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Geospatial Operations of Discrete Global Grid Systems—a Comparison with Traditional GIS

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Abstract

As the foundation of the next-generation Digital Earth, Discrete Global Grid Systems (DGGS) have demonstrated both theoretical and practical development, with a variety of state-of-the-art implementations proposed. These emerging DGGS platforms or libraries support preliminary operations such as quantization, cell-level navigation, and conversion between cell addresses and geographical coordinates, while leaving the other more complicated functions unexplored. This paper discusses the functional operations in a DGGS environment, including the essential operations defined by the Open Geospatial Consortium (OGC) Abstract Specification, and the extended operations potentially supported by DGGS. The extended operations are discussed in comparison to the traditional GIS, from the aspects of database techniques, data pre-processing and manipulation, spatial analysis and data interpretation, data computation, and data visualization. It was found that with the OGC-required operations and pre-processing operations as the baseline of development, some function algorithms can facilitate the algorithm development of other analytical functions. Several future research directions regarding the data modeling uncertainties, extended analytic algorithm development, and database and computation technologies are presented. This paper provides a comparison between DGGS and traditional GIS operations and can serve as a reference for future DGGS operation development.

Keywords Discrete Global Grid Systems · GIS · Open Geospatial Consortium · Geospatial operations

Introduction

A Brief Overview of Legacy GIS

Geographic Information Systems (GIS) appeared as a framework for managing, analyzing, and visualizing spatial data in the 1960s (Bernhardsen 2002). GIS changed the way the world functions, from paper maps to organized geospatial data, pure navigation to knowledge discovery, and citizens' daily life to governors' decision making. GIS technology has been constantly improved in terms of database management, spatial indexing mechanisms, computation performance, and hardware capability (Bernhardsen 2002). Nonetheless, many concepts of GIS have barely changed.

First, the spatial information of one location is sliced into multiple theme layers. For example, to understand if temperature and air humidity influence vegetative growth, one needs to overlay the layers of influencing variables on the vegetation layer to find out the answer. Spatial information is stored as thematic layers in a geodatabase instead of being vertically integrated and associated with specific locations. This is practical for gathering information on one theme, but it leads to difficulties when assembling themes of interest about one location (Goodchild 2018).

Second, the GIS community has been habituated to projecting the curved Earth's surface to a 2D plane. Consequently, data models used to record geospatial information (e.g., vector and raster) are essentially flattened, although this causes spatial-analysis functions to be more simplified compared to performing analysis on a curved surface (Goodchild 2019). Furthermore, map projections result in distortions in shape, area, distance, or direction, depending on the location on the Earth and the projection method used. End-users are left with the responsibility to understand these distortions when doing analysis, interpreting results, and making decisions (Goodchild 2019).

Third, the geo-features have been commonly represented at a single resolution level, and the analysis on the modeled world is usually at a single resolution as well. This complies

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with a human's habit of observing the world at a single resolution, while a single resolution potentially causes limitations when analyzing the spatial phenomena. Although researchers have increasingly realized the importance of carrying out studies at multiple spatial scales, the scale levels are not always systematically defined and are ambiguous in the local, regional, national, and global concepts.

With the advances of hardware and computing technologies, people started to construct a digital representation of spatial information on a globe. Many of the existing Digital Earth platforms are open-source and allow users to customize a digital globe for individual purposes, such as Cesium, NASA WorldWind, and Google Earth Enterprise (Cesium 2019; GEE 2017; NASA 2018). These platforms benefit various spatial analysis and decision-making processes including environmental conservation, emergency response activities, and geospatial visualization (Bradley et al. 2011; Kang et al. 2018; Pirotti et al. 2017). However, these Digital Earth platforms have common limitations: (1) the fixed, pre-processed global base maps cannot be used for data incorporation or spatial calculations (PYXIS 2008); (2) they remain essentially flattened technologies given that their underlying data models are flattened (Goodchild 2019); and (3) they have inconsistent spatial resolutions in an east-west direction among latitudes because of the inherent flattening process (Goodchild 2019).

Other than these limitations, the main challenge remained: a way to enable people including citizens or researchers without the GIS expertise, to obtain meaningful information from massive geospatial data (Peterson and Shatz 2019). To achieve this goal, data with different formats from multiple sources need to be organized in a "congruent geography" environment, and Digital Earth platforms need to support enriched spatial analysis (Goodchild 2018).

Discrete Global Grid Systems

These days, the emergence of Discrete Global Grid Systems (DGGS) provides great opportunities for innovation of legacy GIS. DGGS have been recognized as the foundation of Digital Earth in the next generation (Goodchild et al. 2012).

Discrete Global Grid is a partitioning approach to divide the Earth's surface into nearly uniform cells and represent each cell by a single identifier (Goodchild 2000). A DGGS consists of a series of Discrete Global Grids with nested resolutions, and is expected to support global sampling, information storage, data modeling, analysis, integration, and visualization (Alderson et al. 2020; Goodchild 2000). The term DGGS was formally coined in the 1980s when Geoffrey Dutton proposed and mathematically presented the global Geodesic Elevation Model (GEM; Dutton 1984) which was later modified to a simpler structure Quaternary Triangular Mesh (QTM; Dutton 1989). In the same period, the opportunity to create global grid systems was identified by a group of scientists who leveraged the previous work experience and set the stage for the development of the modern DGGS (Goodchild and Yang 1989; Tobler and Chen 1986; White et al. 1992). The advances in computing power also accelerated the DGGS development during that period. Stepping into the twenty-first century, a variety of DGGS designs appeared, which called for the standardization and compatibility among the different spatial data infrastructures (Gibb et al. 2013; Gorski et al. 2005; Hall et al. 2020; Sahr et al. 2003, 2015; Song et al. 2002; White 2000). DGGS was first confirmed by the Open Geospatial Consortium (OGC) as a new Earth reference standard in 2017 (OGC 2017). Based on the DGGS criteria given by Goodchild (1994) and Kimerling et al. (1999), the OGC Abstract Specification codified the common qualities of DGGS that support interoperability and allow flexibility in the development (OGC 2017).

The OGC defined DGGS as "a spatial reference system that uses a hierarchical tessellation of cells to partition and address the globe" (OGC 2017). As stated in the OGC Abstract Specification, "DGGS are characterized by the properties of their cell structure, geo-encoding, quantization strategy, and associated mathematical functions" (OGC 2017). One can imagine Discrete Global Grids as a spreadsheet where cell locations are fixed at a specific resolution and spatial information can be assigned to individual cells (Peterson 2016). A DGGS normally begins with a platonic solid, an initial discretization of the Earth into planar cells. The initial cells can then be hierarchically refined to certain resolutions and mapped from planar cells to spherical cells by an equal-area projection method (Mahdavi-Amiri et al. 2015a). Other approaches to construct a DGGS include the direct surface tessellation by polyhedral-small circle boundaries (Song et al. 2002). Recently, scientists are exploring regular polyhedra with more faces to further reduce distortions when projecting to a datum surface (Hall et al. 2020), and extending a DGGS to a third dimension which tessellates the volume instead of the surface of the Earth (Ulmer et al. 2020).

Advantages of DGGS

As discussed earlier, the traditional GIS have some legacy properties such as sliced spatial information layers, projection distortions, and single resolution levels. DGGS, on the other hand, use discrete cells as the basic unit to store the spatial information, which can outperform the traditional GIS to some degree.

First, DGGS cell locations are fixed at a certain resolution level, and the spatial data associated with a cell can be aligned in a DGGS (Alderson et al. 2020). Hence, the spatial information is stored in a "congruent geography" instead of the sliced theme layers, which can accelerate data queries based on locations (Goodchild 2018).

Second, DGGS provide a discrete reference system instead of continuous coordinates (Mahdavi-Amiri et al. 2015a). This contributes to a more precise space because an areal cell can mitigate uncertainties around a geographic location while a dimensionless point cannot. When being stored in the computer memory, a cell index with finite length is more precise than coordinates with rounded digits. Besides, a discrete reference system offers the potential to observe successive phenomena at the same geographic location defined by a cell or a group of cells at a certain resolution level, which is not practical for a point-based coordinate system.

Third, because of the traditional vector and raster divide, storage techniques, indexing mechanisms, topology detection methods, and data query functions must be developed separately for these two different data models (Bernhardsen 2002). However, a DGGS can serve as a uniform data model to transform geospatial information from various data sources and to be independent of the original data formats (Peterson 2016).

Fourth, DGGS use a hierarchical tessellation of cells to partition and address the globe (Fig. 1), where resolutions are inherently defined with cell indices (Goodchild and Yang 1989). Due to the nearly unified cell size at a certain resolution, DGGS offer the consistent spatial resolution at each level. Multi-scale analysis can be carried out by taking advantage of the hierarchical nature of DGGS.

Furthermore, the Earth's curvature is considered in DGGS to achieve a better analysis accuracy. Compared to the Digital Earth based on the traditional graticule defined by geographic coordinates, a DGGS provides aggregation units of uniform size and shape in most cases, so that all parts of the Earth's surface are treated consistently and fairly, and the information can be conveyed without a visual deformation of the content when being displayed (Goodchild 2019).

DGGS Implementations

There have been some DGGS implementations proposed to provide researchers with platforms to generate various DGGS cells, conduct sampling designs, integrate datasets from heterogeneous sources, or carry out the basic spatial analysis. Current DGGS implementations include Global Grid Systems (previously known as PYXIS), H3, OpenEAGGR, DGGRID, HEALPix, rHEALPix, SCENZ-Grid, and geogrid. Table 1 summarizes their base polyhedra, the finest resolutions, indexing methods, available language bindings, and open-source licenses for those open-source libraries, and indicates if they have a graphical user interface and allow the user-defined configurations such as the cell shape, refinement ratio, orientation of the grid relative to the Earth's surface, and polyhedral projection method.

Among these implementations or libraries, Global Grid Systems is a commercial implementation based on an ISEA3H DGGS (GGS 2019). It offers a graphical user interface and functions such as the multi-source data integration, image processing pipelines, and statistical summaries. H3 is an open-source library based on an icosahedron-hexagonal DGGS, and rHEALPix is an open-source web service based on Gibb's rHEALPix DGGS (Bowater and Stefanakis 2019; Gibb 2016; Uber 2017). DGGRID and OpenEAGGR allow end-users to choose from various DGGS configurations (OpenEAGGR 2017; Sahr 2020). HEALPix was developed by NASA's Jet Propulsion Laboratory (JPL) to store background cosmic microwave energy, aiming to map the sky above the Earth's surface (JPL 2018). SCENZ-Grid, based on the rHEALPix DGGS, was proposed by Landcare Research in New Zealand for environmental modeling purposes (LCR 2017). The open-source library geogrid provides functions to generate and manage the ISEA3H DGGS and presents the data in the browser via the JavaScript library geogrid.js (Mocnik 2018).

The supported operations of these DGGS implementations are summarized in Table 2. All the listed DGGS implementations support conversions between the cell addresses and geographical coordinate pairs. DGGRID, which offers users multiple grid configuration choices, also supports direct conversions between cell addresses under different grid configurations without using geographical coordinates (Sahr 2020). Cell centroid, cell boundary, and cell size determination, neighborhood and parent-child cell navigation, and

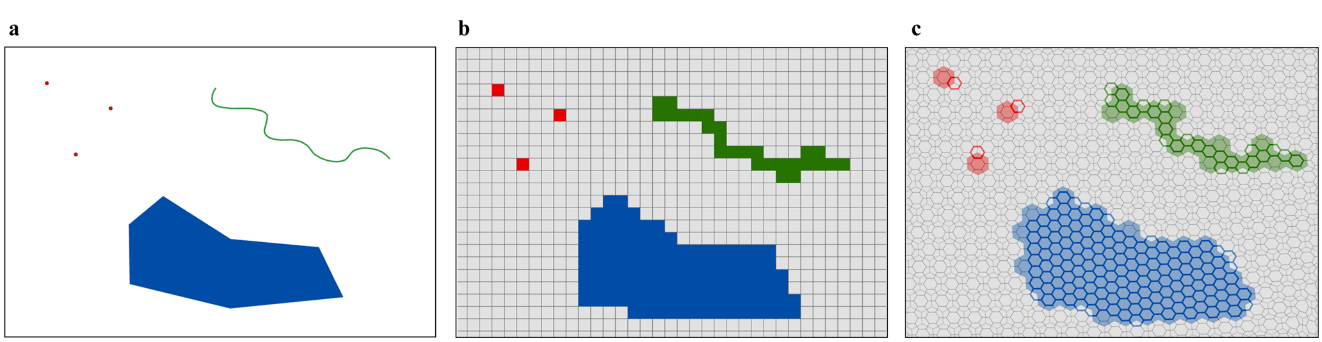

Fig. 1 Modeling spatial objects by **a** the vector model, **b** the raster model, and **c** the hexagonal DGGS model at two different resolution levels: solid cells and hollow cells represent the modeling at the coarse and fine resolutions, respectively

Table 1 Features of the state-of-the-art DGGS implementations, platforms, or libraries

	Global Grid Systems (PYXIS)	H3	OpenEAGGR	DGGRID (dggridR, pydggrid)	HEALPix	rHEALPix	SCENZ-Grid	Geogrid (geogrid.js)
Base Polyhedron	Icosahedron	Icosahedron	Icosahedron	Icosahedron	Rhombic dodecahedron	Cube	Cube	Icosahedron
Supported Resolution Level	mm^2	m^2	cm^2	cm^2	milli-arcseconds	m^2	NA	0.002 km^2
Indexing Methods	Hierarchy-based and UV coordinate indexing	Hierarchy-based	Hierarchy-based or offset coordinate indexing	Hierarchy-based	Quadrilateral tree pixel numbering	Hierarchy-based	Hierarchy-based	Identifier scheme using the geographic coordinates of the centroids
Language Bindings	NA	C++, Erlang, Go, Java, JavaScript, OCaml, PHP, Python, R	C, C++, Java, Python	C++, R, Python	C, C++, Fortran90, IDL, Java, Python	Python	NA	Java, JavaScript
Open-source License	NA	Apache 2.0 License	GNU Lesser General Public License v3.0	GNU Affero General Public License v3.0	GNU General Public License v2.0	NA	NA	MIT License
User-defined Configuration Options	NA	NA	ISEA4T, ISEA3H	ISEA3H, ISEA4H, ISEA43H, ISEA4T, ISEA4D, FULLER3H, FULLER4H, FULLER43H, FULLER4T, FULLER4D, and customized orientation	NA	Customized orientation	NA	Customized orientation
Graphical User Interface	Supported	Not supported	Not supported	Not supported	Not supported	Supported	Supported	Not supported
Reference	GGS (2019)	Uber (2017)	OpenEAGGR (2017)	Sahr (2020)	JPL (2018)	Bowater and Stefanakis (2019)	LCR (2017)	Mocnik (2018)
URL	https://www.globalgridsystems.com/	https://github.com/uber/h3	https://github.com/riskaware-ltd/open-eaggr	https://github.com/sahrk/DGGRID	https://healpix.sourceforge.io/index.php	http://atlas.gge.unb.ca/rHEALPix/	https://www.seegrid.csiro.au/wiki/SCENZGrid/WebHome	https://github.com/giscience/geogrid

Table 2 Operations supported by the state-of-the-art DGGS implementations, platforms, or libraries; references and links to the library websites are provided in Table 1

	Global Grid Systems (PYXIS)	H3	OpenEAGGR	DGGRID (dggridR, pydggrid)	HEALPix	rHEALPix	SCENZ-Grid[a]	Geogrid (geogrid.js)
Conversion between Cell Addresses and Geographical Coordinates	✓[b]	✓	✓	✓	✓	✓	✓	✓
Determine Cell Centroid and Boundary		✓	✓	✓	✓	✓		✓
Determine Cell Size	✓	✓	✓	✓		✓		✓
Cell Navigation	Hierarchy and neighborhood	Hierarchy and neighborhood	Hierarchy		Hierarchy and neighborhood			
Data Query	✓	Need to be integrated with geojson2H3 or kepler.gl	Need to be integrated with PostgreSQL or Elasticsearch		✓		✓	
Other Supported Operations	Image processing pipelines, aggregated summaries, on-the-fly data integration	Find cells in the vicinity of an origin cell, determine how to traverse the grid from one to another, convert cell indices to and from polygonal areas, encode the directed edge from one cell to a neighboring cell	Analysis such as disjoint, equal, and containing tests between points, line-strings, and polygons, determine if the constructed object is on a single polyhedral face	Conversion between cell addresses on different grid tessellations, sampling, determine an appropriate grid resolution based on users' desired cell size	Spherical harmonics analysis, mask processing, smoothing and filtering, find the indices of all cells within an angular distance, a spherical polygon, a latitude strip, or a spherical triangle	Determine the cells constructing a region boundary	Data processing workflows	Execute parallel computation

[a] Summary of supported operations of SCENZ-Grid may not be complete because of the inaccessible source code and unavailable documentation

[b] The check mark symbols represent that the operations are supported

quantization methods are supported by most of the implementations. With the on-the-fly data integration and auto-mosaicking of images, Global Grid Systems has the most mature data query functions among the others. It can dynamically generate statistical summaries based on either spatial locations or non-spatial attributes (GGS 2019). Data query of H3 and OpenEAGGR needs to be integrated with the third-party applications (OpenEAGGR 2017; Uber 2017).

Some other basic geospatial functions have been included in these libraries. For example, topological relationships between geo-features can be determined by OpenEAGGR, locating cells around the target cell under a searching criterion is realized by H3 and HEALPix, and determining the cells that consist a region boundary is supported by rHEALPix (Bowater and Stefanakis 2019; JPL 2018; OpenEAGGR 2017; Uber 2017). Bondaruk et al. (2020) reviewed four

DGGS implementations including dggridR, H3, OpenEAGGR, and S2, and compared them against the OGC Abstract Specification released in 2017 (OGC 2017). The study showed the basic functionality supported by the evaluated software and concluded that dggridR had the best performance of handling large datasets (Bondaruk et al. 2020). Given the characteristics and supported operations of the existing DGGS implementations, users are provided with options to work with different libraries depending on specific objectives. Global Grid Systems is recommended when the on-the-fly data integration and immediate data visualization are needed. DGGRID and OpenEAGGR are advisable if users intend to customize grid configurations. rHEALPix is useful for latitudinal data analysis because of its iso-latitude property. HEALPix was initially designed for astronomical analysis, and has been applied to astronomical studies (e.g., Fernique et al. 2015).

Nonetheless, applying DGGS to solving real-world problems is still in its infancy, and there is a lot of work remaining to develop more complicated functions such as interpolation, network analysis, and geostatistics. Efforts are also needed to ascertain if the existing algorithms used by the traditional GIS can be applied to DGGS with or without modification, and to compare if these operations in DGGS can outperform those run by the traditional GIS software.

The paper aims to provide the viewpoints and discussion regarding the DGGS operations, including those that have been realized so far and will be developed in the future. The remainder of the paper is organized as follows. The next section introduces the basic operations of DGGS required by the OGC Abstract Specification. The third section discusses the extended operations that should be supported by a DGGS platform and compares them to the traditional GIS. The fourth section presents the discussion on the analytical operations in terms of the algorithm development and potential performance. The fifth section gives the future research directions, and the last section draws the general conclusions.

Basic DGGS Operations Required by the OGC

The OGC Abstract Specification has listed three basic categories of operations that should be defined in a DGGS specification, including quantization operations, spatial relation operations, and interoperability operations (OGC 2017; Fig. 2). These basic operations guarantee that a DGGS implementation can support assigning data to cells and retrieving data from cells, performing spatial relation queries, applying connectivity and hierarchical operations to cells, and transforming cell addresses to other Coordinate Reference Systems.

Quantization Operations

Quantization operations are mechanisms of assigning data values to cells and retrieving information from cells. A DGGS is a multiscale "congruent geography" that has multiple geospatial information associated with fixed cells (Goodchild 2018). The OGC does not limit quantization strategies used for transforming raw data values into DGGS cells. Rather, it allows DGGS cells to play the roles of data tiles, data cells, coordinates, tags, graphic cells, and graphic tiles (Fig. 2). Different approaches should be used to associate the raw spatial datasets from multiple sources to DGGS cells in terms of different roles they play and different DGGS designs adopted. For example, when DGGS cells play the role of data cells, spatial observations are assigned to individual cells according to their geometries (OGC 2017). Multiple studies have proposed methods of data cell quantization operations for different data formats. Hierarchical cell rasterization can be used to store vectors in DGGS which, for example, uses quadtrees to approximate geo-features by recursively refining a quad cell until the achieved approximation of the feature meets the requirement (Mahdavi-Amiri et al. 2018; Sahr 2008). Image datasets are commonly resampled to DGGS cells, where the values of the original images are assigned to the corresponding DGGS cells which are usually referenced by the cell centroids. Considering that the traditional images consist of square pixels, transformation algorithms between different cell geometries have been developed (Mahdavi-Amiri et al. 2018), and formats to encode cartographical meshes other than squares have been proposed (e.g., hexagonal meshes; de Sousa and Leitão 2018). Some open questions have remained, such as how to define the sample rate when sampling geospatial signals, what is the criterion of fidelity maintenance of the original information, and how to aggregate geospatial information when moving from a fine resolution to a coarse resolution in DGGS. The quantization strategy adopted by Global Grid Systems is based on the Nyquist–Shannon sampling theorem, which states that the minimum sample rate is ought to double the frequency of its highest frequency component (GGS 2019; Mohamed-Ghouse et al. 2020; Shannon 1949). In the work of Robertson et al. (2020), the basic quantization resolution is selected as the nearest one to the original raster's cell size or selected according to the positional accuracy of the original vector data. These decisions will lead to further uncertainties when applying a DGGS, such as data quality, geometric measurement, and topology validity. The impact of conversion to DGGS on data quality can be evaluated in multiple ways based on the original data models. When converting image data or terrain raster data to the DGGS model, the data quality can be

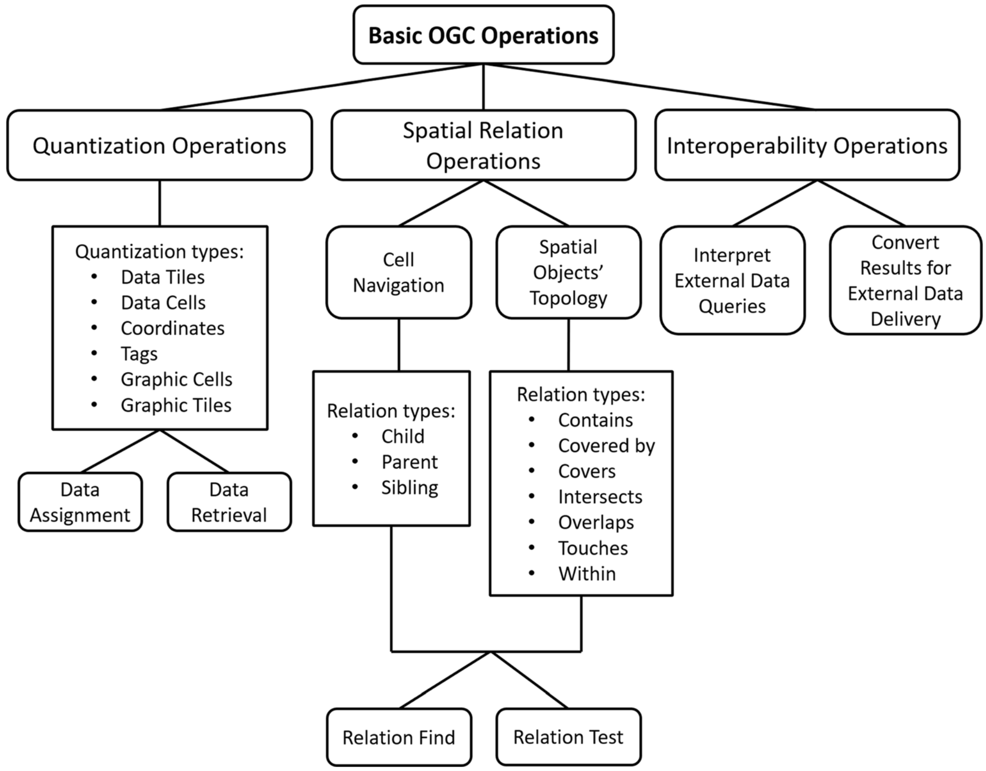

Fig. 2 Basic DGGS operations required by the OGC Abstract Specification

investigated by comparing pre-DGGS and post-DGGS values for a set of sample points (e.g., compute the root mean square error). When converting vector data to the DGGS model, the data quality can be evaluated by the point position displacement and line and polygon features' geometry fidelity. For instance, Li and Stefanakis (in press) quantitatively measured the geodesic distance between the original point and converted cell centroid as the point position displacement, the difference between the original length and the total inter-centroid distance as an indicator of the preserved fidelity of the modeled line features, and the difference between the original polygon area and the total cell area as an indicator of the polygon features' geometry fidelity.

Spatial Relation Operations

The OGC requires that a DGGS specification should include methods to perform cell navigation operations as well as basic spatial analysis operations across its entire domain, which can facilitate queries necessary to retrieve data from DGGS cells (OGC 2017). Topology is used to describe spatial relations based on the principles of feature adjacency and feature connectivity, including contains, covered by, covers, crosses, intersects, overlaps, touches, and within (Fig. 2). Spatial analysis operations cover topological functions, which support both querying the objects having certain relationships with the target and testing if a certain relationship exists between the targets (OGC 2017).

With DGGS, topology can be defined at two levels: the cell level and the spatial object level. At the cell level, the topology detection, conducted as the cell navigation, is less complex because the referencing method (e.g., space-filling curve and hierarchical-based index) together with the cell indices can naturally carry the topological relationships between neighboring cells (OGC 2017). Cell navigation operations include navigation through both hierarchy relationships (i.e., parent-child) and neighborhood associations (i.e., siblings), which have been developed in most of the state-of-the-art DGGS implementations (Table 2). Particularly, a hierarchy-based indexing method can help to determine neighboring or parent-child relationships by identifying the cell identifiers' common patterns, for example, prefixes.

On the other hand, determining and maintaining the topological relationships between spatial objects when modeling on DGGS need more exploration. Egenhofer's Dimensionally Extended Nine-Intersection Model (DE-9IM) was used to define relationships between two geometries by defining the external, border, and interior areas for each geometry (Egenhofer and Herring 1990). This topology description model was adjusted and extended to work in Global Grid Systems by ignoring the geometries' border, defining the border using DGGS cells' connectivity, or defining the border via the coverage information regarding the geometry for each cell (GGS 2019; Peterson 2016). However, the original topology among spatial objects may not remain valid after migrating to a DGGS. For example, a line that should be disjoint from a polygon may end up with intersecting with the polygon after being modeled on a DGGS. Finer resolutions are expected to mitigate the violation of such topological relationships. Li and Stefanakis (in press) showcased the potential invalidity of topological relationships when modeling geo-features on various DGGS tessellations at multiple resolutions. Zhou et al. (2020) proposed a method to preserve the vector geometries' topology in DGGS, which determines the topological distortion at the spatial object level by detecting the topology at the cell level, and increases the local resolution of the vector features to fix their topological invalidity. This approach was applied to solving the topological distortion between the same geo-feature types, i.e., point-to-point, line-to-line, and polygon-to-polygon, when they are modeled on a DGGS (Zhou et al. 2020).

Interoperability Operations

Interoperability has been recognized as an important feature for Digital Earth platforms to promote the multi-source data integration. The interoperability can be achieved by internationally standardized service interfaces and standardized data and metadata models (Nativi and Domenico 2009). The interoperability is especially critical for compliant DGGS infrastructures to realize the communication and connectivity, although it emphasizes the usage of a unified model type and the conversion between the traditional models and the DGGS model (OGC 2017). It stipulates that DGGS implementations should have the capability to convert DGGS cell addresses to other DGGS specifications or a traditional longitude-latitude graticule (e.g., Mahdavi-Amiri et al. 2015b). This enables a DGGS implementation to read, translate, and interpret the external data queries and to process commands (OGC 2017). It also enables a DGGS to translate the DGGS-generated results with an internal data format to a format that is ready for delivering to external data infrastructures or external clients (OGC 2017). External clients and infrastructures incorporate web-based clients, software clients on the same Information and Communications Technology infrastructure as DGGS, or other DGGS infrastructures (OGC 2017). The transformed formats include but are not limited to ASCII, GML, HDF, JSON, netCDF, and XML (OGC 2017). Alderson et al. (2020) also mentioned the ongoing development of a common Application Programming Interfaces (API) language for DGGS that can further support interoperability between compliant DGGS infrastructures and encourage more implementation of DGGS technologies.

As summarized in Table 2, all of the listed DGGS implementations support the conversion between the cell addresses and their geographical coordinates. Typically, DGGRID supports the transformation among different grid tessellations without using geographic coordinates (Sahr 2020). What is more, DGGRID can save the generated DGGS grids in the format of ESRI shapefile or KML, which can then be visualized or further analyzed on other platforms (Sahr 2020). OpenEAGGR also supports the linkage to the third-party applications like PostgreSQL/PostGIS and Elasticsearch, which facilitates the delivery to the external data infrastructures or external clients (OpenEAGGR 2017).

Extended DGGS Operations Compared to Traditional GIS

The extended DGGS operations discussed in this paper include database techniques, data pre-processing and manipulation, spatial analysis and data interpretation, data computation, and data visualization (Fig. 3). Database management is viewed as the base technique that supports follow-up functionalities. Data pre-processing and manipulation aim to prepare the raw data to be ready for analysis. Spatial analysis and data interpretation are core geospatial operations, including those conventionally vector-based and raster-based operations. This section does not intend to enumerate all the specific functions that are supported by the traditional GIS software, but to list the representatives and to discuss how these operations compare to those in the traditional GIS, what solutions have been proposed for DGGS, what other algorithms are expected, and what key points should be paid attention to in the future development. As shown in Fig. 3, the development of some of the functions can facilitate the development of the other functions. Data computation and data visualization are also discussed in the context of DGGS. General comments are listed in Table 3 and the detailed discussion is provided in the following sections.

Database Techniques

GIS communities have begun to employ the object-relational database to manage geospatial data since the early 1990s (Stonebraker and Moore 1996). A geodatabase can be a single-user or multi-user database. Typical data operations for geodatabase include storage, edits, retrieval, acquisition from other databases, security and integrity maintenance, and coping with system failure (Meaden and Chi 1996). Among these operations, traditional approaches to communicate with other databases were inefficient due to various data formats, different data models, and the lack of the accepted standards (National Research Council 2003). Exchanging data between systems was difficult for the traditional geodatabases, and data integration from heterogeneous sources into one unified format has been recognized as a key problem (National Research Council 2003).

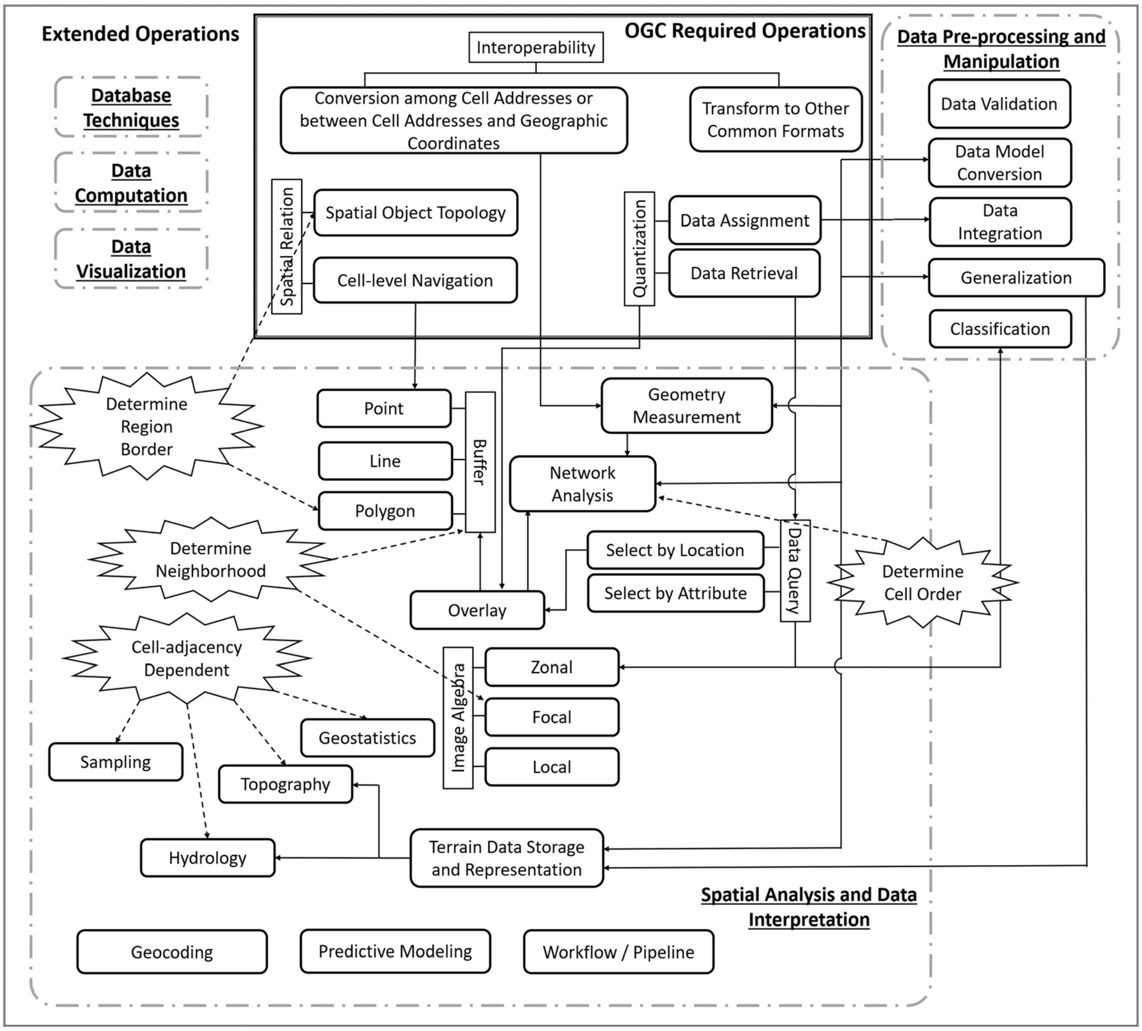

Fig. 3 The OGC required operations and the extended DGGS operations discussed in this paper. Arrows mean that the development of the prior can facilitate the development of the latter operation

In the context of DGGS, assigning and retrieving data are the basic quantization operations required by the OGC (Fig. 2). Adding, updating, or deleting attributes should be supported by DGGS databases. However, compared to the traditional GIS, DGGS should solve the problems of accessing data across distributed data sources and exchanging geospatial data among various data infrastructures. To realize the accessibility and interoperability of distributed databases, APIs are needed to gather geospatial data sources with all available types from published services, fuse them into a coherent format containing metadata and spatial or non-spatial information, and transform them into a ready-for-analysis fashion (Peterson and Shatz 2019). To support the communication or data sharing among different DGGS infrastructures, a multi-cluster deployment model and custom cluster communication protocol are recommended (Peterson and Shatz 2019).

In today's big geospatial data context, parallelized data storage is advisable. In a recent DGGS implementation, a distributed geospatial database was built on a Netezza analytics data warehouse appliance, which had the potential to be applied to any distributed or centralized data storage technologies that support relational data tables (Robertson et al. 2020). The DGGS cell indexing can contribute to the robust spatial positioning and hierarchical and neighboring cell navigation. The independence of DGGS cells benefits distributed data storage and parallel computing mechanisms. DGGS-powered in-database spatial analysis has shown a simplified, flexible architecture to support massive data analysis (Hojati and Robertson 2020). DGGS can also be integrated with cloud-enabled high performance computing techniques to fulfill the functional and performance requirements in the big data era (Yao et al. 2019).

Table 3 Comparison between operation classes of the traditional GIS and DGGS; classification of traditional GIS operations was partially derived and summarized from the research of Meaden and Chi (1996) and Stefanakis and Sellis (1998)

Operation classes		Traditional GIS: Comments or examples	DGGS
Database techniques	Data storage and retrieval	Store data in geodatabases and get access to data when needed	Data assignment and retrieval are defined as quantization operations required by the OGC
	Data editing	Edit data records such as creation, updates, and deletion	Can be realized as in a traditional GIS
	Communication with other systems	Allow for data transportation between various data sources with inefficient approaches	Superior to a traditional geodatabase, and can realize convenient data transportation by developing APIs
Data pre--processing and manipulation	Data validation	Validate data quality and correct errors if necessary, such as solving topology errors for vectors and removing voids for rasters	Necessary for DGGS, and various algorithms or approaches are expected depending on specific scenarios
	Data model conversion	Convert between raster and vector models by vectorization and rasterization	Convert various data models onto DGGS by assigning corresponding values to DGGS cells, which is defined as quantization operations required by the OGC
	Geometric conversion	Unify spatial reference systems by reprojections, and unify raster resolutions by up-sampling or down-sampling	DGGS have superior geo-referencing quality on the baseline of having data quantized and unified; information is aligned with fixed cells at a certain resolution
	Integration	Integrate information at specific locations by overlaying thematic layers, may need data model conversion or geometric conversion beforehand	Conveniently integrate data at specific locations regardless of the original data sources because the information is aligned with fixed cells at a certain resolution after quantization
	Generalization	Data-model-specific operations include line simplification and geo-feature combination for vectors, and cell aggregation for rasters	DGGS naturally support generalization because of the hierarchy, which is through sampling at a coarser interval with interpolation or statistical summaries
	Classification	Standard methods include equal interval, quantile, and natural breaks, or reclassify based on attributes or locations	Can be realized as in a traditional GIS; reclassification can be based on data query operations
Data computation	Cloud computing	Limited ability	Supported by DGGS as a unified framework for those ready-for-analysis datasets (e.g., Yao et al. 2019)
	Parallel processing	Limited ability	Facilitated because of the discrete nature of DGGS cells
Data visualization	Theme maps	Create cartographic maps typically with titles, symbols, annotations, etc.	DGGS have the potential to deal with massive datasets (e.g., Stough et al. 2014)
	Statistics and reports	Generate statistical summaries like charts, figures, and tables	Interactive statistics can be realized as in *Global Grid Systems* (GGS 2019)
	Application	Embed in web pages and mobile applications	Can be realized as in a traditional GIS with supported APIs
Spatial analysis and data interpretation	Data queries	Query data based on attributes, location, or a combination of both	Support selection based on attributes or location; the efficiency of data retrieval depends on the indexing mechanism of DGGS
	Overlay analysis	Typical operations on vector data include intersect, spatial join, union, and clip	Straightforward to exploit by performing spatial queries on DGGS cells to filter a new set of cells meeting multiple select-by-location criteria
	Buffer	Create buffer zones around a point, line, or polygon feature	Need to detect the cells within the buffer zone and merge them with the original targets; buffering polygons needs to identify the boundaries
	Geometry measurement	Report coordinates, length, and area	Cell addresses are analogous to coordinates, the length is the total distances between representative points, and the area is the total area of the DGGS cells; measurement varies among different resolutions
	Network analysis	Based on network data consisting of edges and nodes, and solve problems like the shortest distance	Based on quantized line features as edges and distances or other attributes as costs; results vary among different resolutions
	Image algebra	Classified as local, focal, and zonal operations according to Tomlin's model (Tomlin 1994)	Local operations can be realized as in a traditional GIS; zonal and focal operations need to be developed upon

Table 3 (continued)

Operation classes	Traditional GIS Comments or examples	DGGS
		data query operations and defining a searching window similar to a buffer zone
Terrain data storage and representation	Data formats include DEMs, TINs, and contours	Can realize hierarchical storage of terrain data (e.g., Dutton 1984); data quality and resolution need attention during application
Topography	Terrain data derived products include slope, aspect, hill, and shade	Functions like slope and aspect need new algorithms considering different cell adjacency among squares, triangles, and hexagons
Hydrology	Typical functions include flow distance, flow direction, and flow accumulation, dependent on terrain data	Functions like flow direction need new algorithms considering different cell adjacency among squares, triangles, and hexagons
Geostatistics	Describe spatial patterns based on regular or irregular systems of sites, such as point pattern analysis	Spatial relations need to be redefined based on DGGS cell geometries (e.g., hexagon; White and Kiester 2008)
Sampling	Usually include random, fishnet, and stratified sampling	Hexagonal DGGS are advisable for systematic sampling at a large spatial scale (e.g., Gong et al. 2013)
Geocoding	Transform geographical addresses or names of places to geographic coordinates	DGGS have the potential to provide gazetteer service (e.g., Wāhi; Adams 2017) and geocoding textual documents (Melo and Martins 2015)
Predictive modeling	Limited ability; need to rely on other techniques	DGGS benefit finite element, agent-based, and cellular automaton models due to the discrete cell structure (e.g., Kiester and Sahr 2008)
Workflows and pipelines	Enable users to combine multiple analysis steps	Have great value for DGGS, and may be shared among users by common formats such as XML and JSON

Data Pre-processing and Manipulation

Generally, the pre-processing or data manipulation functions supported by the traditional GIS include data validation, data model and geometric conversion, data integration, and generalization and classification. Data validation is a data cleansing process when data errors can be corrected, such as solving topology errors for vector data and removing voids for raster data. This process is also necessary in the context of DGGS because the quantization operation which converts the original data onto DGGS can introduce uncertainties regarding the data quality. Various algorithms or approaches to validate data on DGGS are expected to be developed depending on specific scenarios. For example, spatial relations among cells were used to detect topological invalidity of geo-features, and the topological distortion can be repaired by increasing the local resolution of the vector features (Zhou et al. 2020).

As before mentioned, DGGS are expected to power data integration or conflation regardless of the original spatial reference system, spatial scale, data format, signal frequency, or acquisition time, where the quantization strategies are essential and have been discussed above (OGC 2017). Researchers have developed hexagonal image resampling techniques (Gardiner et al. 2011), modeled vector data in hexagonal DGGS (Tong et al. 2013), transformed heterogeneous data to hexagonal DGGS (Mahdavi-Amiri et al. 2016, 2018), etc. With the baseline of having data unified, DGGS have the quality of superior geo-referencing, where each piece of information is associated with an area, and records associated with the same area are aligned automatically (Goodchild 2000). This quality applies to the entire DGGS domain and among all supported resolution levels (OGC 2017). Although polyhedral projection methods are unavoidable when constructing a DGGS in most cases, complex algorithms that transform among various projections or register maps to specific datums are not necessary before doing any analysis at the users' end. This contrasts with users' experience with the traditional GIS when they need to unify the spatial reference system, spatial scale, and data format by reprojection, up-sampling and down-sampling, vectorization and rasterization, etc.

With the traditional GIS, generalization and classification involve data-model-specific operations like line simplification, geo-feature combination, reclassification of cell values, and aggregation of cell values from a fine resolution to a coarse resolution by determining the dominant value or by a certain mathematical function (i.e., mean, maximum, and minimum). As a unified data model with the hierarchical characteristic, DGGS should naturally support generalization, which aggregates spatial information from a native resolution and presents at coarser resolutions. The prerequisite is the quantization process that samples the cell centroids at a certain interval and assigns that value to the corresponding DGGS cells. Based on this, an aggregation operation can be done by sampling cell centroids at a coarser interval with the nearest, bilinear, or bicubic interpolation if the original data are in the raster format, as suggested by Global Grid Systems (GGS 2019). Another way to realize aggregation is based on the statistical summaries of the values at the native resolution, and this is feasible for both vector and raster being the original data models (GGS 2019). With DGGS, classification operations can be realized by the standard methods like equal interval, quantile, and natural breaks, or reclassification with assigning new values based on the attributes or locations.

Spatial Analysis and Data Interpretation

Data Queries

Typically, data queries can be performed based on non-spatial attributes, spatial attributes, or a combination of both. Data filtering functions should also be available in DGGS to support attribute-based and location-based data queries. Data retrieval operations, as one of the main parts of quantization operations, set the stage for data queries. The efficiency of data retrieval partially depends on the indexing mechanism adopted by a DGGS implementation, and the indexing methods have been continuously developed and optimized (e.g., Bai et al. 2005; Sahr 2008, 2019; Uher et al. 2019).

With the conventional GIS, data layers are analogous to the sliced spatial information, where each layer represents a subspace corresponding to a theme. Distinct from the conventional GIS, DGGS use cells as the atom to store spatial information. At each resolution level, the locations of cells are fixed, and data associated with the same cells are aligned in DGGS. This characteristic can benefit the iteration of data queries based on location or attributes, and can further accelerate the statistical summaries based on the selection results.

Overlay Analysis and Buffering

Overlay analysis including union, spatial join, intersect, clip, and update is the foundational operation for vector data in the traditional GIS. In the DGGS data model, vectors are converted to DGGS cells at a certain resolution via quantization, and these overlay functions are straightforward to exploit because of the discrete, fixed cell locations. Union, intersection, and clipping operations are more like performing spatial queries on DGGS cells to filter a new group of cells meeting multiple select-by-location criteria simultaneously (e.g., Robertson et al. 2020). For example, to intersect two spatial objects is to filter out two sets of DGGS cells representing the two target objects at a certain resolution, and then to keep those common cells while leaving out the others. In the same manner, the union operation is to keep all cells representing the target objects at a certain resolution.

Traditionally, buffer zones can be established around points, lines, and polygons depending on the buffer distance, usually as a length unit. To buffer these objects in DGGS, assuming that original data has been quantized, an algorithm needs to firstly detect the surrounding cells within the defined buffer zone and then merge the surrounding cells with the cells representing the original objects at specific resolutions. The merging operation can be viewed as one of the overlay analysis operations, which leaves the main development part as finding the surrounding cells constructing the buffer zone. Additionally, applying a buffer function on a converted polygon in DGGS needs to identify the polygon's boundary beforehand, because those converted vector data does not contain boundary information naturally (Robertson et al. 2020). The boundary can be determined by the number of neighboring cells, for example, having less than six neighbors stands for a boundary cell in a hexagonal DGGS (Robertson et al. 2020). Specific buffering algorithms also depend on the DGGS tessellations. For example, Robertson et al. (2020) explored the buffering operation on an aperture 3 hexagonal DGGS and approximated the buffer distance by detecting the closest DGGS resolution to the distance precision, altering the native resolution to the detected resolution for the target object, and generating the buffer zone according to the altered resolution. Bowater and Wachowicz (2020) developed the algorithms to determine the cells in the buffer area around a point object at a single resolution and multiple resolutions by using the indexing structure of the rHEALPix DGGS (Gibb 2016).

Geometry Measurement

With the traditional GIS, the typical geometry measurements include reporting coordinates (i.e., longitude/latitude pairs or Cartesian x/y pairs) and length or area calculations. On the base of interoperability operations and quantization operations in DGGS, indices of cell centroids as the reference points can be reported as the cell addresses or be transformed to the geographical coordinates. Line length can be calculated as the sum of the distances between representing points (e.g., centroids or midpoints; Stefanakis 2016) of the cells representing the line feature, or the sum of the distances between vertices modeled on DGGS. Similar to raster, the area is the total area of the group of DGGS cells making up the areal object. However, it should be noted that the geometry measurements are more meaningful at the native quantization resolution at which the original spatial data are sampled and modeled on DGGS. Geometry measurements will encounter the imprecision at coarser granularities because the geometry of a target object can distort after being aggregated onto a coarse resolution. Besides, when modeling the original object on DGGS with different tessellation schemes, such as different cell shapes and apertures, the calculated geometries can be different (Li and Stefanakis in press).

Network Analysis

Network analysis typically analyzes the distances, directions, and costs of an object traveling along the edges of the network (Fischer 2006). Network analysis in DGGS requires the quantization operations, particularly the modeling of line features. The junctions can be detected by the intersection operation which filters out the common cells from two sets of cells representing the original line features (Robertson et al. 2020). The cost along the edge between two nodes is calculated as the geometric distance at a certain resolution as described in the above section, or as another attribute assigned to the edge. Other network impedance attributes can also be encoded as auxiliary information and stored with the cells representing edges (Robertson et al. 2020). If a network with edge directions is expected, the order of the cells representing edges should be defined in advance of analysis, where the cell order can be stored as integer values starting from 0 with an increment of 1 to denote the direction as suggested by Robertson et al. (2020). Analysis algorithms such as Dijkstra's algorithm (Dijkstra 1959) traditionally used for optimal path analysis can then be run based on the created network elements, determined edge costs, and established network connectivity. Determining an appropriate analysis resolution is of importance before solving real-world problems, because the network analysis results may vary among different resolution levels at which the analysis is performed.

Image Algebra

Image algebra operations are grouped into three categories based on Tomlin's model (Tomlin 1994): functions on individual cells (local operations), functions on the defined neighborhood for each cell (focal operations), and functions on cells associated with a specified zone (zonal operations). Tomlin's classification is still useful in the context of DGGS because the algorithm development can be classified in line with these three image algebra categories (Robertson et al. 2020). Those individual-cell-based analyses, such as Boolean, mathematical morphology, and frequency transforms, can be applied with DGGS as in the traditional GIS environment (Peterson 2016). Zonal operations in the context of DGGS consist of two steps: filtering cells by mask queries and performing follow-up algebra operations. Algorithms of focal operations with DGGS need to consider the cell connectivity characteristics which differ among squares, triangles, and hexagons. The searching window is analogous to a buffer zone around a cell within a searching radius which can be defined as the number of rings or a distance.

Topography and Hydrology Analysis

There are three common elevation data formats: digital elevation models (DEMs), triangulated irregular networks (TINs), and contours (Hengl and Evans 2009; Peucker et al. 1978). DEMs contain terrain information in the regular grids, TINs represent elevations with sets of triangular faces by storing values at the triangle vertices, and contours are line features connecting positions with the same elevations (Hengl and Evans 2009; Peucker et al. 1978). To model original elevation datasets on DGGS, DEMs can be transformed to DGGS cells from the original flat, square cells, contours can be represented by a group of linearly connected DGGS cells, and TINs can be converted to DEMs then transformed to DGGS cells (Mahdavi-Amiri et al. 2015a). Terrain modeling and rendering have been developed on hierarchical, multi-resolution models (De-Floriani and Puppo 1992; Pajarola and Gobbetti 2007; Weiss and De Floriani 2011). As one of the earliest DGGS designs, GEM was proposed to assemble and manage global terrain data (Dutton 1984). GEM recursively tessellates a regular solid into refinements of nine partially nested equilateral triangles and assigns elevations to each successive triangular facet (Dutton 1984, 1988). Hence, DGGS have the potential to realize the hierarchical storage and management of terrain data, enabling users to understand and use topography data with the granularity on demand. Terrain data quality is another key point, where the errors usually come from the original data acquisition technology, preprocessing methodology, characteristics of the land surface, and land cover types (Mukherjee et al. 2015). Both data quality and spatial resolution have been found to affect the application outcomes such as hydrological modeling, topographical modeling, and land cover mapping (Hancock 2005; Jarihani et al. 2015). When modeling terrain data on DGGS, data quality and spatial resolution issues also exist, and the quantization strategy adopted by a specific DGGS implementation plays an important role to control the data quality during the data model conversion process. Additionally, generalization operations on the DGGS-based terrain data need attention because different aggregation products are expected for different application purposes. For example, over the waterbody area, the minimum elevation is helpful for determining stream channel areas while maximum elevation is useful for ship navigation (Danielson and Gesch 2011).

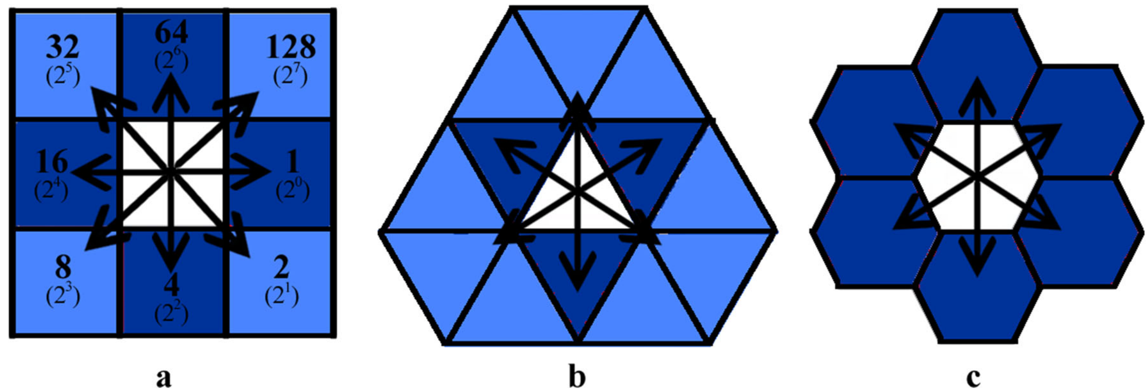

Fig. 4 Flow directions on **a** square, **b** triangular, and **c** hexagonal grids

Based on DEMs, the traditional GIS has a series of topographical and hydrological functions developed, such as generating slope, aspect, and flow direction. Working with DGGS, some analytical algorithms need to be reconsidered depending on the cell adjacency characteristics. For example, to produce slope or aspect values, traditional algorithms take the eight neighbors for each center cell into the calculation and give more weight to those orthogonal neighbors than those diagonal neighbors (Burrough and McDonell 1998). While with a hexagonal DGGS, the equal weight should be given to six neighbors for each center cell, and a different weight scheme should be used for a triangular DGGS.

Another example is the flow direction analysis. Traditionally, eight directions are defined for individual center cells, which is referred to as the eight-direction (D8) flow model (Jenson and Domingue 1988; Fig. 4a). The D8 model can be applied to the DGGS consisting of quadrilateral-shaped cells although the represented direction of each of the eight numbers may change due to the potentially changed cell orientations (e.g., 1-to-2 refinement; Mahdavi-Amiri et al. 2013). However, to perform such a flow direction analysis on a triangular or hexagonal DGGS needs redefined directions and redeveloped algorithms due to their different cell adjacency (Liao et al. 2020; Wang et al. 2020; Fig. 4b and c).

Geostatistical Analysis

The geostatistical analysis includes point pattern analysis, spatial autocorrelation analysis, and interpolation, before which the spatial relation needs to be conceptualized based on the nature of the regular or irregular system of the sites (Besag 1974). As shown in Fig. 5a, Rook's case contiguity (four

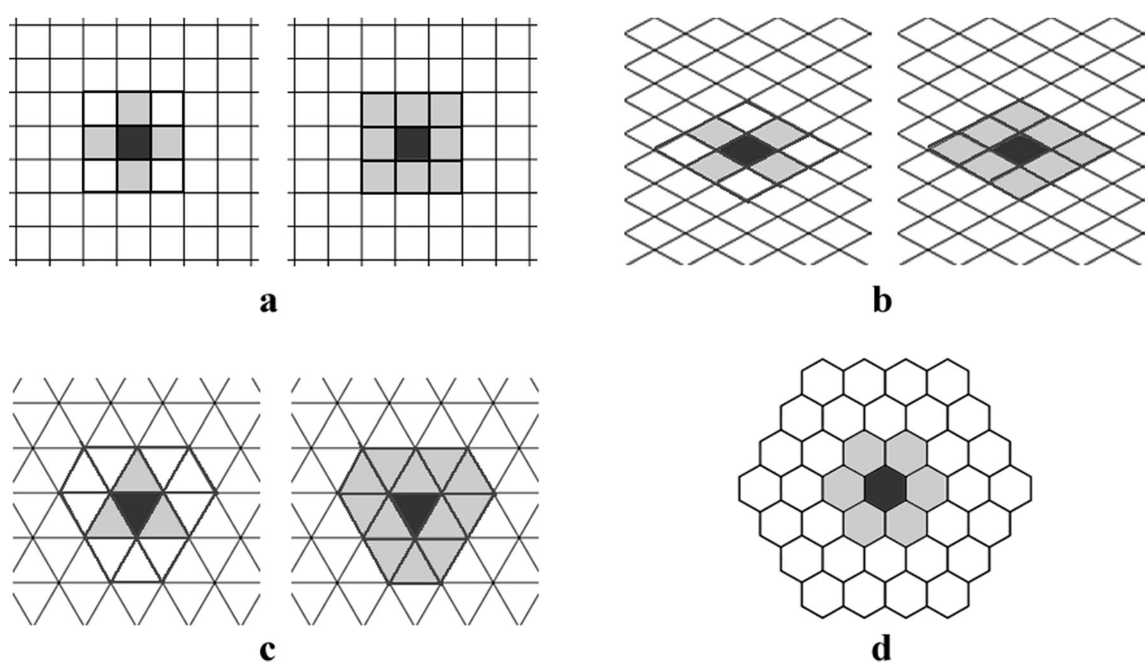

Fig. 5 **a** Rook's case (left) and Queen's case (right) contiguity on square grids, **b** pseudo Rook's case (left) and Queen's case (right) on diamond grids, **c** pseudo Rook's case (left) and Queen's case (right) on triangular grids, and **d** adjacent contiguity on hexagonal grids

orthogonal neighbors) and Queen's case contiguity (additional four diagonal neighbors) are traditionally used to define neighbors in a regular, square lattice. Performing geostatistical analysis in the context of DGGS needs attention to the cases of the triangular or hexagonal lattice which will lead to different spatial relations and eventually inconsistent study results (White and Kiester 2008). For example, instead of four orthogonal neighbors and four diagonal neighbors, triangular cells have three neighbors connecting to each of its three sides and nine neighbors adjacent to its three vertices, while hexagonal cells have six side-connecting neighbors with the uniform adjacency (Fig. 5). Besides, because of the hierarchical characteristic of DGGS, modeled spatial relations vary with different levels of granularity. The interpolation techniques on spherical, geodesic grids were proposed (Cohen et al. 2000; Renka 1997) and compared among different tessellation schemes and multiple resolutions (Carfora 2007).

Sampling Functions

Sampling is another frequently used operation by the traditional GIS, including random sampling, fishnet generating, and stratified sampling based on the spatial locations. The nearly equal-area characteristic of DGGS provides the global grids with spatial units having an equal probability of contributing to an analysis at multiple resolutions (Alderson et al. 2020; OGC 2017). The uniform adjacency characteristic of hexagonal grids is particularly useful to make systematic sampling when the study area is at a large spatial scale. Gong et al. (2013) generated sample points based on a globally systematic unaligned sampling strategy over the Earth's surface to test the accuracy of the global land-cover maps. The samples were collected by partitioning the entire globe with a hexagonal scheme then randomly assigning sample points in each hexagon (Gong et al. 2013). Similar sampling strategies were adopted in other previous studies (e.g., Chen et al. 2019; Lu et al. 2017; Mertes et al. 2015).

Geocoding Analysis

Geocoding functions are used to transform geographical addresses (e.g., postal codes and street numbers) or names of places of interest (e.g., names from a gazetteer) to geographic coordinates on the Earth's surface. Possibilities to do geocoding analysis in the context of DGGS have been investigated. For example, Wāhi, as a discrete global grid gazetteer, was built based on linked open data and was able to map between the named toponyms and DGGS cells (Adams 2017). Multiple application scenarios have been shown practical with Wāhi, such as modeling demographic data, indexing unstructured textual data, and linking social data and environmental data (Adams 2017). Another research applied geocoding to georeferenced Wikipedia documents in the context of DGGS (Melo and Martins 2015). In their study, the geospatial location of a text document can be automatically detected merely by applying supervised classification methods to its text with a discrete binned representation on a HEALPix scheme (Melo and Martins 2015).

Predictive Modeling Techniques

Because of the discrete cell structure and data integration characteristics of DGGS, predictive modeling techniques such as finite element modeling, agent-based modeling, and cellular automata have exceptional application potentials in the context of DGGS (Peterson 2016). For instance, a hierarchical, multi-resolution cellular automaton was performed using a DGGS-based topology-independent discrete simulation library (Kiester and Sahr 2008). In their modeling system, the dynamics of a center cell was determined by its neighboring cells, parent cells, and child cells, which demonstrated the value of the cell-based simulation techniques with DGGS at a global scale (Kiester and Sahr 2008). A recent study integrated the cellular automata and DGGS and applied to wildfire spread modeling by using in-database approaches (Hojati and Robertson 2020). The study revealed that the DGGS–integrated cellular automata can provide a simplified architecture to support spatial analysis, and its flexibility is particularly meaningful in the big data era (Hojati and Robertson 2020).

Workflows and Pipelines

Other than the operations discussed above, the GIS software usually supports setting up workflows or pipelines, enabling users to combine multiple analysis steps, remove unnecessary intermediate products, save as new analysis tools, and batch-process multiple datasets. For DGGS, this is of great value considering the storage-saving when processing high volume datasets, the reduction of repetitive operations, and dissemination of the analysis flow with others. With SCENZ-Grid proposed by Landcare Research in New Zealand, users can collaboratively establish a workflow for a specific application and share it with colleagues (LCR 2017). Global Grid Systems has developed many pipelines to enable geo-encoding of data sources, image processing on quantized data, spatial join over data sources, etc., and can share the pipelines in the XML or JSON format (GGS 2019).

Data Computation

In the big data era, DGGS are expected to have more advanced capability to process voluminous data. Cloud computing and parallel processing are two typical approaches to effectively deal with massive datasets. Evidence has shown that a DGGS is a suitable environment to support these big data geospatial analytics.

DGGS-driven computing techniques provided opportunities to manage big Earth observation data. Recent research proposed a solution to the global Earth observation data processing, which integrated cloud computing as the computing power and DGGS as the unified framework into a closed-loop (Yao et al. 2019).

Additionally, the discrete nature of DGGS cells allows researchers to distribute data with boosting volume for parallelization, and thus enables much easier distributed processing compared to the traditional spatial algorithms (Peterson 2016; Robertson et al. 2020). In the era of big data, some countries or institutions developed geospatial datacubes, which are n-dimensional arrays that store geospatial data, to manage and analyze the Earth observation data (e.g., Australian Geoscience Datacube; Mohamed-Ghouse et al. 2020). A DGGS-powered datacube can enhance spatial analysis not only horizontally (i.e., spatial variation of one theme for all locations) but also vertically (i.e., all accessible themes for one location), and facilitate parallel processing using distributed systems (Goodchild 2018; Purss et al. 2019). This is superior to a conventional datacube in terms of the integration or representation of global spatial data and the reduction of the spatial limitations or constraints when dealing with a global scale (Purss et al. 2019).

Data Visualization

Spatial data visualization can help the audience have a better understanding of the spatial information and eventually benefit decision making. Data can be visually communicated in many ways: theme maps, statistical charts or tables, textual reports, and web or mobile applications. Existing Digital Earth implementations have offered the advancement in geospatial data visualization (Keysers 2015). For DGGS implementations, existing APIs like those provided by Leaflet can be deployed to enable visualization in a web map (Leaflet 2019). A DGGS platform can potentially support visualization of huge-volume spatial data and create dynamic, interactive graphs or tables given its powerful integration capability, although it may encounter the low rendering speed especially when visualizing large-scale data even at a low resolution (e.g., Stough et al. 2014, 2020). The higher level-of-detail can be achieved adaptively based on the resolution level, for example, the selective omission may be adopted based on the size of the object relative to the cell size at a certain resolution. Global Grid Systems is one of the few state-of-the-art DGGS implementations that achieve on-the-fly visualization and interactive statistics at any place and any level of granularity (Table 2). OpenEAGGR visualizes data with the support of linking to the third-party applications like PostgreSQL/PostGIS and Elasticsearch (OpenEAGGR 2017). Additionally, a DGGS avoids a visual deformation of the content no matter in which way the data is presented, or specifically, what projection is used to display the DGGS. This is not true for a traditional map where different impressions of the conveyed content occur if different projections are used. In other words, although a DGGS may need to be projected in order to be displayed, the conveyed information is usually independent of the projection chosen because the cells are known to be with almost equal size and shape.

Discussion of DGGS Operation Development

From the development perspective, the DGGS operations listed in Table 3 and Fig. 3 are classified as basic operations, ordinary operations, and advanced operations (Fig. 6). Basic operations include those operations required in the OGC Abstract Specification and some of the data pre-processing operations. These operations or functions set the stage for all the other functions in the DGGS environment (Fig. 3). In particular, the quantization operations prepare the DGGS cells with values by converting data onto the DGGS model at specific resolutions regardless of the original data format, spatial scale, acquisition time, acquisition method, etc. On top of this baseline, operations like reprojections via complex mathematical functions and unifying raster pixels by up-sampling or down-sampling can be avoided when applying a DGGS implementation at the users' end. Compared to the traditional GIS environment, data integration in DGGS is more convenient in this manner because spatial information is aligned to fixed cell locations at a specific resolution. Spatial relation operations are to query and test relationships among cells and spatial objects. The capability to test parent-child and sibling cell relationships is useful to develop other functional algorithms, such as to determine the object-level topology (Zhou et al. 2020) and to create a buffer zone around a point object in DGGS (Bowater and Wachowicz 2020). Interoperability helps to bridge a DGGS implementation to other spatial data infrastructures or other DGGS implementations, and this is meaningful for the information dissemination and the visualization process. Other basic operations like data validation, generation, and classification make quantized data ready to be analyzed, and the algorithm development depends on the specific application scenarios.

Common spatial analysis functions can be developed on top of the above basic operations, and they are grouped as ordinary operations in Fig. 6. The purpose was not to list all functions that have been supported by the traditional GIS software, but rather present the most representative ones and discuss their potentials in a DGGS environment. It was found that the development of some analytical functions can facilitate some of the other function development (Fig. 3). In other

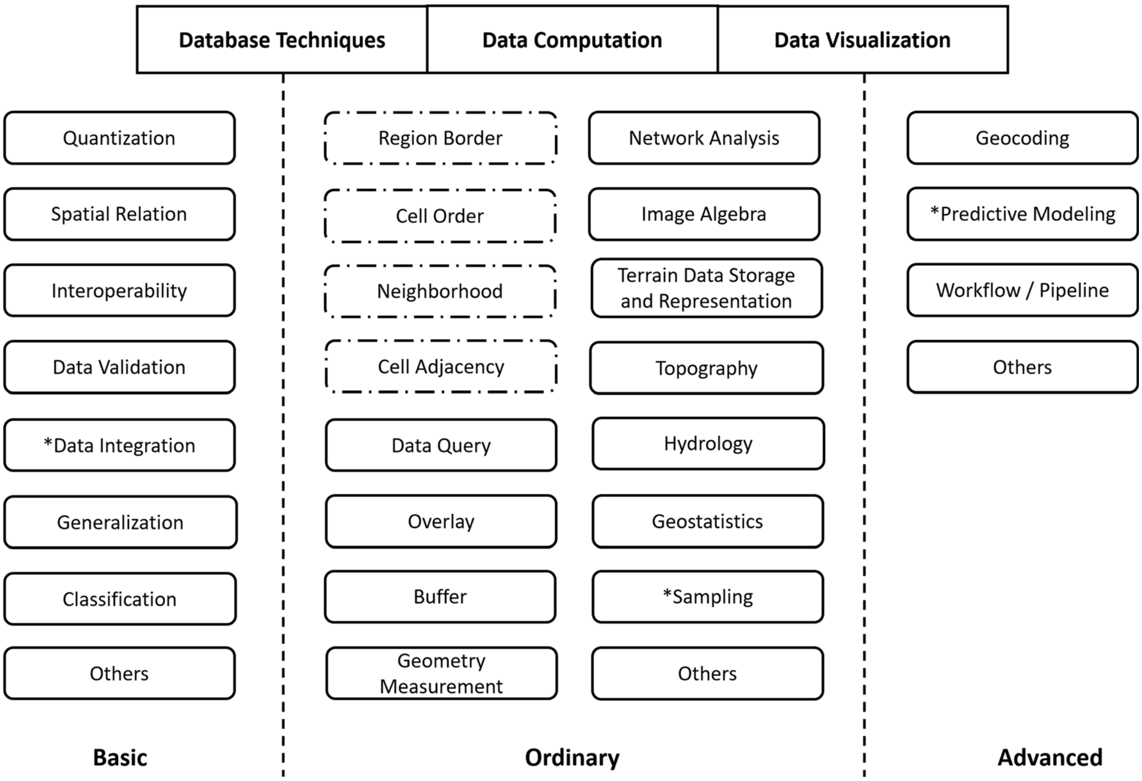

Fig. 6 Classification of DGGS operations in terms of algorithm development. Operations expected to outperform the traditional GIS platforms are marked with *

words, some developed algorithms can be called and wrapped in other algorithms to realize another function. For example, data query functions can facilitate a classification function as well as a zonal image operation, i.e., functions on cells associated with a specified zone, and the select-by-location algorithm can be specifically used in an overlay function. The overlay algorithm can be employed in a buffer operation when combining the original cell set and the determined neighboring cell set, and can also be employed when defining nodes in a network analysis operation by intersecting cell sets representing edges. It was also noticed that, due to the characteristics of DGGS grids, some algorithms need special consideration during the development process. Examples include the following: (1) the region border needs to be determined when buffering cells constructing a polygon and modeling topological relationships between spatial objects by using extended DE-9IM (Egenhofer and Herring 1990; Peterson 2016); (2) a cell order needs to be stored within the cell attribute when running a network analysis with directed edges (Robertson et al. 2020); (3) a neighborhood needs to be set according to the required number of rings or a certain distance for a buffer operation and a focal image operation (Robertson et al. 2020); and (4) new algorithms need to be developed when the operation is based on the cell adjacency characteristics such as slope, aspect, flow direction, and geostatistics, and the developed algorithms will vary among DGGS with different grid tessellations (Fig. 3). The uniform adjacency characteristic of hexagonal grids is advisable to make systematic sampling over a large study area (Gong et al. 2013). Although many spatial operations need new algorithms, some algorithms utilized by the traditional GIS are useful in the DGGS context. Individual cell–based functions in DGGS can remain the same as those local image processing functions in the traditional GIS platform. Besides, after quantizing network data in DGGS and assigning necessary attributes to edge cells, traditional algorithms used to solve the network problems (e.g., the shortest distance) are still valuable to solve network problems in DGGS.

Beyond the basic operations and ordinary operations, advanced operations have been explored in the DGGS context (Fig. 6). For example, a gazetteer service named Wāhi was proposed to map entities from the GeoNames database to triangular and hexagonal DGGS (Adams 2017). Workflows or pipelines have shown great value by combining a series of processing. SCENZ-Grid and Global Grid Systems provide opportunities to create workflows and share with others (GGS 2019; LCR 2017). Predictive modeling techniques such as agent-based modeling and cellular automata have great potentials to be applied in DGGS because of the discrete cell structure (Peterson 2016). Other than these geospatial operations, database techniques, data computation, and data visualization need further development to fit in the DGGS environment considering the potentially distributed and voluminous data. A DGGS platform is expected to implement efficient linkage between the distributed database systems, powerful computation ability, and fast-response visualization via various ways.

Future Directions

Basic operations required by the OGC Abstract Specification and data pre-processing operations such as data validation, integration, and generalization are the base of the other analytical functions. Although many state-of-the-art DGGS implementations have proposed solutions to some of these basic operations, there are still open questions remained. The decisions made on the quantization operations include, for example, at which resolution are original data sampled when converting to a DGGS and what spatial units and methods should be used for aggregation when reducing the level of details on DGGS. These decisions will lead to further data quality uncertainties during the follow-up operations, such as spatial objects' displacement, maintenance of spatial objects' topology, and preservation of original data fidelity. In the DGGS environment, cell-level topology tests are advanced by indexing mechanisms, while more methods related to the object-level topology need to be developed. Global Grid Systems proposed an extended DE-9IM for object-level topology representation (GGS 2019) and Zhou et al. (2020) proposed algorithms to solve topological distortions between the same type of geo-features. Other approaches are expected to realize representation, query, test, maintenance, and repair of the object-level topology. In terms of interoperability, more work needs to be done to enable communications between DGGS and the other spatial data infrastructures. Current DGGS implementations can transform information among DGGS with different configurations (e.g., DGGRID), integrate with third-party applications (e.g., OpenEAGGR), and save DGGS grids as common data formats (e.g., rHEALPix and DGGRID), while the overall interoperability should be further strengthened.

Furthermore, efforts are needed to develop algorithms to enrich analytic functions for DGGS implementations. Due to the features of DGGS, some special consideration is required during the algorithm development, which includes determining the region border, determining the cell order, and determining the cell sets representing a neighborhood. Some other algorithms such as the slope and aspect calculations need to be redeveloped from a mathematical perspective when applying on a triangular or hexagonal DGGS. Grid-based predictive modeling is particularly expected to outperform the traditional GIS and needs exploration. Further research can also concentrate on comparing operation results among different DGGS tessellations and resolution levels.

Last, database techniques and data computation capability require additional studies in the context of DGGS. Due to the diversity of the currently available data repositories, it is impractical to transport all data to a localized data warehouse. Distributed geospatial databases are more practical for DGGS implementations. As mentioned above, technologies to realize the accessibility and interoperability of the distributed databases are needed. These technologies may include a series of APIs to connect a DGGS to existing data repositories. Advanced computing technologies include parallel processing and cloud computing. Future research on parallel processing may focus on enhancing the ability to store multi-dimensional arrays, improving the quality of spatio-temporal data, and addressing the spatial integrity constraints in spatial multi-dimensional databases (Baumann et al. 2018; Purss et al. 2019). In terms of the cloud computing field, grid indexing and data query methods, extended DGGS framework with the time dimension, and the integration with the cloud computing environment need more comprehensive studies (Tong et al. 2019; Yao et al. 2019).

Conclusions

This paper reviewed the basic operations of a DGGS specification stated by the OGC Abstract Specification and discussed other potential operations of DGGS in comparison to the traditional GIS. Three OGC required operations are quantization, spatial relation, and interoperability operations, which ensure that a DGGS implementation is capable to assign and retrieve data values, determine simple spatial relations, and communicate with other spatial data infrastructures. The extended DGGS operations discussed in this paper include database techniques, data pre-processing and manipulation, spatial analysis and data interpretation, data computation, and data visualization. The OGC required operations together with the data pre-processing operations serve as the baseline for the other analytical functions, and the development of some functions can facilitate the algorithm development of other functions, where the prior algorithms can be called and wrapped in the latter algorithms to realize other operations. Although there have been some solutions proposed in the previous research, many operations are left with open questions and need improvement. Future research directions include data quality improvement during the modeling on DGGS, advanced interoperability among spatial data infrastructures, extended analytical functions, distributed database management, and superior computing technologies. The discussion and conclusions in this paper can offer the guidelines in the future DGGS operation development.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Code Availability Not applicable.

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