Building geospatial infrastructure
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ABSTRACT
Many visions for geospatial technology have been advanced over the past half century. Initially researchers saw the handling of geospatial data as the major problem to be overcome. The vision of geographic information systems arose as an early international consensus. Later visions included spatial data infrastructure, Digital Earth, and a nervous system for the planet. With accelerating advances in information technology, a new vision is needed that reflects today’s focus on open and multimodal access, sharing, engagement, the Web, Big Data, artificial intelligence, and data science. We elaborate on the concept of geospatial infrastructure, and argue that it is essential if geospatial technology is to contribute to the solution of problems facing humanity.

1. Introduction
Many visions for geospatial technology have been advanced over the past half century since the contents of maps and Earth images were first digitized and stored in computers. Yet the rate of advance in information technology continues to accelerate, and the social, economic, political, and environmental contexts in which geospatial technology is embedded continue to evolve in largely unpredictable ways. It is entirely reasonable, therefore, that the geospatial community should look at this time for a new vision, one that can help us to move forward and give us a sense of direction. Where are we going with this technology, and how can it address the challenges that we currently face, and will face in the coming years? In this paper we describe the emerging concept of geospatial infrastructure as a contemporary and comprehensive vision for geospatial technology. We review its relationship to earlier visions, place it within the context of today’s information technology, and address issues of access, engagement, and the protection of individual privacy.

Humanity today is faced with numerous challenges. The world we humans have created and in which we find ourselves is unlike any world of the past; and a return to the past is not a possibility. Many of these challenges can be addressed with geospatial technology, especially if that technology is built appropriately, is sufficiently comprehensive, and is open and accessible to all. In this paper we describe the major features of our vision for geospatial infrastructure, and outline how those features will address the challenges.

2. Earlier visions

2.1. Maps in computers
The international meetings which Roger Tomlinson convened in 1970 and 1972 (Tomlinson 1971, 1972) brought together like-minded individuals from around the world who had recognized the rich benefits that could accrue from storing the contents of maps and images of Earth in computers. He himself had demonstrated how computers could analyze digital maps to produce accurate statistics on the potential uses of Canadian land; others had used computers during the editing stages of map compilation; and still others had shown how representations of the contents of maps could be used to improve transportation planning. Yet the lack of suitable data structures and models for representing geographic information, and the almost complete absence of software, suggested that it was the handling of spatial data that posed the most immediate problem and provided the basis of a vision for the way forward – and the term spatial data handling persists today in a biennial series of international conferences.

2.2. A geographic information system
By the late 1970s the concept of a Geographic Information System (GIS) had been widely adopted by corporations, educators, agencies, and individuals. Out-of-the-box software had become available, and simple data models allowed for the efficient capture of many types of geographic information. In this vision a GIS was a monolithic computer application, performing a wide range of functions that included capture, storage, and analysis. It became possible to think of the ultimate GIS as a package running in
a mainframe computer and capable of performing any conceivable function on any conceivable type of geospatial data. Several companies began marketing GIS software, and the GIS industry began its long expansion. Over the subsequent decades the set of functions proliferated, as did the underlying data models, in the interests of supporting new applications and providing the input to new kinds of decisions, and GIS software migrated from mainframes to minicomputers, and ultimately to the desktop. Although geospatial technology has moved far beyond this vision, the acronym GIS is used throughout the remainder of the paper as an umbrella term.

2.3. Spatial data infrastructure

Two very significant changes to this vision of GIS occurred in the early 1990s. First, the production of geographic information, in the form of maps and images and increasingly of digital data, had up to that time been the almost exclusive preserve of well-funded agencies, typically of national governments. Production was expensive, and efforts were made in many jurisdictions to recover at least part of the cost from users. But as information technology had advanced, it had become possible for local agencies, corporations, and even individuals to create their own data. The Global Positioning System (GPS) had greatly reduced the cost of measuring location, requiring only a cheap hand-held device; photogrammetry had been largely automated; and scanning had made it possible to convert paper maps to digital databases quickly and cheaply. A new vision of geospatial data production was required, and was provided by a report of the US National Research Council (1993) which advanced a vision of a National Spatial Data Infrastructure. The report was timely, and its recommendations were implemented in an Executive Order from the President, authorizing a series of programs to be organized by the Federal Geographic Data Committee. These included the development of standards for the description of geospatial databases (metadata), the identification of framework layers, and efforts to improve the interoperability of databases, an initiative that was taken up by the Open GIS Consortium (now the Open Geospatial Consortium).

2.4. The Web and the Internet

The second change began with the popularization of the World Wide Web and with it the Internet and the first Web browser, Netscape. Groups such as Xerox PARC quickly saw the potential for sharing maps and geospatial databases electronically, and for putting entire collections of geospatial data online for use by anyone. The concept of a geoportal emerged (Maguire and Longley 2005), as a Web site that allowed access to a wide range of geospatial databases. By the late 1990s the average Web user had become both a consumer and producer of information in a development sometimes termed Web 2.0. The result was a dramatic rise in user-generated content, and ultimately in the concept of volunteered geographic information (Sui, Elwood, and Goodchild 2013).

2.5. Digital Earth

By the late 1980s graphics workstations had advanced to the point where it was possible to create and manipulate the representation of a three-dimensional object on a display screen. Moreover a two-dimensional image could be draped over the object, and rotated and zoomed at will. Although the image on the screen was still in principle two-dimensional, the ability to manipulate it gave the user the illusion of seeing a three-dimensional object. Applications were developed in short order to drape Earth imagery over a sphere, creating a virtual Earth. Hierarchical data structures allowed the image on the screen to be zoomed smoothly from a 10km-resolution image of the entire planet to an image of a small area at sub-meter resolution.

The phrase Digital Earth was coined in a book by US Vice-President Al Gore (1992), and in 1998 a speech was prepared for delivery by Gore describing a virtual environment that could be used to explore many dimensions of the Earth’s surface, both present and past. The first International Digital Earth Symposium was convened in Beijing in 1999, and in 2005 Google released Google Earth to the general public as an application that could be downloaded and run on a device as simple as a personal computer, accessing vast amounts of Earth imagery and other geospatial data from the Internet in a simple implementation of the concept of Digital Earth. It provided a compelling illustration of how geographic information could be shared and examined without the need first to flatten and distort the Earth with a map projection, and helped to free geospatial technology from the constraints of the map metaphor that had been so important in earlier visions (Goodchild 2018).

Today we might describe Digital Earth as an instance of a digital twin, or a digital replica. Systems such as Google Earth have emphasized the replication of how the Earth looks, but in principle a digital twin should also replicate how the Earth works, by using software to reproduce the processes that modify the Earth’s physical and social systems.

2.6. Time and the third spatial dimension

As the costs of acquiring and processing geospatial information continued to fall, many of the assumptions of earlier visions were challenged. Maps and geospatial data had been expensive to acquire and
 compile, leading to an emphasis on those types of features that changed least rapidly, so that their cartographic representation could be valid for as long as possible. But today it is easy to create maps of phenomena such as road congestion that are valid only for a few minutes, and available free to the user through mapping apps. Sensors in the environment are able to create an abundance of time-dependent geospatial data, making time an important element of today’s vision of geospatial technology. Similarly, contemporary technology such as GPS, BIM (building information management), structure-from-motion, ground-based LiDAR, and ground-penetrating radar have made it cheap and easy to acquire three-dimensional representations of geographic features. Today we think of the basic element of geospatial technology as a tuple $<x,y,z,t,a>$ where $x$, $y$, and $z$ are location in three-dimensional space, $t$ is time, and $a$ is an attribute of that location in space-time.

2.7. A nervous system for the planet

The human nervous system collects signals from many parts of the body and transmits them to the brain, where they can be processed and combined, leading eventually to actions. Expressed in this way, there are obvious analogies between the nervous system and geospatial technology as it exists today. Given the stresses that humans are placing on the planet, a system to collect, assemble, and disseminate multi-dimensional Earth information is clearly of immense value. Yet in practice there is enormous variation in how the planet is sensed, how the resulting data are transmitted and to whom, how the various signals are conflated and stored, and how the costs of all of this are met. Along with Digital Earth, the nervous-system analogy provides a vision for a more comprehensive, international, and holistic approach to the acquisition, distribution, and processing of geospatial information.

3. GIS today

Today, geospatial technology extends into virtually all areas of human activity, helping to solve problems and make decisions, predict outcomes, and discover and explain how the Earth’s environmental and social systems work. Geospatial technology allows its users to “see what others can’t,” by using maps and statistics to reveal what would otherwise not be visible, appreciated, or understood. Government agencies, corporations, researchers, and nonprofits use GIS in many aspects of their businesses and activities. Individual citizens encounter GIS in mapping and wayfinding apps, and in apps that provide information that is customized to the user’s location. The reach of GIS has extended far beyond the term itself, which many individuals and organizations that use geospatial technology may not even recognize. Following is a brief review of some of the major areas of application of GIS today.

3.1. Environmental monitoring, assessment, and conservation

GIS is used to keep track of the state of the environment, based on data gathered by Earth-observing satellites, aircraft and drones, field observation, and ground-based sensors. It is used to identify areas of critical concern, to preserve biodiversity and human heritage, and to develop and assess the effects of conservation strategies. Movements can be tracked using GPS sensors, and the results analyzed to draw inferences about habitat suitability.

3.2. Forestry and land management

As early as the 1970s, management of forests was one of the first significant applications of GIS. Starting with detailed maps, analysts were able to evaluate the productivity of forest stands, and to plan silviculture and harvesting. GIS made it easy to estimate the volume and quality of timber in a stand and the associated costs of extraction, and to address conflicts with other uses such as wildlife habitat and human recreation.

3.3. Health, demographics, and statistics

Some of the most compelling applications of GIS focus on social data, and are expanding rapidly due to the recent availability of fine-resolution data from social media and electronic medical records. GIS is used to analyze the comparative rates of infectious diseases and other medical conditions across large areas of the globe, to provide early warning of outbreaks, and to study how the accessibility and cost of medical services vary across regions. We know that life outcomes depend to some extent on where one was born and raised, but can now study these effects in unprecedented detail (Cook 2019). GIS is also widely used in planning school service areas, and in manipulating voting districts for political advantage. GIS is also widely used in business applications, where location always plays a critical role.

3.4. Transportation planning and management

GIS is used by corporations to plan and route deliveries, garbage pickup, bus systems, and many other services. Relying on GIS rather than traditional manual methods has been shown to produce significant savings in time and fuel consumption. New data sources, such
as transit user cards, are providing much richer information than before for planning and scheduling transit systems. GIS also has enormous value in anticipating and planning for major disruptions of transportation systems, both short-term due to major events and long-term due, for example, to the introduction of driverless vehicles and ride-sharing services.

3.5. Building and facility management

Adding the ability to handle the third spatial dimension has opened a host of new applications for GIS. Techniques are being developed and implemented for mapping the interiors of buildings and for providing accurate determinations of position, in an indoors extension of GPS. GIS can be used to plan and manage the assignment of activities to interior spaces, and to support wayfinding and emergency evacuation in the complex three-dimensional spaces of airports, shopping centers, and mines. GIS is also extensively used for the management of complex campus facilities, military bases, and corporate headquarters.

3.6. Public safety and national security

Law enforcement makes use of GIS in numerous ways, from the planning of police districts and patrols to the analysis of geographic patterns of crime. The military have long made extensive use of GIS, from basic mapping and the analysis of trafficability to real-time situation awareness. Recently, the need to fight wars in compact urban spaces has led to a new perspective that emphasizes the third spatial dimension and the ability to sense and understand human movement and behavior.

3.7. Preparing for and responding to disasters

GIS is invaluable in all four stages of disaster management: planning, response, recovery, and mitigation (National Research Council 2007). In the planning stages it provides the means to put in place the databases that will be needed, and to negotiate arrangements for data sharing. In the response phase the emphasis must be on operationalizing GIS quickly, to provide essential maps for responders, and situation awareness for managers. In recovery, GIS is used to map the impacts of the disaster, and to prioritize recovery efforts. And in the mitigation phase GIS is used to plan and implement measures that will minimize losses in future events. GIS is also an essential tool in predicting and estimating the extent of damage, in managing evacuations, and in directing evacuees to shelters.

4. A rapidly changing environment

It is now half a century since the concept of a GIS was first implemented, on mainframe computers with very limited memory, less computing power than today’s smartphone, and no ability to communicate electronically with other computers. Data were in short supply, and had to be created by painstaking conversion from physical media, most often paper maps. Many technical advances have since been made in computational power, storage capacity, and communication. Many data today are born digital, and databases are easily found and shared over the Internet. Moreover the pace of change continues to accelerate, as new technologies come online and new uses proliferate.

But other aspects of GIS are remarkably unchanged. Raster and vector remain the basis for representation; the map remains the conceptual metaphor, in the form of GIS layers; map projections are still widely used to flatten the Earth; and little advance has been made in measuring, representing, and dealing with the uncertainty that is always present when geographic reality is measured and captured in digital data, but not always present in published maps. On the one hand we see an ever-expanding potential for GIS, as it takes advantage of the still-accelerating changes in information and computer technologies. On the other hand, our training encourages us to follow practices that have survived the test of time, as legacies of earlier solutions. Thinking outside the box, dealing with major technical disruptions, and recognizing the full potential of new opportunities, have always been difficult, and it is always easier to see new developments as making old practices easier, faster, and cheaper; and more difficult to see the new questions and new practices that technological advances make possible. Following is a brief review of some of these new practices.

4.1. Portals

The development of digital map libraries, spatial data warehouses, and geoportals had a dramatic impact on the availability of digital geospatial data, beginning in the mid 1990s. Early GIS workflows had been dominated by the tedious task of digitizing, and databases could only be shared by exchanging physical media. Today the vast majority of geospatial data sets are either born digital, or shared electronically through portals. Metadata provide the means both to find data, and to assess its suitability for use in a given application; and
today’s GIS software makes it easy to publish data from within an application for others to use.

4.2. Open data

The 1993 report that recommended the National Spatial Data Infrastructure anticipated the dramatic impacts that the changing economics of geospatial data production would have. Nowhere perhaps is this more obvious than in the case of the Open Street Map project (OSM). Born in 2004 out of frustration with the very high cost of geospatial data being produced by some government agencies, OSM set about creating a free, open-to-all digital map using the efforts of volunteers, fine-resolution Earth imagery, and GPS. Today OSM is often the most complete and accurate source of base mapping in many parts of the world, and plays an invaluable role in emergency response.

4.3. Engagement

The notion of GIS as a system of engagement is comparatively recent, dating perhaps from the Digital Earth speech of the late 1990s. Even at that time the vision involved access through libraries, which seemed at the time to be the best institutions for offering the high-end devices and broadband connectivity needed. Today, of course, those devices and that kind of connectivity are available to everyone, through smartphones, laptops, and desktops. As Turner pointed out (Turner 2006), the average citizen is now both a consumer and a producer of geospatial information, and there is no longer an effective distinction between the geospatial expert and the geospatial amateur. Location-based services are available and used by almost everyone, almost daily, and often without the conscious awareness of the user.

4.4. Enterprise GIS

Every organization has adopted a way of segmenting itself into departments, each with its own thematic emphasis and set of associated responsibilities. As GIS grew it was initially applied to the work of individuals or groups, and later to entire departments. An oil company, for example, might adopt GIS to manage its leases and surface assets, but might use entirely different systems for subsurface exploration or for marketing. The vision of enterprise GIS sees all of these systems as integrated, and supported by a single unified database and associated software – a system of systems. An enterprise GIS uses a single, universal language to describe geospatial features and their interrelationships, helping to break down the barriers to communication that always emerge in a segmented or stove-piped organization.

4.5. A network of collaboration

The Web and Internet, and the engagement of large numbers of organizations and individuals, have led to a new sense that the old model of a GIS supporting an individual investigator has been transformed into a vision of GIS as a network of collaboration. Today’s technology allows not only the sharing of data, either directly or through portals, but also the sharing of software and workflows. It is now easy to capture a workflow and to share it with others. Workflows can be saved, preserving a record of how a particular analysis was performed, and opening it to use by others. Networks have become an essential component of geospatial infrastructure, allowing groups to work together remotely without face-to-face interaction.

4.6. Story maps

Written reports and publications have long been the traditional means of communicating results, augmented perhaps by presentations that combine slides with narrative. But humans have always valued the story, a mix of narrative, gesture, examples, and sometimes illustrations, as a way of communicating a message in a compelling way. In the geospatial world the map has always played an important role in communication, and principles of map design have reached a high level of sophistication in what are known today as "smart maps". Recently the "story map" has become a novel and important way of communicating GIS results, combining text, interactive maps, video and audio in a linear fashion and under a simple user interface. Story maps are easy to create, and millions can now be found online. They tell stories about human conflict, progress in solving environmental issues, changes in the social fabric of cities, historic heritage, and a host of other topics. Story maps have been enormously successful in opening new ways of sharing the results of GIS projects and in engaging the general public.

One of the most fundamental and far-reaching changes in the technological environment for GIS has been device independence, the ability to access and engage with GIS through virtually any device, from a smartphone or tablet to a laptop or desktop. While some interactions still occur through wired connections, increasingly the user’s device is able to switch as needed between cellular, WiFi, and wired communication. GIS users have long preferred extensive screen real-estate, and multiple screens are often employed, but smartphone mapping apps have demonstrated that even the small hand-held screen can be adequate for many applications.
4.7. The Cloud

Another far-reaching change of the past few years has been the replacement of specific servers by the Cloud. Much GIS functionality is now available through Cloud-based services such as ArcGIS Online, and many users now receive e-mail and maintain their files in the Cloud, rather than on specific servers that must be periodically backed up. Local hard drives, such as have long been an essential part of laptops and desktops, are increasingly a thing of the past in this new world of device-independent access to everything from anywhere.

5. Advances in GIS

Prediction is always foolhardy, but it is possible to list some of the changes that are already in the pipeline, and likely to appear in the next few years. Some of these originate in the rapid growth of data science, and some in a general concern for replicability in science. Others originate in dramatic advances in the availability of satellite imagery, in the increasing sophistication of drones, and in the rapidly falling costs of various kinds of sensors. Here are some of the most promising advances that are just around the corner.

5.1. GeoAI

Tools of artificial intelligence (AI) have had remarkable success in many areas. They allow massive bodies of raw data to be analyzed, looking for patterns and performing simple analyses, and in many cases outperforming the more traditional tools of analysis, many of which were developed long before the advent of massive computation and Big Data. Image analysis has provided some of the most compelling early applications of AI to geospatial data; it is able to analyze vast amounts of imagery very rapidly, finding features such as streets and roads, classifying crops, and learning the factors that are indicative of disease or fire risk.

5.2. Scripting and workflows

In the past users of GIS have had to rely on memory or hand-written notes to keep track of the many steps in some applications. ModelBuilder is a longstanding and very useful feature of Esri software, but recent developments in notebook software promise to revolutionize the creation, recording, and sharing of workflows. Jupyter Notebooks have become an important aid in complex GIS analysis and in GIS education, allowing processes to be recorded and reproduced in a rigorous way, and will likely soon become an important part of the GIS toolkit.

5.3. Replicability

Although scientists have long been trained to describe and document their research in sufficient detail to allow others to reproduce and replicate its results, and have regarded replicability as a major feature of the scientific method, in recent years concern has been expressed over failures to replicate results, especially in experimental psychology (National Research Council 2019). A somewhat broader issue has long been recognized in geography and in other disciplines that deal with phenomena located in space and time: should we expect that results obtained in one part of the world, at one time, should also apply to other parts of the world and at other times? This is often termed generalizability, but it is strongly related to replicability. If results in physics or chemistry turn out not to be generalizable across space and time, then they would certainly be rejected, so what right do geospatial scientists have to proclaim non-generalizable results as scientific? Openness, especially open data and open software, will go a long way to ensuring that results can be reproduced by others. Containerization, using tools such as Docker, will also allow the specifics of a given study to be captured and frozen, so that they can be reproduced exactly.

5.4. Predictive modeling

Much of the excitement that has surrounded Big Data and data science in the past few years has stemmed from prediction, using vast amounts of data from disparate sources and the techniques of artificial intelligence and machine learning. Prediction typically forecasts when something will happen, but in the geospatial world there is also great interest in where, in addition perhaps to when. Prediction can be very useful, and yet science has traditionally concerned itself more with understanding and explanation, and with questions of why. So this new emphasis on predictive modeling is a somewhat novel departure for the scientific community, and support for predictive modeling is similarly a mostly new departure for GIS. A variety of tools are under development, and will likely be appearing in new releases of GIS software over the next few years.

5.5. Real-time analysis

Besides volume, Big Data are characterized by velocity, and more and more data are becoming available in real time, sourced from sensors and distributed through the Internet. Instead of weeks, the delay in obtaining remotely sensed imagery from satellites is falling steadily, and it is possible to anticipate a day when it will be possible to obtain digital representations of the
Earth’s surface as it currently looks, or looked a few minutes ago. Images from drones may already be available in real time.

This immediacy of data leads to some interesting questions. Is it possible to process real-time data fast enough, so that results are also available in real time? Is it possible, for example, to sense and process an evacuation of a major city sufficiently quickly to make decisions about traffic control? Is there any role for real-time analysis if science is concerned primarily with understanding and explanation, and if scientific discoveries are expected to be true at all times and in all places? What is the relevance of the issues discussed earlier under the heading of replicability? Yet real-time analysis is immensely valuable for situation awareness, allowing the user to monitor events on or near the Earth’s surface through dashboards and other suitably designed interfaces.

6. Geospatial infrastructure

Geospatial infrastructure is GIS at scale, grown from small beginnings half a century ago to embrace a host of important applications, a community that extends from the average citizen to geospatial scientists, and services that meet the needs of individuals, organizations, and entire enterprises. The pace of change is accelerating, whether it be in computing or communication technology, in the problems and challenges facing humanity, or in our ability to sense many aspects of the geographic world. Clearly humans find themselves in a place where they have never been before, and needing the power of digital geography and the science of where more than ever.

What, then, should be the goals of geospatial infrastructure, and how should it be configured? Following are some of the many possible goals.

6.1. Envision what’s possible

One of the greatest challenges of advancing technology lies in seeing what these advances make possible; in thinking “outside the box”. Past practices evolved to exploit earlier technology; as technology advances it follows that practices must advance also. Decisions that were made during periods of very limited computing power become enshrined in practices that may be very hard to shake. Many practices in statistics, for example, such as the fitting of regression lines by minimizing total squared deviation, reflect choices that were made before computing was even possible.

6.2. Build and manage essential data

Not all geospatial data sets are of equal value. Some, such as the seven “framework” data sets of the US National Spatial Data Infrastructure, provide an essential foundation onto which other data can be added. Base maps of major streets, named places, coastlines, and lakes and rivers are used in a vast array of applications, as is fine-resolution Earth imagery. They need to be open, freely accessible, and accurate, in order to support those other applications and as a foundation for the geospatial infrastructure.

6.3. Improve productivity and efficiency

Productivity and efficiency are valuable goals in many areas of GIS application, from the routing and scheduling of vehicle fleets to site selection for retail outlets, the logistics industry, health services, or emergency response. Spatial decision support systems address such issues using the tools of GIS, combined with goals such as minimizing fuel consumption, minimizing response times, minimizing adverse health outcomes, or maximizing profit.

6.4. Develop sustainably

Productivity and efficiency are of course only one basis on which to make decisions. Sustainability is another, and related goals such as minimizing environmental impact. In recent years the concept of geodesign has been introduced as a GIS application dealing with projects that seek to modify the Earth’s surface, rather than making an inventory of it. Geodesign combines the esthetic task of design with the more scientific task of assessing impacts. The ability to design should be an important part of any vision of geospatial infrastructure, along with concepts of stakeholder engagement, sharing of designs, and techniques of consensus building.

6.5. Engage citizens

Citizen engagement has become a major focus of geospatial technology in recent years. It is enabled by device-independent access, by the kinds of geospatial services that citizens use every day, and by the ability of citizens to provide data and other kinds of input using Web 2.0 services. At the same time this growth of engagement is changing GIS, making it more important than ever that user interfaces are intuitive, and use terms that are meaningful to the average citizen, rather than to the geospatial expert. Interfaces now recognize the names of places and points of interest, in contrast to early GIS interfaces that worked exclusively in terms of measured coordinates.

6.6. Protect biodiversity

GIS has found many compelling applications in conservation. Techniques have been developed for determining the suitability of habitat, for preserving corridors between areas of habitat in order to avoid isolating
subpopulations, and for measuring and mapping diversity. All of these are excellent illustrations of the principle that GIS is a set of tools for making visible what would otherwise be hard or impossible to see, and for promoting ideals through story maps. Conservation, and the protection of biodiversity, should be one of the primary goals of geospatial infrastructure.

6.7. Make agencies smarter

Information, and the technology to process it, are clearly essentials for smart decisions. Geospatial technology is already playing a major role in the emerging concept of the smart city, and in rural activities such as agriculture and forestry. Geospatial infrastructure can help to make agencies smarter, especially when it fully exploits the power of the third spatial dimension and time, enabling real-time decision making in time-critical situations such as emergencies.

6.8. Design for resilience

A resilient system is a system that can survive shocks, especially shocks that are difficult or impossible to anticipate. Geospatial technology has played many critical roles in dealing with emergencies, but it can also be used to measure resilience (National Research Council 2012), and resilience can be included as one of the objectives of geodesign.

6.9. Share and collaborate

Sharing and collaboration should be among the most important goals of a geospatial infrastructure, enabled by the kinds of engagement and accessibility that are an increasing feature of geospatial technology.

6.10. Ensure individual privacy

Finally, while many jurisdictions have adopted various forms of privacy protection, it is clear from recent analyses and media reports (New York Times 2019) that vast amounts of personal information are being acquired and in some cases sold. Geospatial information is especially vulnerable, since it is trivial in many cases to infer identity and other personal characteristics from a few records of location. Few users read or understand the Terms and Conditions of Use of apps, or the implications of sharing personal data. Protection of personal privacy must be an important goal of geospatial infrastructure.

7. Summary

The next few years will see massive transformation, in society as a whole but also in geospatial technology. To achieve the goals set out in the previous section, especially with regard to openness, access, and engagement, the geospatial infrastructure of the future will have to be Web-based. It will have to integrate information, processes, and workflows, and capture sufficient information to support replicability. It will have powerful techniques for integrating the variety of data sources that are characteristic of Big Data: conflation, resampling, upscaling, and fusion. It will need to track the provenance of data, and allow intermediate products to be recovered. All of this is already available in some form, and incremental changes are constantly being made. But what is missing in our view is a vision, a “moonshot,” a statement of principles against which progress can be measured. More than 20 years ago the Digital Earth speech provided such a moonshot, and led to a number of research and development projects that came close to achieving Gore’s vision. Today, we believe that another moonshot is needed, as a vision for the emerging geospatial infrastructure that we have described in this paper.

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No potential conflict of interest was reported by the authors.

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