgi/wms_cdlall.cgi? ; see also CropScape (Web Map Application), http://nassgeodata.gmu.edu/CropScape/.
[17] Illinois State Geological Survey. ArcGIS REST services directory, http://maps.isgs.illinois.edu/arcgis/rest/services.
[18] US Geological Survey. The national map, orthoimagery, http://nationalmap.gov/ortho.html.
[19] Illinois Geospatial Data Clearinghouse. 2011 Illinois Department of Transportation orthophotography—compressed countywide collections, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/idot2011/.
[20] Illinois Geospatial Data Clearinghouse. U. S. Geological Survey digital raster graphic files, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/drgs/.
[21] US Geological Survey. The National Map, US Topo Quadrangles—Maps for America, http://nationalmap.gov/ustopo/.
[22] Illinois Geospatial Data Clearinghouse. Illinois Height Modernization: LiDAR Derivatives, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/ilhmp/county/dsm-dtm.html.
[23] US Geological Survey. Center for LiDAR information coordination and knowledge, http://lidar.cr.usgs.gov/.
[24] Esri Data & Maps 10. Esri white paper, November 2010, available from: http://downloads.esri.com/support/whitepapers/ao_/Esri_Data_and_Maps_10.pdf.
[25] Illinois Geospatial Data Clearinghouse. Illinois Public Land Survey System (PLSS) boundaries, 2003, http://crystal.isgs.uiuc.edu/nsdihome/webdocs/st-basem.html.
[26] Carman CH., Locke II RA, Blakley CS. Update on soil CO_2 flux monitoring at the Illinois Basin – Decatur Project, USA, Energy Procedia, 2014 (this issue).
[27] van Rossum G. Python tutorial, Technical Report CS-R9526. Amsterdam: Centrum voor Wiskunde en Informatica (CWI); 1995. Current Python version available from: https://www.python.org/.
[28] US Department of Energy Office of Fossil Energy, National Energy Technology Laboratory. The United States 2012 carbon utilization and storage atlas, 4th ed.; 2012.
[29] US Department of Energy Office of Fossil Energy, National Energy Technology Laboratory. National carbon sequestration database and geographic information system (NATCARB), http://www.natcarbviewer.com/.
[30] Gorecki C D. Bell Creek CO_2 EOR and CO_2 storage demonstration project, Montana, International workshop on knowledge sharing in MVA/MMV in CCS demonstration projects and large-scale CO_2 injection tests; 2012, available from: http://www.secarbon.org/wp-content/uploads/2011/05/Gorecki3.pdf.
[31] Big Sky Carbon Sequestration Partnership (BSCSP). BSCSP GIS, http://www.bigskyco2.org/atlas/gis, website accessed July 2014.