Chapter 2
Spatial and Temporal Analysis for Energy Systems

In this book, the concepts and procedures for assessment of energy systems are discussed in order to apply a number of spatial and temporal analyses with geographic information system (GIS). In addition to digital mapping, GIS can change the way of viewing our Earth's resources in a more complex way by integrating data from remote sensing, GPS, and a wide range of databases. Many GIS packages are freely available as open software or as commercial software broadly used in industry, government, and academia. This chapter introduces some fundamental concepts that are dealt with in next chapters. After identifying certain open issues in spatial and temporal analysis, a case-oriented approach is proposed for assessment of energy sources including nonrenewable sources and renewable sources with their temporal dynamics and spatial patterns. Also presentation of new GIS technologies will discuss the strengths and weaknesses, along with the opportunities and limitations of using GIS methods for wide-ranging applications in assessment of energy sources.

2.1 Energy Sources and Energy Consumption in the Scale of the Earth

The field of digital mapping systems is concerned with the exploration, description, explanation, and prediction of patterns and processes at geographic scales on the Earth's surface, which is illustrated by Earth's surface imageries in Figs. 2.1 and 2.2 that combine many satellite images to produce cloud-free views of the landscape.

The Earth's surface is mostly covered by water with much of the continental shelf below sea level. It represents about 361 million km^2, which is about 70.8% of the whole Earth's surface. The remaining 149 million km^2 (29.2%) consists of mountains, deserts, plains, and other landforms. About 97.5% of the water is saline. The remaining water (2.5%) is fresh with about 68.7% in ice caps and glaciers. Natural resources are available in the whole world, but the accessibility is dependent on many natural, economic, political, and social factors. Based on the Earth's

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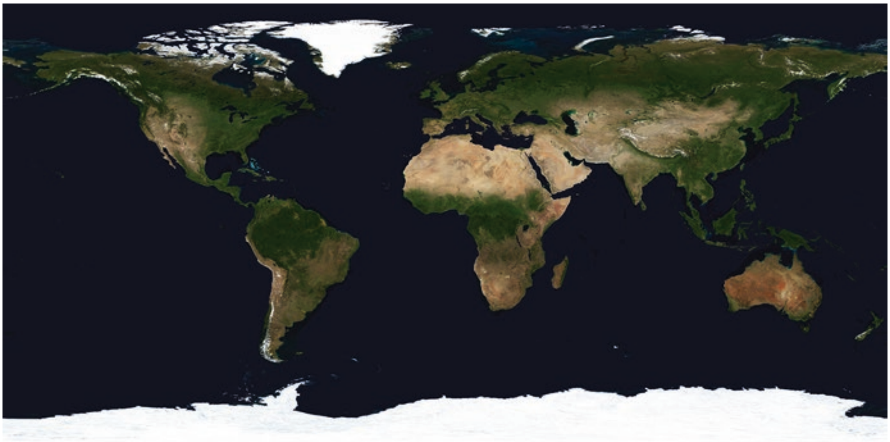


Fig. 2.1 The Earth's surface. Source: www.pixabay.com, 2016

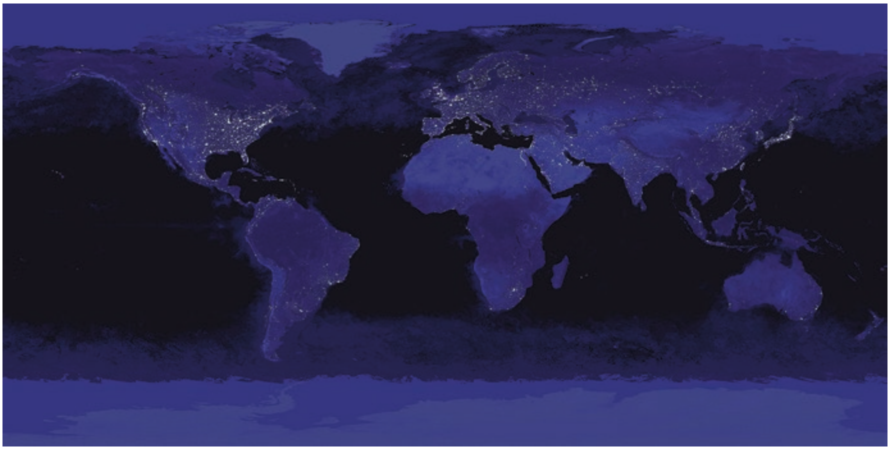


Fig. 2.2 The Earth's surface at night. Source: www.pixabay.com, 2016

surface, we can classify biotic natural resources such as forests and potentially the animals, which are obtained from the biosphere. But they represent just a part of actual, potential, or reserve resources that also include widely used fossil fuels formed from decayed organic matter.

The Earth's surface at night is very helpful for observation of spatial distribution of human activities that are mostly in the sites with easy living, plentiful resources, kindly climate, and rich harvest. The brightest areas are generally the most urbanized but not necessarily the most populated sites. Most major cities are near transportation networks, which are along coastlines and near rivers. Areas with more lights are usually more economically developed, because electricity is widely used to keep production, business in thriving cities or countries. Poor areas may have

Fig. 2.3 An open-pit diamond mine in Siberia, Udachnaya pipe. Source: Google Earth, 2016

probably lower usage of electric lights to conserve money. Initial studies show that these satellite images complemented by topographic data and thematic maps can approximately estimate the economic state of certain regions.

In a local scale, more detailed view of human activities is identified with satellite images and aerial photographs. Extractive industries represent a large growing activity that cause depletion of natural resources resulting in losses of ecosystem services of many countries. They are, along with agriculture, the basis of the primary sector of economy. Apparent depletion of natural resources is directly caused by mining, petroleum extraction, forestry, as well as changes in demography, economy, and politics. As an example of a nonrenewable natural resource, an open-pit diamond mine in Siberia, Udachnaya pipe, is illustrated in Fig. 2.3.

2.2 Spatial Data Models in GIS

Our interaction with objects on the Earth's surface is diverse and can be described in many ways. Consider the first example, energy sources that include coal mines, oil wells, or renewable sources of energy such as wind power plants, solar power plants, and biogas stations. They are used for our energy supply, delimit land cover or administrative areas, and are an important feature in the shape of a surface. There are many ways how to describe energy sources in spatial modeling. Larger objects such as surface mines can be delineated by polygons that are formed by a set of lines that enclose an area. Smaller objects such as oil wells or individual installations of renewable sources can be marked with point symbols. Consider the second example,

Fig. 2.4 Manhattan Island, bounded by the East, Hudson, and Harlem Rivers in the state of New York in the United States. Source: Google Earth, 2016

transport routes that include oil pipelines, roads, railroads, water transport, or electrical power lines. They make connection between energy sources and manufacturing industry or consumers. Each route can be formed by a line that has attributes such as flow direction and flow volume. A set of routes is connected into a network that can be optimized in relation to transportation costs and transportation volume. Consider the last example, a set of consumers such as industry, transportation, and end consumers. Larger objects such as factories and residential areas are delineated by administrative boundaries that are formed with polygons. Transport lines are formed by lines. Smaller objects such as small business installations, residential buildings, and other public utilities can be marked as point symbols. An example of a complex area of interest for transformation into spatial data objects is illustrated in Fig. 2.4 that shows Manhattan, a part of New York City in the United States. The attached lines symbolized water transport, subway network, and road network.

Based on previous examples, it is evident that real objects on the Earth's surface can be represented in a variety of ways in dependence on a spatial scale and on a scope of work. The target data model has to represent an abstraction of the real world that utilizes a set of data objects in order to support map display, spatial analysis, and visualization. GIS organizes information into a series of layers that are integrated using spatial location. At a fundamental level, GIS datasets are organized as a series of thematic layers to represent and answer questions about a particular problem set, such as geology, hydrology, transportation, or environment. A simplified data model based on a few thematic map layers is illustrated in Fig. 2.5. The base map is represented by an aerial image of the area of interest. The next map layers contain a road network and central energy consumers classified in dependence on energy consumption into two thematic layers.

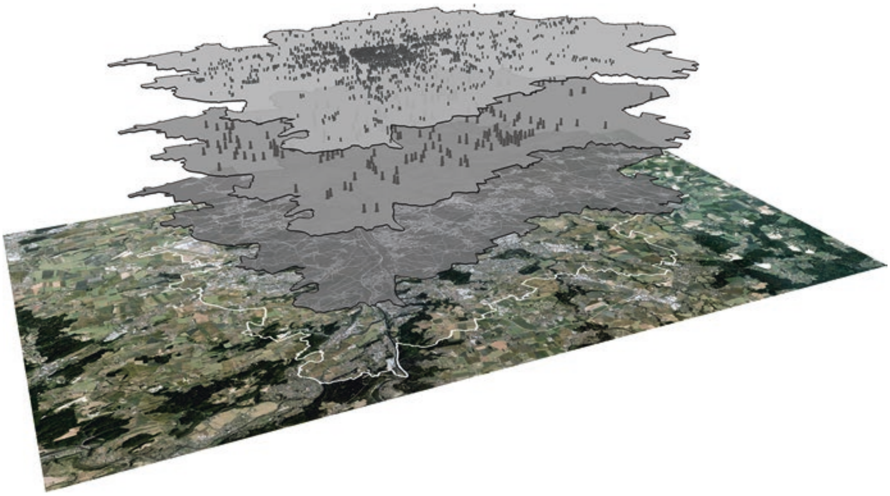


Fig. 2.5 A few thematic layers that represent a simplified data model of energy consumers in Prague (an aerial image, a road network layer, and energy consumers classified in dependence on energy consumption into two layers)

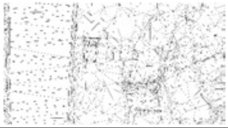
2.2.1 Representing of Spatial Data with Vectors

Vector data can represent the shapes of features precisely and compactly with associated attributes in dependence on the precision of an ordered set of coordinates. The vector representation supports geometric operations dealing with calculating length and area and set operations and finding other features that are spatially related. In a simplified way, vector data classified by dimension are represented by points, lines, polygons, and, optionally, annotations. An annotation is associated with each feature and represented by a label for display of attributes or their compositions. In real applications, labels can contain name of site, sustained yield of energy source, or transport capacity. The vector datasets are stored in dependence on their dimension and relationships in a feature container, which manage vector spatial objects and nonspatial objects and their relationships based on defined rules. In GIS, the vector layers are used to be stored in shapefiles or geodatabases (Table 2.1).

Points are zero-dimensional shapes representing spatial features too small in a selected scale to be depicted as lines or areas. Points are stored in the GIS datasets as single *x-y* coordinates with attributes. Point layers can model locations of oil wells, locations of underground mines, and installations of power plants in energy systems.

Lines are one-dimensional shapes that represent spatial features too narrow to depict as areas. Lines are stored in the GIS datasets as a series of ordered *x-y* coordinates with attributes. The segments of a line can be straight or shaped by defined functions. Line layers are used for modeling of transport networks, electrical power energy distribution, and distribution piping in energy systems.

Table 2.1 Spatial data representations in the GIS

	Vector data 	**Raster data** 	**TIN** 
Purpose of use	-vector data are used for mapping of discrete features with precise shapes and boundaries.	-raster data are used for mapping of continuous phenomena, and satellite or aerial images.	-triangulated datasets are used for mapping of a surface that mostly represents elevation.
Source of data	-digitized from map manuscripts, raster data, satellite images or aerial photographs, -collected from GPS receivers, -contours from DEM, -imported from other software tools.	-satellite images or aerial photographs, scanned blueprints and photographs, -converted from DEM, -rasterized from vector data, -outputs of raster algebra and other complemented software tools.	-outputs of 3D tools for building of DEM, -converted from other software tools dealing with construction and editing of DEMs.
Spatial storage	-points stored as x, y, (z) coordinates, -lines stored as paths of connected x, y, (z) coordinates, -polygons stored as closed paths.	-each cell is located by its row and column position from a coordinate in the lower-left corner of the raster and cell height and width, -rasters that are combined to form a multiband image are numbered.	-each node in a triangle face has an x, y, (z) coordinate value.
Feature representation	-points represent small features in a given spatial scale, -lines represent features with a length but small width in a given spatial scale, -polygons represent features that span an area.	-points features are represented by a cell, -line features are represented by a string of adjacent cells with common value, -polygon features are represented by a region of cells with common value.	-node z values determine the shape of a surface, -breaklines determine changes in the surface such as ridges or streams, -areas of exclusion define polygons with the same elevation such as lakes or broad rivers.
Topological association	-line topology keeps track of which lines are connected to a node, -polygon topology keeps track of which polygons are to the right and left side of a common line.	-neighboring cells can be simply located by incrementing and decrementing row and column values.	-each triangle is associated with its neighboring triangles.
Spatial analysis	-topological map overlay, -buffer generation and proximity, -spatial and logical queries, -address geocoding, -network analysis.	-spatial coincidence, -proximity, -surface analysis, -dispersion, -least-cost path, -spatial interpolation.	-elevation, slope, aspect calculations, -volume estimation, -vertical profiles on alignments, -viewshed analysis.
Map output	-best for drawing the precise position and shape of point, line and polygon features, -not well suited for continuous phenomena or features with indistinct boundaries.	-best for presenting images and continuous phenomena with gradually varying attributes, -not well suited for precise drawing point and line features.	-well suited for rich presentation of surfaces, -color display can show elevation, slope, or aspect in 2D or 3D perspective.

Polygons are two-dimensional shapes that represent plane features. Polygons are stored in the GIS datasets as a series of segments that form a set of closed areas. Polygon layers model large-sized objects such as land cover structures, administrative units, and borders of towns. In mapping of energy systems, polygons can be used for delineation of surface mines, sites of biomass production, and larger power plant installations.

2.2.2 *Representing of Spatial Data with Raster Datasets*

Much of data are captured from aerial and satellite images that record data as pixel values in a two-dimensional grid. The two-dimensional grids can be arranged into three-dimensional grid comprised of spatial dimension in the x and y coordinates and spectral data or thematic data in the z coordinate (Table 2.1). In general, a pixel value stores reflectance of a part of the electromagnetic spectrum captured from aerial or satellite images. It can also store a thematic attribute such as land cover type, elevation, or other surface values. The grid layers are used to be stored in a wide range of various raster formats such as TIFF (Tag Image File Format), BMP (bitmap image file) or JPEG (Joint Photographic Experts Group). In case of GIS datasets, grid layers need to be embedded with georeferencing data that include spatial localization and additional information about map projection. Thus, more specific raster formats must be used such as GeoTIFF, IMG-ERDAS IMAGINE, and Multi-resolution Seamless Image Database (MrSID) developed by LizardTech. Three-dimensional grid data can be also stored in the mentioned extended raster formats. Besides these raster formats, the band-sequential (BSQ), band-interleaved-by-line (BIL), and band-interleaved-by-pixel (BIP) are used for data exchange between GIS and other advanced computer modeling tools.

2.2.3 *Representing of Spatial Data with Triangulated Irregular Network*

A triangulated irregular network (TIN) is designed for surface models in GIS. It is represented by a set of nodes with elevations and triangles with edge. TIN is widely used for surface analysis such as delineation and estimates of slope, aspect, and visibility. It can also depict the relief of terrain (Table 2.1).

2.2.4 *Other Data Structures in Spatial Models*

Many common spatial tasks deal with finding a location or an address. Thus, spatial models have to manage these locators and allow to create features for locations. Other distinctions between prevalent information systems and GIS are represented by sharing a common coordinate system and topological associations, which enables to create spatial relationships between spatial objects, geometric networks for modeling of linear systems such as transport networks, and planar topologies model systems of line and area features as a continuous coverage of an area such as counties sharing an outer boundary with a state.

2.3 Spatial Data Types

Spatial analysis in GIS is a process for looking at spatial patterns in datasets and at relationships among them. Method and functions for spatial analysis differ in many ways. The basic difference originates from types of analyzed features: discrete or continuous. For discrete features (point locations, lines, and areas bounded by polygons), the location is pinpointed by its position and optionally by its elevation. At any given spot, the feature is either present or not. For continuous phenomena such as precipitation, temperature, or pollutant concentration, the occurrence can be measured anywhere, at any given location. Continuous data are used to be represented by raster datasets, which are represented as matrixes of cells in continuous space. Each raster is represented by a layer with one attribute. Each cell in its boundary is characterized by a value of the attribute such as precipitation, temperature, or pollutant concentration. The cell size affects the precision of mapping phenomena. Using too large a cell size will cause some information to be lost. Using too small a cell size will require a lot of storage space in order to cover the whole area of interest and will take longer processing, without adding additional precision to the map. Generally, any feature type can be represented using either model, discrete, or continuous (Fig. 2.6). While locations of discrete features are dependent on precision of coordinates, their precision after conversion into the raster datasets depends on a cell size.

Each spatial feature has attributes that contain associated information such as categories, ranks, counts, and ratios (Fig. 2.7). The categories of attributes predetermine the types of possible spatial analysis. Their data formats include integer or real numbers, strings of characters, logical values, and even multimedia files or link to them.

Categories represent features with similar properties such as categories of energy sources or transport routes. They are mostly formed as text abbreviations or numeric codes. The simple abbreviations and codes are recommended in order to reduce errors. The category attribute can support database selections and ways in which features are processed and displayed.

Ranks can express state of features or processes such as the level of source reserve or meteorological conditions. Ranks put features in order, from low to high, or in the reverse order. They are used when direct measures bring inaccurate information. For example, quantify air pollution in the surroundings of emission can be indicated by a few levels (low, middle, high, very high) instead of the local direct measures.

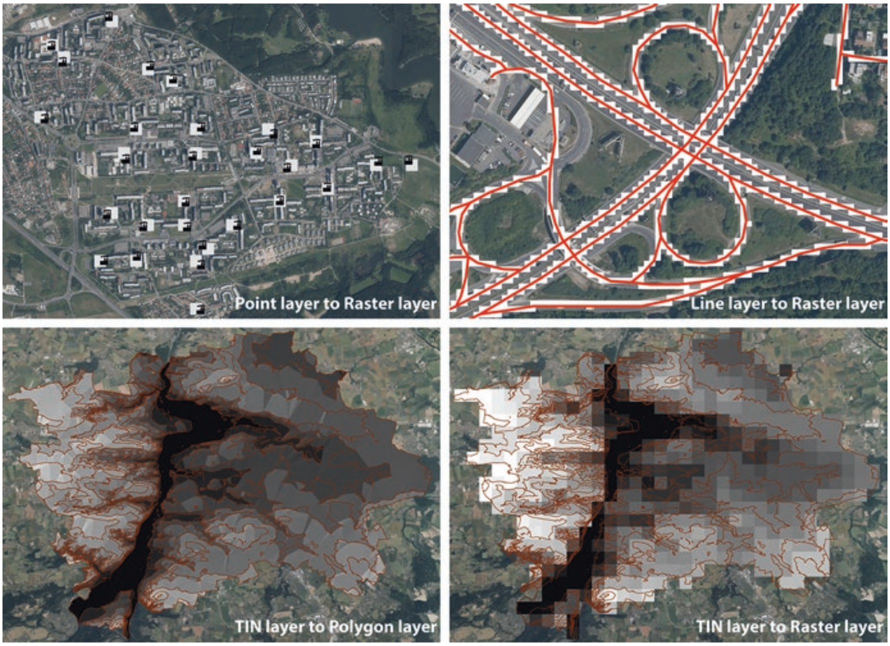


Fig. 2.6 A comparison between discrete features (location of energy systems in an urban area, roads near a crossroad, and contours complemented by DEM) and raster datasets converted from discrete features

Counts express total numbers. A number can be any measurable quantity associated with a feature such as power of a power station or consumption of a consumer. Using counts enables to see the actual value of each feature. Counts are used to be displayed in the maps by symbols with various sizes or shades. Sometimes they are transformed into the ranks in order to simplify information about amounts.

Ratios can express the relationship between two quantities such as densities that show the distribution of features per unit area. For example, dividing the number of people per area of each country gives its population density, which can better even out differences between large and small countries. Similar effects like densities can be expressed by proportions, which show what part of a total value is. For example, dividing a number of people in the selected age classes by the total population in each part of a country gives the proportions of people in this age class over the whole country.

The tables of attribute values are used to be analyzed by selection, calculating and summarizing. Selection of features is provided by using queries. The query is usually in the form of a logical expression. The subsets of features can serve for calculating and summary statistics. Calculating enables to assign new values in attribute tables such as ratios and densities or other derived characteristics of features. Summarizing of specific attributes is used to get statistics such as arithmetic average, median, modus, and standard deviation.

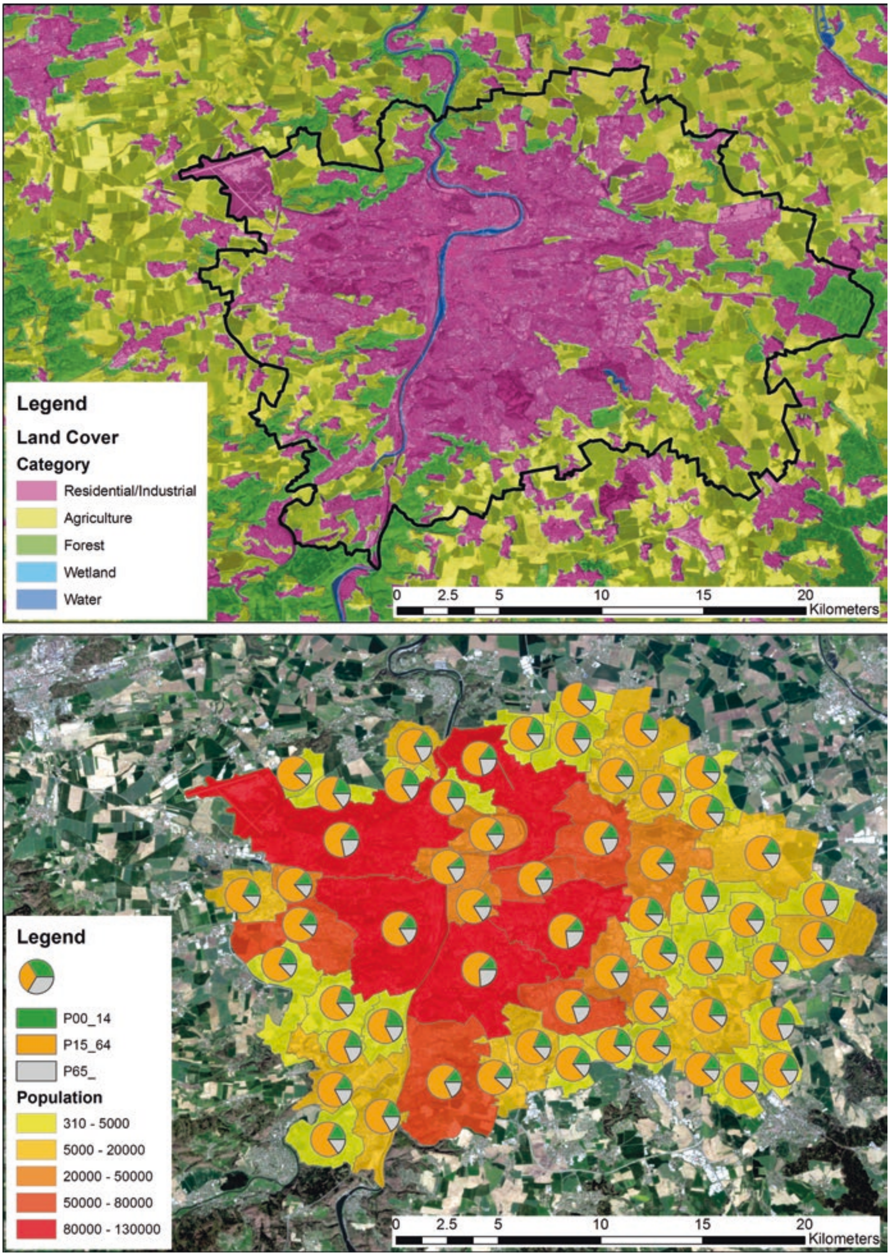


Fig. 2.7 Presentation of associated information in attributes of spatial features with categories of land cover classes, ranks of population, and counts of population classes (0–14, 15–64, 65 and higher)

2.4 Coordinate Systems

The coordinate system for spatial data provides a frame of reference in order to identify the location of features on the surface of the Earth, align data, and create maps. Dozens of map projections for displaying features from the curved surface of the Earth to a flat sheet of paper or display have been created by geodesists for a few centuries to preserve one or more specific properties of the spatial data: shape, distance, area, and direction. The shape of the Earth can be regarded approximately as a sphere, but a more accurate spatial approximation is an ellipsoid. However, the Earth's surface has irregularities above and below the approximating ellipsoid. The elevation is described with respect to a given reference datum. Once the ellipsoid and the datum are given, the location of a point is uniquely defined on the Earth's surface. Coordinates on the Earth's surface are therefore specified in terms of latitude and longitude over a reference surface and elevation above and below a datum. Elevations are used to be measured above a reference mean sea level, which gives coordinates in the framework of a geographic coordinate system (GCS). A common GCS is represented by the World Geodetic System defined in 1984 (WGS84), which has adoptions to represent region-specific data with higher accuracy in different countries.

In order to calculate lengths and areas in the local scale, the ellipsoid is approximated by a plane or another surface that can be flattened on a plane. Then the coordinates on the plane may be defined by metric distances from a reference point along two orthogonal directions. The mathematical conversion of coordinates from the ellipsoid into the corresponding coordinates on an approximating plane is called a projection. Some of the simplest projections are made onto geometric shapes that can be flattened without stretching their surface. Some examples of map projections which are widely used in GISs are shown in Table 2.2.

Thus, GISs contain geographic and projected coordinate systems that represent the world in very different ways. In geographic coordinate systems, points are referenced by their longitude and latitude values. Longitude values are measured east-west, while latitude values are measured north-south. The linear distance between two points separated by the same angular distance may differ, depending on their locations, because the reference surface is curved and lines of longitude converge at the poles. In projected coordinate systems, the Earth is simplified by mapping location on a flat surface with map projection. It has two-dimensional coordinate system with orthogonal axis. The link between geographic and projected coordinate systems involves mathematical formulas, map projection. A projected coordinate system is always dependent on definition of a geographic coordinate system, because this information is needed to properly convert locations to a projected coordinate system.

Using map datasets that were originally curved on a two-dimensional surface causes distortions in one or more of the spatial properties such as distance, area, shape, and direction. Concurrently, no map projection can preserve all these properties. Each map projection is judged by its suitability for representing a particular area of the Earth's surface from the view of preserving distance, area, shape, and direction. According to these imperfections, some map projections minimize distor-

Table 2.2 Examples of map projections which are used widely in GISs

Projection	Schema	Simplified description
Equirectangular projection (equidistant cylindrical projection)		It maps meridians to vertical straight lines of constant spacing and circles of latitude to horizontal straight lines of constant spacing. This projection is mainly used for thematic mapping, due to its distortion. It has become a standard for global raster datasets, such as Celestia and NASA World Wind.
Mercator (presented by the Flemish cartographer Gerardus Mercator in 1569)		It was the standard map projection for nautical purposes because of its ability to represent lines of constant course, as straight segments that conserve the angles with the meridians. The linear scale is equal in all directions around any point, thus preserving the angles and the shapes of small objects. It distorts the size of objects as the latitude increases from the Equator to the poles, where the scale becomes infinite. It is still used commonly for navigation.
Universal Transverse Mercator (UTM)		It divides the Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width. Zone numbering increases eastward to zone 60, which covers longitude 174° to 180° E. Each of the 60 zones uses a transverse Mercator projection. It is also used for the military grid reference system, which is the geocoordinate standard used by NATO militaries.
Web Mercator (Spherical Mercator or WGS 84/Pseudo-Mercator)		It is a variant of the Mercator projection that is used primarily in Web-based mapping programs. It uses the same formulas as the standard Mercator as used for small-scale maps. The Web Mercator uses the spherical formulas at all scales whereas large-scale Mercator maps normally use the ellipsoidal form of the projection.
Winkel tripel projection (Winkel III)		It is a modified azimuthal map projection of the world, one of three projections proposed by Winkel. The name "Tripel" refers to a goal of minimizing three kinds of distortion: area, direction, and distance. It is the standard projection for world maps made by the National Geographic Society and many educational institutes.

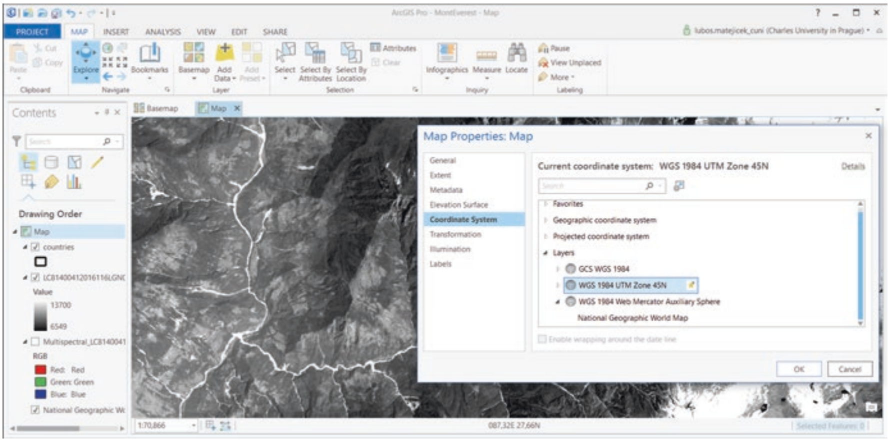


Fig. 2.8 A list of coordinate systems linked to map layers that represent: countries in the world (WGS 1984), a Landsat 8 image (UTM Zone 45 N), and a National Geographic World Map (Web Mercator Auxiliary Sphere). The map layers are preprocessed by on-the-fly projection in dependence on a projection of the first map layer on the top of a list in the table of contents (ArcGIS Pro)

tion in one property at the expense of another, while others attempt to balance the overall distortion. In comparison with projected coordinate systems, geographic coordinate systems make it easy to identify locations on a globe and contain less distortion. Projected coordinate systems offer easier to calculate spatial locations and relationships, but quantities such as distances and angles have distortions in dependence on the selected map projection.

The features in map layers with different coordinate systems cannot be displayed together, because they are transformed into different coordinates. They must be reprojected into a common coordinate system or preprocessed by on-the-fly projection, which can affect drawing performance. The datasets with a small number of simple features may display relatively quickly. The large datasets can take longer to draw. Thus, the reprojection with GIS tools is highly recommended in many cases. As an example, the GIS project in Fig. 2.8 illustrates display of a few map layers in different coordinate systems. It combines map layers in different projections preprocessed by on-the-fly projection. The map layers include countries in the world (WGS 1984), a Landsat 8 image (UTM Zone 45 N), and a National Geographic World Map (Web Mercator Auxiliary Sphere).

2.5 Spatial and Temporal Modeling in GIS

Using GIS for spatial analysis helps to find out location of spatial objects and their relationships. But GIS gets more accurate and up-to-date information, which can be extended by many methods and functions such as 3D modeling, raster map algebra,

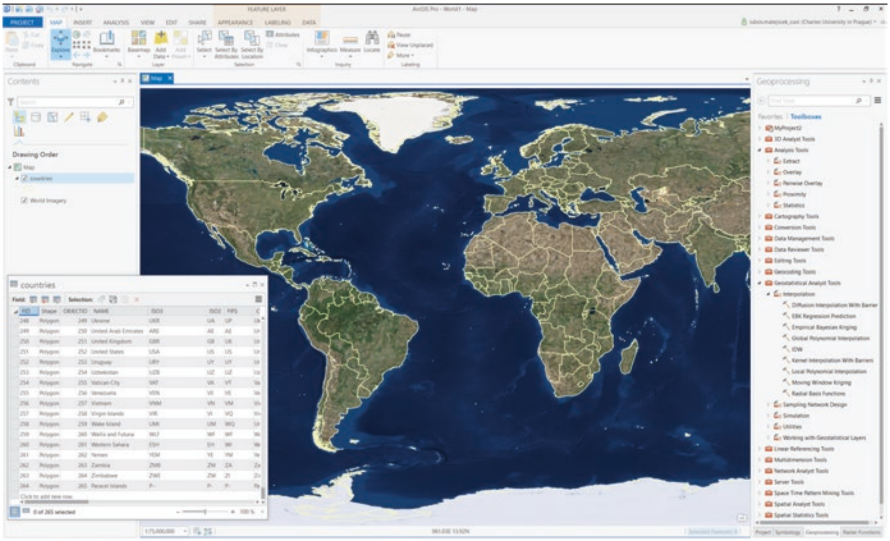


Fig. 2.9 A world map, an attribute table for the layer of countries, and an example of a list of selected groups of geoprocessing methods are displayed in the environment of ArcGIS Pro

spatial exploratory data analysis, spatial statistics, and network optimizations. As an example, a desktop image of ArcGIS Pro from ESRI is shown in Fig. 2.9. It demonstrates the rich GIS environment for spatial processing and advanced analyses. A new version of ArcGIS Pro also provides tools for visualization and analyzes and shares data in both 2D and 3D environments.

Advanced spatial processing is represented by spatial modeling, which is used to be supported by map algebra. It manages a set of raster layers that contain numerical attributes and have all exactly the same pixel size and numbers of rows and columns and are located in the same coordinates. Map algebra applies algebraic expressions for each single pixel in the same coordinates using values of individual raster layers. The results are stored in a new raster layer. For example, if the raster layer containing digital elevation model (DEM) and the raster layer of the height of buildings and infrastructure above ground are counted up, the resulting raster layer represents the digital surface model (DSM) of the area of interest (Fig. 2.10).

Besides spatial analysis described by many guidebooks, GIS can provide spatial modeling extended with temporal dynamics. Over the years, GIS has devised a limited number of ways of handling time within its data structures derived from the representation of the essentially static contents of maps. But the actual GIS can manage a number of cases that are dealing with space-time phenomena. Some tools are included in statistical methods for analyzing data distributions and patterns in the context of both space and time. For example, a new version of ArcGIS form can take time-stamped point features that are structured into Network Common Data Form (netCDF) data cube. Points are aggregating into space-time

Fig. 2.10 Raster algebra applied on building of the digital surface model (DSM) in ArcGIS Pro (ortofoto of a residential area on the left side, DEM in the middle part, and DSM on the right side; the DEM and the DSM are displayed in different elevation intervals represented by color classes in order to recognize surface objects properly)

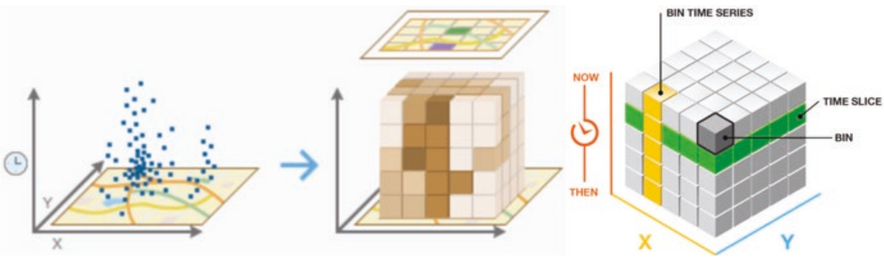


Fig. 2.11 Time-stamped point features structured into Network Common Data Form (netCDF) data cube and aggregated into space-time bins. ESRI, 2016

bins where they are counted in order to calculate summary field statistics for bin values across time at each location. It enables to examine time series trends across an area of interest (Fig. 2.11).

A typical recent approach to integration of dynamic phenomena into spatial modeling is that data are managed with GIS but processed through dedicated software tools in order to provide dynamic modeling. For example, hydrological software tools for modeling of matter flows in a river basin such as Soil and Water Assessment Tools (SWAT) are based on this architecture. The ArcGIS extension ArcSWAT represents a graphical user interface for data management in the GIS environment. After setting of input data (watershed parameters, land classes, soil properties, and meteorological data), the dedicated SWAT model starts to predict surface water quality variables such as sediment, nitrogen, and phosphorus loadings into a system of multiple hydrologically connected watersheds. The outputs include predictions of the impacts of land management practices on surface water, sediment, and agricultural chemical yields in complex watersheds with varying hydrology, land use, soils, and management practices. Integration of dynamic models and spatial methods implemented in GIS can offer a wider range of functionality for many other decision-making tools and software applications (Fig. 2.12).

A wide range of spatial analyses implemented in GIS is described by many books, guides, and help tools inside GIS programs. A list of selected methods and functions implemented in many desktop GISs is generally presented in Table 2.3. Many methods and functions can be available through the development programming tools based on scripts that can be run in the GIS environment.

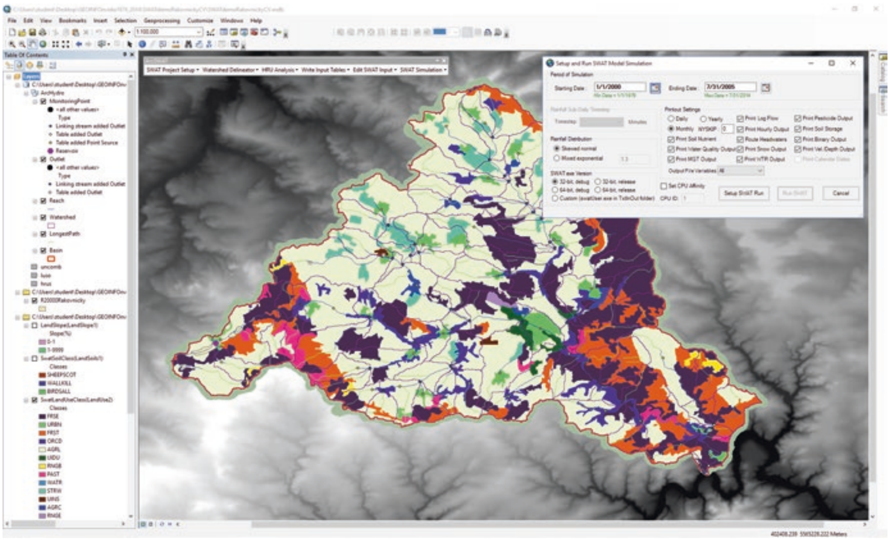


Fig. 2.12 The ArcGIS extension ArcSWAT for modeling of matter flows in a river basin such as with SWAT model (an example of a small basin with a land cover classification layer and a DEM layer on the background)

Table 2.3 A list of selected methods and functions implemented in desktop GISs

GIS functionality	List of selected methods and functions
Data management	Data creation and conversion (geodatabase, shapefile, coverage)
	Vector, raster, and TIN editing
	Projection and transformation
	Selection by location and attribute
	Archiving, data migration, and data export
Map display	Navigation
	Classification and symbolizing
	Display properties, page layout, and printing

(continued)

Table 2.3 (continued)

GIS functionality	List of selected methods and functions
Spatial analysis	Set operations (clip, split, merge, union, intersect)
	Proximity methods (buffer, Thiessen polygons, point distance, polygon neighbors)
	Generalization (dissolve, eliminate)
	Summary statistics
	Vector transformation (feature to point, line, or polygon)
	Raster management (composite bands, mosaic dataset, resample, statistics)
	Relationship classes
	Sampling (random points, generate points along lines, generate tessellation with triangles, squares, or hexagons)
	Geocoding tools (create address locator, geocode and standardize addresses)
	Linear referencing tools (create routes, locate features along routes, transform route events)
	Multidimensional tools—making Network Common Data Form (netCDF) feature/raster layer
Advanced spatial analysis	Raster algebra
	Distance mapping (cost distance, Euclidian distance, path distance)
	Analyzing patterns, mapping clusters, measuring geographic distribution
	Modeling spatial relationships (exploratory regression, geographically weighted regression)
	Groundwater (Darcy flow, particle track, porous puff)
	Hydrology (flow accumulation, flow direction, stream link, stream order)
	Multivariate analysis (band collection statistics, supervised and unsupervised classifications, principal components)
	Fuzzy membership
	Solar radiation (area solar radiation, points solar radiations)
	Surface (aspect, contour generation, curvature, hillshade, observer points, slope)
	Zonal statistics
Geostatistics	Exploratory spatial data analysis
	Spatial interpolation with deterministic functions and statistical methods
Network analysis	Creating a network dataset
	Finding the best route
	Finding the closest services
	Calculating service area and origin-destination cost matrix
3D tools	DEM creation and conversion (TIN, raster)
	Editing and shape interpolations, surface volume
	Visibility (sight lines, observer points, skyline barrier, viewshed)
Spatial and temporal modeling	Creating space-time cube
	Analysis spatiotemporal data
	Visualization space-time cube in 2D and 3D
Case-oriented extensions from other developers	ArcSWAT: http://swat.tamu.edu/software/arcswat/
	Geospatial Modelling Environment: http://www.spatialecology.com/gme/

2.6 Computer Systems for Spatial Data Management in GIS

Apart from a wide range of various data models, which are bind into specific data formats, implementation of database models linked to GIS is highly used way for management of spatial and temporal data. In a simplified way, a database contains a set of related data organized into collection of tables, forms, queries, reports, and other objects. The content of data is adapted to model aspects of reality in order to support processes requiring information, such as querying the capacity of energy sources in a way that supports finding the optimal energy sources near the area of interest. Access to all data in a database is provided by database management system (DBMS) that consists software tools for entry, storage, and retrieval of information. Modern database systems are supported by the relation model that is managed with the structured query language (SQL). Each user can control data in a database in dependence on access rules that are linked to database administration, data definition and update, data retrieval, and data view.

Physically, database systems are running on dedicated computers, which are supported by servers designated for network administration, World Wide Web, and other complemented services. Administration of database systems in data centers is extended by expert groups on data collection and data analysis besides other services. A simplified schema of a data center that is dealing with database management and public data services is illustrated in Fig. 2.13.

Spatial data models require a database that can store and query data representing objects in a geometric space such as points, lines, and polygons. In addition to previous database systems, extended functionality is required for databases to process spatial data types efficiently. An Open Geospatial Consortium (OGC) and International Organization for Standardization (ISO) created Simple Feature Access that specifies a common storage and access model of mostly managed two-dimensional spatial data such as point, line, polygon, and other features. Instead of using basic index practices, spatial databases use a spatial index to speed up database methods such as spatial selection, measurement, and topology.

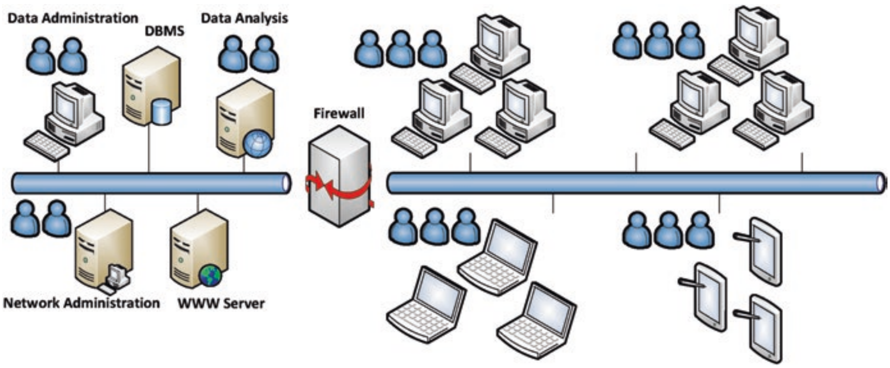


Fig. 2.13 A simplified schema of a computer center for database management and public data services

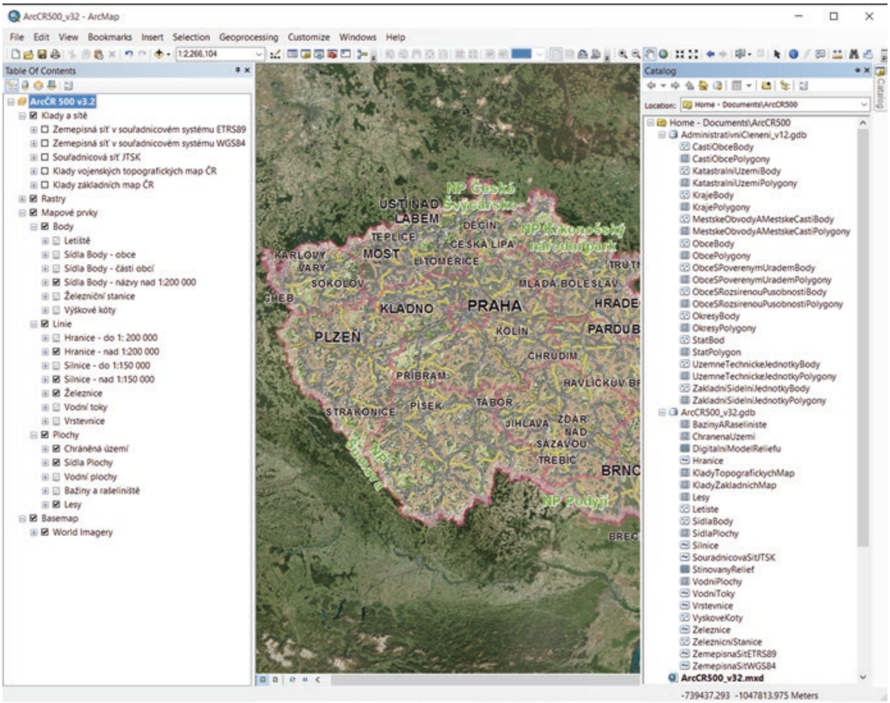


Fig. 2.14 Processing of digital vector geographic database of the Czech Republic ArcČR® 500 in the ArcGIS environment (the list of map layers is on the left side and the structure of geodatabase is on the right side)

A new complex object-oriented data model, geodatabase, was also introduced by Environmental Systems Research Institute (ESRI). A geodatabase, likewise other GIS data models, can manage four representations of geographic data: vector data for symbolizing features, raster data for representing images and gridded thematic data, triangulated irregular network (TIN) for designing surfaces, and addresses and locators for finding a geographic position (Fig. 2.14). The geodatabase is a collection of spatial datasets of various types held in a common file system folder, a Microsoft Access database, or a multiuser relational DBMS of many platforms such as Oracle, Microsoft SQL Server, PostgreSQL, Informix, or IBM DB2. It enables to manage spatial data in many sizes and have varying numbers of users in the scale from a single user to large workgroups. Main benefits of the geodatabase data model are:

– Uniform repository of spatial data: spatial data can be stored and managed in a database, which allows common data entry, more accurate data editing, and advanced validation.
– User works with more intuitive data objects: a geodatabase can contain data objects that better correspond to the reality such as producers of energy, power lines, transformers, and consumers instead of generic points, lines, and areas.

- Objects can be extended by relationships: definition of feature quantities is extended with topological associations and general relationships, which enables to specify what happens to features when related features are modified.
- Advanced map design can be implemented: drawing methods can be extended by writing scripts and features on a map display and can respond to changes in neighboring features.
- Larger datasets can be managed simultaneously: sets of features are continuous without tiles or other spatial partitions and can be edited by many users in a local area with reconciliation of any conflicts that emerge.
- Common setting of coordinate systems and map projections in feature datasets and raster datasets: all the data layers have to be in the same map projection and coordinate system in order to draw them on top of each other or combine them by analytical tools to see relationships.

The spatial datasets managed by database systems or saved as stand-alone files are used by desktop GISs, which are listed in Table 2.4. A list of selected GISs represents just a few software applications from a broad range of tools, which involve desktop GIS, Web map servers, software development frameworks and libraries (for Web and non-Web applications), extensions of computer-aided design (CAD), and mobile GIS implemented on mobile computing tools such as smartphones and tablets. The Web map server is implemented with ArcGIS for server dealing with accessing maps and geographic information on desktop applications and mobile computing tools. Its extensions can provide complete range of ArcGIS functionality such as manage Web services for mapping, spatial analysis, dataset editing, and geodata management. Also ArcGIS for server can manage the geodatabase, apply rules, define data models, maintain data integrity, and enable multiuser data processing. Similarly, MapServer on an open-source platform can be used for interactive mapping applications to the Web. The applications can be complemented by extensions developed with a scripting programming language.

2.7 GIS Tools for Processing and Presentation of Data Focused on Energy Sources

GIS can change the way of viewing our Earth's resources. GIS-based spatial modeling enables analysis of aerial and satellite images together with terrain properties such as digital terrain models, river network, road and railroad transport, industrial sites, and residential areas. The optional using of renewable resources can be improved by more precise prediction of local wind, solar, biomass, and surface water conditions. The next examples are focused on new applications of methods implemented in GIS and related computer systems. The selected methods dealing with mapping and spatial analysis will be presented using tools that can address a wider audience of energy researchers, academics, and practitioners.

Table 2.4 A list of selected desktop GISs and other related software tools

GIS	Description and the key features	Website and development
ArcGIS family Environmental Systems Research Institute (ESRI) [commercial]	Advanced analysis and data management capabilities, including geostatistical and topological analysis tools. It includes desktop GIS, server GIS and other tools such as ArcPad and mobile GIS for mobile computers. ESRI created a number of spatial data formats such as shapefile, geodatabase, and coverage	www.esri.com Environmental Systems Research Institute was founded in 1969 as a land-use consulting firm. The company has a network of many international distributors and hosts an annual International User's Conference complemented by European User's Conference and many meetings on the national level
GeoMedia [commercial]	Managing geospatial databases, creating maps, publishing geospatial information, and analyzing mapped information	www.hexagongeospatial.com/products/producer-suite/geomedia The application was developed by Intergraph, which was acquired by Hexagon
TerrSet (formerly IDRISI) [commercial]	The package dedicated originally for education is integrated geographic information system and remote sensing software	www.clarklabs.org GIS and image processing product developed by Clark Labs at Clark University in 1987. In January 2015 Clark Labs released the TerrSet Geospatial Monitoring and Modeling Software, version 18
GRASS (Geographic Resources Analysis Support System) [open source]	Geospatial data management and analysis, image processing, spatial and temporal modeling, and visualizing. It contains over 350 modules that can handle raster, topological vector, image processing, and graphic data	grass.osgeo.org The development of GRASS was started by the USA-CERL with the involvement of many others, including universities and other federal agencies in 1982. In October 1999, the license was changed to the GNU GPL

(continued)

Table 2.4 (continued)

QGIS (previously known as Quantum GIS) [open source]	Geospatial data management of raster and vector layers. Extensive functionality is given by integration with other open-source GIS packages, including PostGIS, GRASS, and MapServer	qgis.org The development of Quantum GIS started in early 2002, version 1.0, was released in January 2009. As an application under the GNU GPL, QGIS can be freely modified to perform different or more specialized tasks
Map Windows GIS [open source]	The GIS application and set of programmable mapping components. It can be reprogrammed to perform different or more specialized tasks. There are also plug-ins available to expand compatibility and functionality	www.mapwindow.org GIS package was adopted by the USEPA as the primary GIS platform for its Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) watershed analysis and modeling software
ENVI (Environment for Visualizing Images) [commercial]	Written in Interactive Data Language (IDL), ENVI enhanced the text-based IDL and enabled a suite of graphical user interfaces specialized in remote sensing imagery analysis. The package contains a number of algorithms which are mostly contained in automated, wizard-based approach	www.exelisvis.com The software package was released in 1994. After a few transformation, the former division Exelis Visual Information Solutions was purchased by the Harris Corporation in 2015, becoming Harris Geospatial
ERDAS IMAGINE [commercial]	The package is designed for remote sensing application with raster graphics editor abilities. It allows users to prepare, display, and enhance digital images for mapping use in GIS and computer-aided design (CAD)	www.hexagongeospatial.com The first version of ERDAS was launched in 1978. The application was developed by ERDAS, which was acquired by Hexagon
SAGA (System for Automated Geoscientific Analyses) [open source]	The package represents a user friendly platform for the implementation of geoscientific methods. It is achieved by the unique application programming interface. It comes with a comprehensive set of free modules	www.saga-gis.org In 2007, the center of the SAGA development moved toward Hamburg, where it is linked to the Department of Physical Geography

2.7.1 Web-Based Applications

US Energy Information Administration (US EIA) collects and analyzes energy information to promote understanding of energy and its relations to the economy and the environment. Many map views with optional extensions for customization are available through the Web pages on an interactive mapping system (Fig. 2.15).

British petroleum (BP) offers data on world energy markets for a period of a few past decades. Tables, charts, and map views are available through a couple of tools that can filter and analyze information on health, safety, and environmental performance. An example of the energy charting tool is illustrated in Fig. 2.16.

Fig. 2.15 An interactive mapping system dealing with energy sources and energy consumers managed by US EIA

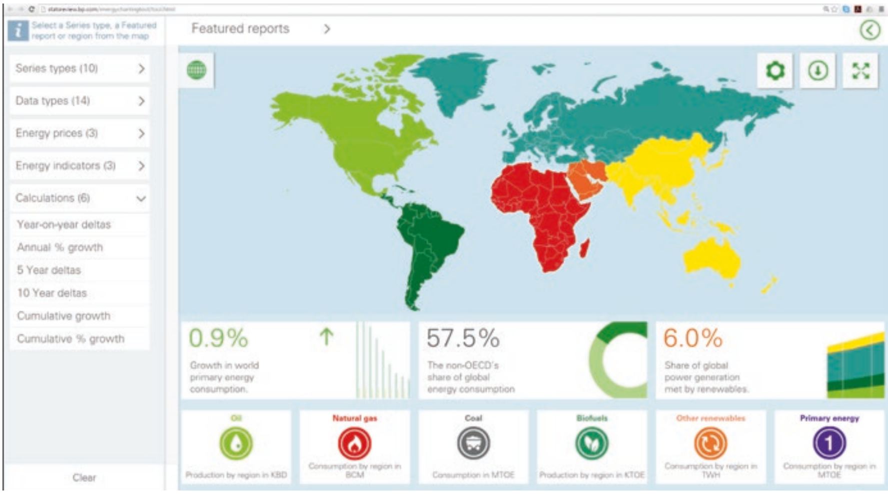


Fig. 2.16 An example of the energy charting tool managed by BP

2.7.2 *GIS Projects*

GIS organizes spatial datasets into projects that enable to combine a variety of data in an infinitive number of ways. As an example, a thematic map in Fig. 2.17, a layout view in Fig. 2.18, and a global scene in Fig. 2.19 show the primary energy consumption in 2013 in tonnes of oil equivalent (TOE) per capita. Ratios about primary energy per capita have been joined with attributes of the map layer: countries of the world. In order to simplify a view, the values are symbolized in the ranks (from ≤1 to ≤22 TOE per capita).

Information about the primary energy consumption in TOE per capita is used to provide comparable results for the whole world. The BP statistical review contains a majority of countries, which are significant primary energy consumers. The overview is given in a map view, which is used to display and work with geographic data in two dimensions (Fig. 2.17). It also shows the ArcGIS Pro environment for processing and analyzing data. The next step focused on finalizing of project results is represented by a layout view in Fig. 2.18. The GIS environment offers a number of items for layout design such as legends, scales, titles, north arrows, and other graphic and text symbols. The output layout views can be printed on large-format printers or exported to cloud GIS services. The results can be also visualized by a scene in a global 3D view (Fig. 2.19), which offers to work with data in three dimensions.

Other example presents mapping of energy utilities with data from US EIA. Vector datasets were imported into a GIS project and added to 2D layers. A vector dataset containing information about power plants was converted to a 3D layer thereafter, in order to provide extrusion of features to the 3D symbology. The loca-

Fig. 2.17 A map view of primary energy consumption in 2013 (TOE per capita) symbolized in the ranks (from ≤1 to ≤22 TOE per capita) in two dimensions. Source: BP Statistical Review, 2015; National Geographic World Map

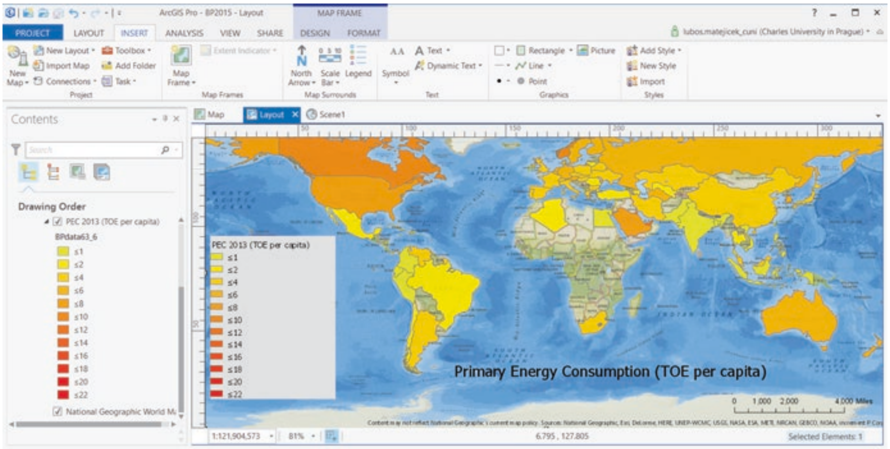


Fig. 2.18 A layout view of primary energy consumption in 2013 (TOE per capita) symbolized in the ranks (from ≤1 to ≤22 TOE per capita) complemented by a legend, a scale, and a title. Source: BP Statistical Review, 2015; National Geographic World Map

tions of power plants are highlighted by vertical lines that have different lengths in dependence on the total power. A part in the southeastern region of the United States is illustrated in Fig. 2.20 with a local 3D map that is complemented by an attribute table with information about local power plants. The rows are sorted in descendent

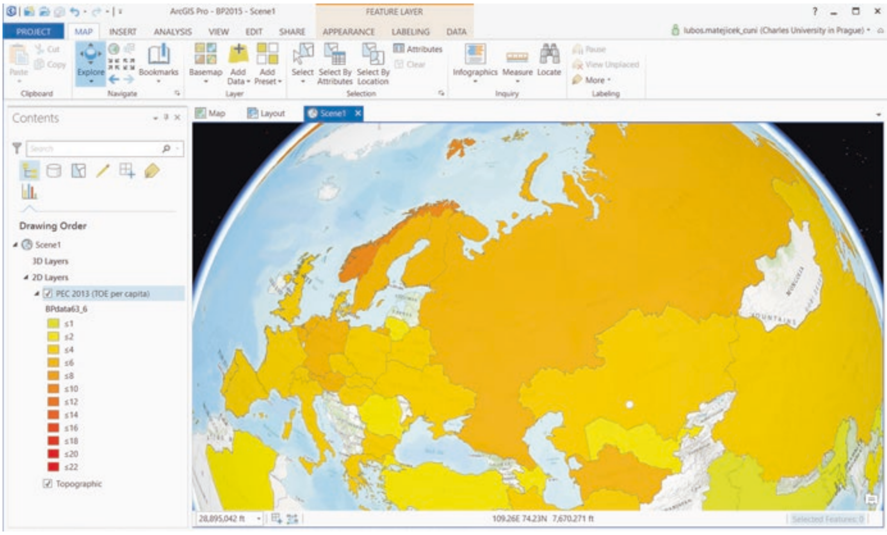


Fig. 2.19 A global 3D scene of primary energy consumption in 2013 (TOE per capita) symbolized in the ranks (from ≤1 to ≤22 TOE per capita). Source: BP Statistical Review, 2015; ESRI Topographic Map

order in dependence on the total power. Ten power plants with the highest total power are selected for indication in the 3D map. There are two natural gas power plants and one nuclear power plant in the list in the area of Florida. Also there are two coal power plants in Georgia and one nuclear power plant in Alabama. The local 3D map is complemented by a number of 2D layers that are focused on biofuel production, natural gas distribution, oil industry, and coal mines.

2.7.3 Development of Case-Oriented Software Applications

Case-oriented software applications for energy analyses mainly deal with enhancement of exiting GISs, utilization of other existing computational tools, or development of stand-alone software applications. As examples from a wide range of scientific research, environmental issues are used for presentation in a final part of this chapter. Energy extraction, transport, and consumption affect air, surface water, groundwater, and food chains. In the last 50 years, with the development of digital computers, environmental modeling has become more powerful for risk assessment of these phenomena. It is a science that uses mathematics to simulate environmental processes with computers. In case of environmental contamination, the models are based on physical and chemical phenomena such as diffusion, advection, sorption, reactions, and other thermodynamic processes. The model structure is also dependent on the spatial scale

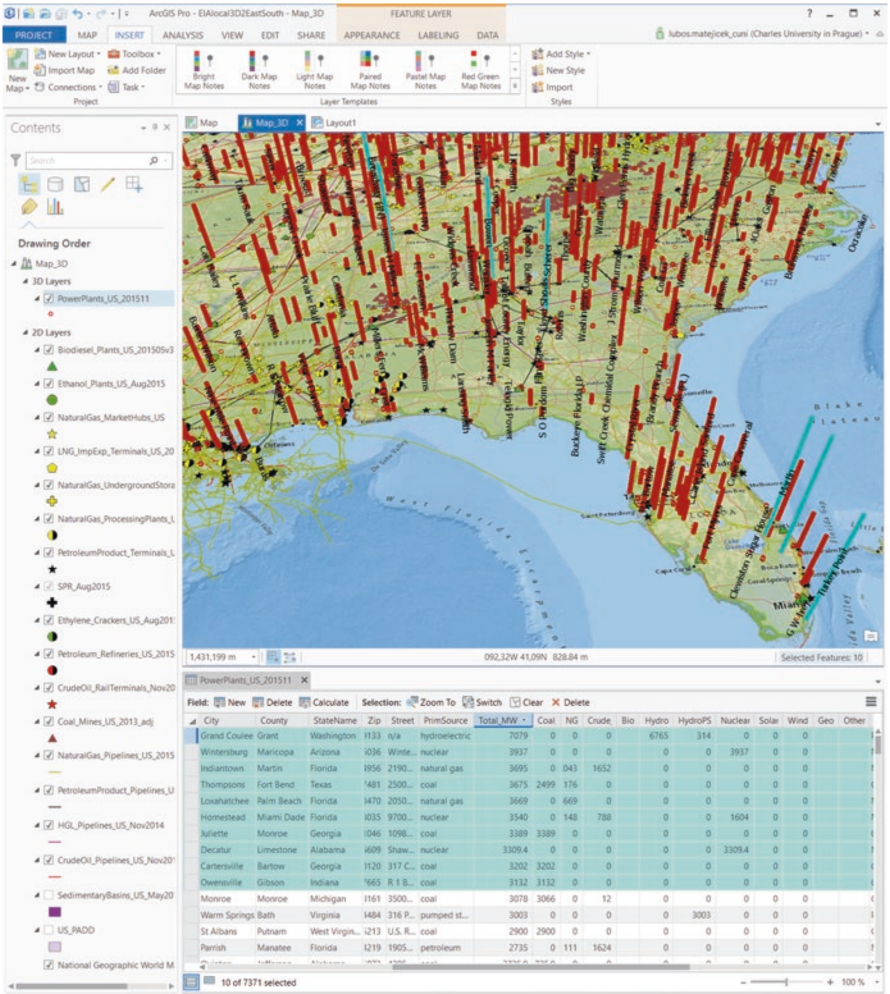


Fig. 2.20 The 3D scene of the primary energy consumption per capita in tonnes in 2013 in the ArcGIS Pro environment. Source: BP Statistical Review, 2015; ESRI Topographic Map

and the time scale of exploration. There are models of Earth's atmosphere or oceans under simulated conditions for long time periods such as hundreds of years, regional models of air pollution or contamination of surface water under simulated conditions for middle time periods such as year or months, and models of contamination caused by local accidents under simulated conditions for a few days or hours. The description of processes is translated into mathematical terms that lead to differential equations solving the change of a variable, like concentration in space and time. In mathematical models, diffusion is predicted by the Fick's second law that describes how the concentration is changed with time and space. It is a partial differential equation, which in one dimension is

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x} \tag{2.1}$$

where c is the concentration, a function $c = c(x,t)$ depends on location x and time t, and D is the diffusion coefficient. This 1D (one-dimensional) formula can be applied to various situations in almost all environmental compartments. The derived models are used in environmental pollution in the modeling of the local concentration distribution due to air emissions from stacks or point pollution in rivers. Modeling of pollutant distribution has to be extended by other phenomena such as advection, chemical reaction, or nuclear decay in addition to diffusion. Thus, the Fick's second law is used to be extended by other terms in three dimensions. The partial differential equation that describes diffusion in three dimensions and advection in one dimension is given by

$$\frac{\partial c}{\partial t} = D_x\frac{\partial^2 c}{\partial x} + D_y\frac{\partial^2 c}{\partial y} + D_z\frac{\partial^2 c}{\partial z} + \upsilon\frac{\partial c}{\partial x} - \lambda c \tag{2.2}$$

where c is the concentration, a function $c = c(x,y,z,t)$ depends on location x, y, z and time t; D_x, D_y, D_z, is the diffusion coefficient in the x, y, z direction, respectively; v is the advection in x-direction; and λ is a degradation coefficient for substances that are subject to degradation or decay processes in addition. An analytical solution for the 3D instantaneous emission source in a constant unidirectional flow field is

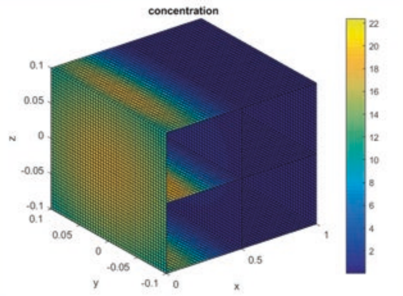
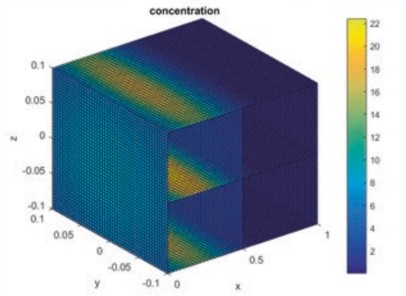
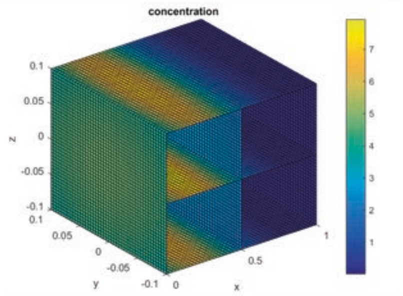
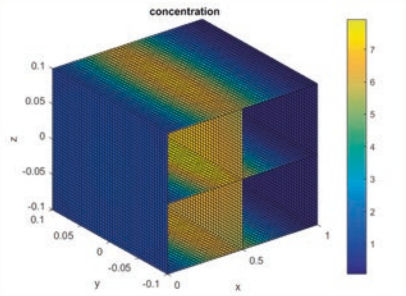
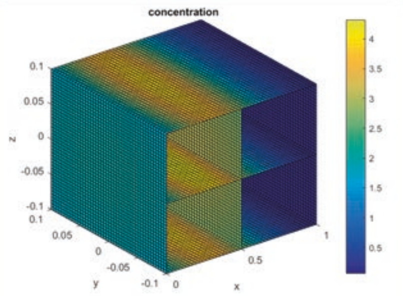
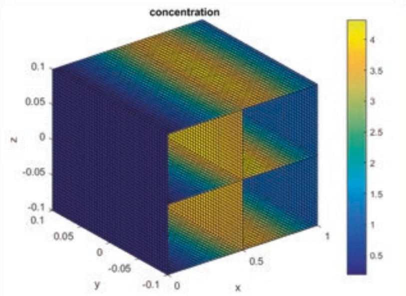
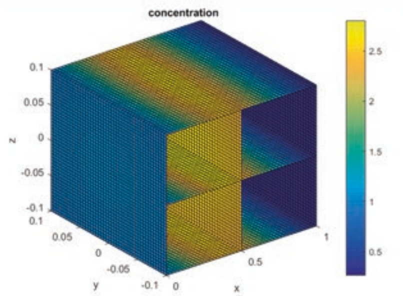
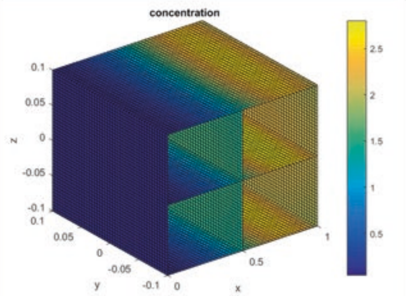
$$c\left(x,,,y,,,z,,,t\right) = \frac{M}{\left(\sqrt{4\pi t}\right)^2\sqrt{D_x D_y D_z}} e^{\frac{1}{4t}\left[\frac{(x-\upsilon t)^2}{D_x}\frac{y^2}{D_y}\frac{z^2}{D_z}\right]-\lambda t} \tag{2.3}$$

where M denotes the total mass per unit area in the fluid system.

There are many applications of this solution, mainly for air pollution modeling. Visualization of concentration distribution from a 3D Gaussian puff is illustrated in Table 2.5. It shows concentration distribution from 3D Gaussian puff for two different advections in x-direction based on an analytical solution for the 3D instantaneous emission source in a constant unidirectional flow field.

The previous simplified description of Gaussian puff has to be extended for applications in the atmosphere by terms that take the ground surface account and other meteorological conditions. Also all decay processes are neglected for which mathematical description requires a more detailed approach. It includes photochemical degradation, dry and wet deposition on the ground, washout due to precipitation, and other chemical reactions. Such more complex models are used extensively for prediction of the local development of a plume in the atmosphere. Simulation of these models often needs high-performance numerical solvers, which can be developed as stand-alone programs with high-level programming languages. More efficient way is represented by using of complex computing tools such as MATLAB,

Table 2.5 Visualization of concentration distribution from 3D Gaussian puff for two different advections in x-direction based on an analytical solution for the 3D instantaneous emission source in a constant unidirectional flow field ($D_x = D_y = D_z = 0.01$ m^2/s; $M = 1$) in MATLAB 2016a

t	v= 0.1 ms^{-1} in the x-direction	v= 0.2 ms^{-1} in the x-direction
1		
2		
3		
4		

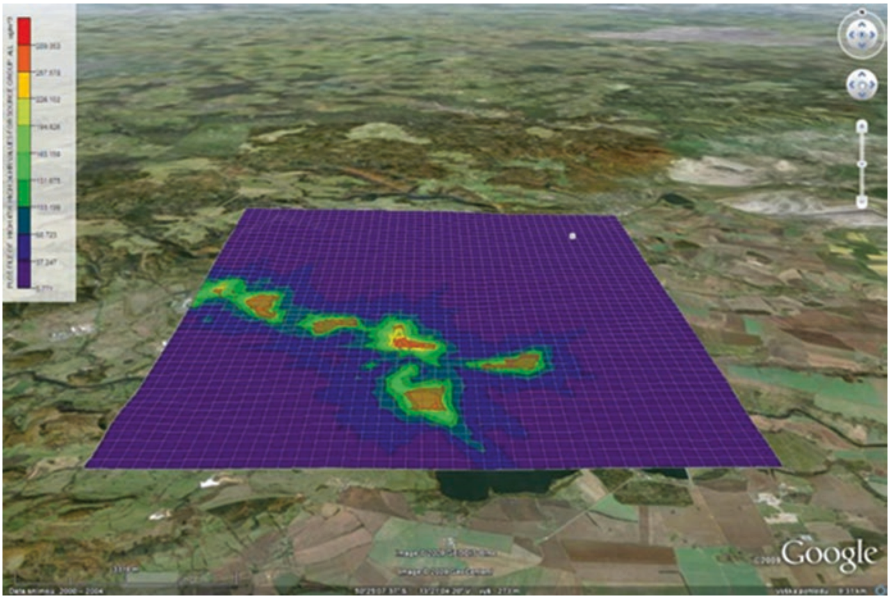


Fig. 2.21 An output of the Industrial Source Short Term (ISCST3) in the AERMOD View, a map layer of air pollution above the surface (concentration of the particulate matter with a mean aerodynamic diameter 10 μm)

Mathematica, Maple, or R. In addition to numerical solvers, they can manage input data, visualize results, and complement risk assessment with a number of optional extensions and toolboxes.

Information about national standards under a variety of environmental laws and about environmental monitoring and modeling are reported by US Environmental Protection Agency (USEPA), which was established for protecting human health and the environment. The EPA was proposed by President Richard Nixon by writing and enforcing regulations based on laws passed by Congress. An example an output of the Industrial Source Short Term (ISCST3) is illustrated in Fig. 2.21, which contains a map layer of air pollution above the surface. It displays concentration of the particulate matter with a mean aerodynamic diameter 10 μm (PM_{10}). The air dispersion model ISTST3 represents a Gaussian plume model, which is widely used to assess pollution concentrations. The model contains extensions of the simplified mathematical description of Gaussian puff in order to provide simulation of emission from more emission sources of various types such as point, line, and area emission sources. It also incorporates the ground surface account and a number of meteorological conditions such as wind speed and wind direction; atmospheric chemistry for NO_x, NO_2, and SO_2 decay; and building downwash. The model is used to be a component of air dispersion modeling packages, which implement other popular EPA models into one interface.

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