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Future SDI – Impulses from Geoinformatics Research and IT Trends*

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Abstract

The term Spatial Data Infrastructure (SDI) was defined in the nineties as a set of policies, technologies and institutional arrangements for improving the availability and accessibility of spatial data and information. SDIs are typically driven by governmental organizations, and thus follow top-down structures based on regulations and agreements. The drawback is that it renders SDIs less easily

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capable of evolving with new technological trends. While organizations are still struggling to implement SDIs, the World Wide Web is increasingly developing into a Geospatial Web, i.e. one that extensively supports the spatial and temporal aspects of information. This article is our contribution to the discussion on the future technological directions in the field of SDIs. We give a conceptual view of the dynamics of both SDIs and the Geospatial Web. We present a picture of the SDI of the future, one which benefits from these developments, based on an analysis of geoinformatics research topics and current ICT trends. We provide recommendations on how to improve the adaptability and usability of SDIs as to facilitate the assimilation of new ICT developments and to leverage self-reinforcing growth.

Keywords: SDI, Information Infrastructures, Geoinformatics, Geospatial Web, Linked Data

1. INTRODUCTION

Increasing awareness of the global challenges that mankind faces today comes with the realisation that only by implementing significant changes in the way we organize our lives on planet Earth will we be able to cope with these challenges. This necessitates both a better understanding of our biophysical and social environment and better management of our activities on all levels and at all scales, whether a global business entity, a national public authority, or a private individual.

Improving our understanding requires a joint effort across several disciplines, organisations and Information Infrastructures (IIs), which support communication and collaboration efficiently (Goodchild, 2008; Craglia et al, 2008). This includes providing a means of sharing spatio-temporal data and computing capabilities, so as to create multi-participative decision-supporting environments, which enable multidisciplinary research teams and decision makers at all levels to achieve their objectives (Hey and Trefethen, 2005).

Spatial data infrastructures (SDIs) are currently the best approximation to these spatial community concerns. SDIs are described as a set of policies, technologies and institutional arrangements leveraging the provision and use of standardized spatial data and processing services, to assist diverse expert user communities in collecting, sharing and exploiting geospatial information resources (Phillips et al, 1999; Nebert, 2004; Masser, 2005; Masser et al, 2007; Bishop et al, 2000; Davis et al, 2009; Vandenbroucke et al, 2009).

The development of SDIs is, in particular, driven by public authorities, like national mapping or environmental agencies (Béjar et al, 2009), whose business processes often involve spatial data and whose tasks are often related to specific territories and geographical locations. Hence any means of exchanging of spatial information between these public authorities and private individuals, business entities or other public bodies saves considerable time and costs. Most importantly, a better information base improves the quality of plans and decisions, though it is challenging to express this in monetary terms.

A prerequisite for implementing an SDI in the public sector is a legal framework that lays down the goals and principles, including details relating to content and technologies as well as the rights and obligations of the parties involved. The most prominent European example is INSPIRE, the Infrastructure for Spatial Information in the European Community (INSPIRE, 2007) which is a European-scale SDI, based on member states' national SDIs. The INSPIRE Directive has been transposed into the member states' national legislation. The European member states are obliged to provide certain data, metadata and web services, so as to support policies and activities that have an impact on the environment. The INSPIRE Guidance Documents recommend very detailed specifications, which have to be implemented so as to achieve interoperability between all the SDIs and their components.

Today, more than ten years after the first working groups and action plans on INSPIRE were first established, INSPIRE displays a significant footprint, even if it is not yet fully operational. The framework directive has been implemented in national laws, organizational structures and workflows have been adapted, and off-the-shelf software now supports the required interfaces and processes. The paradigm of a standards-based open service-oriented architecture has gained broad acceptance. In parallel, and corresponding with the implementation of INSPIRE, national and regional SDIs have been developed, with many spatial content offerings and applications now up and running.

Nevertheless, SDIs have so far failed to achieve the desired level of impact and penetration in the geospatial community. The problem is that SDIs generally suffer from a low rate of user participation and a scarcity of resources (Ackland, 2009; Díaz et al, 2011), a lack of maintenance as they grow in complexity (Béjar et al, 2009), and difficulties in efficiently discovering and processing data (Scholten et al, 2008; Craglia et al, 2007; Craglia et al, 2008; Granell et al, 2010). These shortcomings are obvious, for example in the emergency management domain, where easy access to up-to-date information is crucial for minimizing damage and saving human lives (Diehl et al, 2006; Zlatanova and Fabbri, 2009).

This contrasts with the fact that mainstream IT is developing at a fast pace, offering new and improved means of sharing resources and organizing multi-participative environments across disciplines and user profiles. The Web is evolving into a Geospatial Web, i.e., independently of any SDI initiatives, the Web is increasingly and extensively supporting the spatial and temporal aspect of information. Ubiquitous access, location-aware devices, and user-centric applications are creating a new user experience, which boosts consumers' expectations of the Web's spatial capabilities. The crowd of individual users is increasingly participating in the processes of collecting, communicating and using geographical information. Volunteered Geographic Information (VGI) (Goodchild, 2007) has gained relevance as a source of information which complements the authoritative spatial data.

We have introduced the full picture describing the characteristics associated with the way SDIs are managed and used: building methodologies, data policies and deployment laws are indeed crucial parts on the SDI future development. However the scope of this work focuses on analyzing the technological components of SDIs. From the technological point of view, we are currently observing a widening gap between classic SDIs and what we call the Geospatial Web. Both are improving, but at different speeds, but what is the future of SDIs? What momentum is being created from research activities in the field of geoinformatics? What will be the impact of current IT trends which are already shaping the Geospatial Web?

This article addresses some of these questions. We begin by analyzing the inherent dynamics of SDIs, as an aid to understanding the diverging development of SDIs compared to that of the Geospatial Web. Section 3 analyzes selected fields of research and IT trends, and assesses their relevance in future SDI developments. Section 4 gives a structured overview of IT trends and their anticipated impact on SDIs. Section 5 aggregates the findings of this analysis as a set of hypotheses on the future development of SDIs.

2. DYNAMICS OF (SPATIAL) INFORMATION INFRASTRUCTURES

According to the theories of Hanseth and Lyytenen (2010), the term information infrastructure (II) denotes “shared, open, heterogeneous and evolving socio-technical systems consisting of a set of IT capabilities and their users, operations and design communities” (Hanseth and Lyytenen, 2010). Compared to information systems, IIs (like the Web) are more complex, recursively composed of IT capabilities and controlled by a distributed set of stakeholders across multiple domains. With due consideration for this complexity, Hanseth and Lyytenen (2010) propose a specific set of design principles and rules for the development of IIs, which is more about cultivating a self-organising system than a straightforward engineering process. Referring to the theory of Complex Adaptive Systems (CAS) Hanseth and Lyytenen (2010) emphasise bootstrapping and adaptability as the main challenges facing II development. The bootstrapping problem addresses the fact that an II is useful and self-energising only if it has a significant and growing installed base, in terms of actively used II components and users. The adaptability problem reflects the fact that a lack of flexibility regarding the adaptation of new and improved technologies can constrain the use and further development of IIs.

It seems evident that both bootstrapping and adaptability are in fact significant issues for SDIs. As for the former, after more than a decade, the SDIs installed base still consists predominantly of pre-operational service offerings, and regarding the latter, even though the structure of legal frameworks considers the life cycle of technologies, it will take years to manage any substantial changes, due to the complexity and the characteristics of the processes involved.

In fact, the development of SDIs is not in line with several of the rules and principles of design proposed by Hanseth and Lyytenen (2010). These are:

2.1. Generate Attractors that Bootstrap the Installed Base

The goal as presented by Hanseth and Lyytenen (2010) is to attract a critical mass of users, so as to gain both acceptance and a momentum for self-reinforcing growth. This would be achieved by designing and implementing the infrastructure in such a way that it directly provides and encourages substantial use. Furthermore, it should be built upon an existing installed base and be easy to implement so as to support its acceptance. The installed base should be subsequently extended by persuasive tactics in order to gain further momentum.

However, it is the case that the majority of SDI implementations begin with extensive prototyping and pilot phases, which are not suitable for operational use. Most developments are driven by data providers and their offerings are not aligned to users' requirements.

Most SDIs are built upon an existing installed base. However, specific data models and interfaces are required, which need to be implemented by both users and the Geo-IT industry. This requires investment, which impedes acceptance and slows down adoption.

2.2. Make the System Maximally Adaptive and Variety-Generating to Avoid Technology Traps

The goal as presented by Hanseth and Lyytenen (2010) is to allow for new and improved technologies to replace parts of the II's technology stack. Providing alternatives would support users in selecting the best of breed, which would then establish the next de facto standard for implementing an II with improved capabilities. This would necessitate a modularized structure with low dependencies between the individual components.

However, SDIs are predominantly governed by public authorities, essentially relying on a combined bottom-up & top-down process: ideas, requirements and concepts fuel a political and legislative process, which results in a set of visions, strategies, decisions and regulations, which have to be implemented top down at least throughout the hierarchy of the public administration. There is no alternative to this process for public authorities when it comes to actively managing change on a national and transnational scale. On the other hand, it makes SDIs rigid and less able to evolve with new trends and technologies.

In fact, what we are observing is the agile development of the World Wide Web, which is not really a governed infrastructure and always seems to be evolving at the edge of chaos (Hanseth and Lyytenen, 2010). Actually, the Web's independence of policies and institutional arrangements provides degrees of freedom that allow for ultrafast adoption of new ideas and developments.

One of the main conclusions we can state is that SDIs are intrinsically less adaptive than, for instance, more general information systems such as the World Wide Web, a situation which has led to a growing gap between the capabilities of SDIs and those of the overall information infrastructure.

3. (MOVING FORWARD) AN ANALYSIS OF GEOSPATIAL RESEARCH AND IT TRENDS

The term innovation denotes something new that has gained certain relevance in practice (Roth, 2009). While it is easy to describe current innovations in the field of information infrastructures, for example, by referring to the growth rate of an existing installed base, it is quite difficult and afflicted with uncertainty to predict these developments, due to the complexity and non-linear behaviour inherent in IIs. But it is obvious that trends in the overall IT infrastructure which are beneficial to SDIs create a certain momentum for innovation in SDIs.

The following section discusses research and IT trends and their relevance to SDIs. Some of these trends, such as linked open data, are still research topics and in an early phase of their life cycle. Nevertheless, we regard them as trends if their growing installed base and user community indicate their increasing relevance in the market.

The topics and their analysis are based on each authors' individual expertise, background and research, an overview of SDI research agendas (Gore, 1998; Phillips et al, 1999; Bernard et al, 2005; Craglia et al, 2008; Goodchild, 2010), and IT trend reports (Bundesministerium für Wirtschaft und Technologie, 2010; Capgemini, 2011; Dutta and Mia, 2011; European Commission, 2010; GGIM, 2012) and an internet survey of qualified IT trend statements (CIO/Forrester IT

Trends 2011-2013[1]; BitKom Questionaire 2010[2]; Gartner IT-Trends 2011[3]; U.S. Federal IT Market Forecast 2011-2015[4]).

3.1. Architectural Styles and Interoperable Interfaces

In order to address common user requirements, such as search and retrieval of content, major research carried out in the SDI field has focused on defining standards to improve systems interoperability. Desser et al (2011) describe standardization as being the relevant factor for increasing interoperability to deploy business processes on top of SDIs. Interoperability has been mentioned over the years in both SDI and Digital Earth research agendas, emphasizing different levels. Two relevant pieces of work (Sheth, 1999) and (Goodchild et al, 1999) differentiate mainly between system, syntax, structure or schema and semantic interoperability levels.

While the Internet serves as the basis for systems interoperability, middleware components support distributed computing by means of Web Services and XML-based standard interfaces. Syntactic interoperability includes the ability to deal with formatting and data exchange, adopting ad hoc standards (Sheth, 1999; Feng, 2003) to achieve it. Schematic interoperability is described by common classifications and hierarchical structures while semantic interoperability harmonizes meanings of terms. They can be improved by using metadata standards, data schemas and ontologies (Bishr, 1998). There is a wide range of interoperability standards available for the integration of information systems (Mykkänen and Tuomainen, 2008). In SDIs, interoperability is ensured most prominently by efforts by ISO/TC211 and the Open Geospatial Consortium (OGC) promoting syntactic interoperability through the use of web services (Percivall, 2008). The existing specifications have been shown to help when setting up operational SDI for sharing distributed geospatial data (Bernard et al, 2005).

SDIs exemplify the adoption of a service-oriented architecture (SOA) style to enable distributed access to heterogeneous spatial data and services through a set of common specifications and standards (Yang et al, 2010). Despite the fact that multiple operational SDIs are running worldwide, SDI interconnection and scalability is still an issue, due mainly to the lack of connectivity between SDI nodes (Schade et al, 2010).

Nowadays, this lack of connectivity and the complexity of the SOA-oriented SDIs have given rise to a search for alternative architectural styles, such as representational state transfer (REST) (Granell et al, 2012), which is aligned with the same principles that shape the Web. Some authors (Foerster et al, 2011a,

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[1] http://www.cio.de/strategien/methoden/2252382/

[2] http://www.cio.de/strategien/2220403/

[3] http://www.gartner.com/it/page.jsp?id=1454221

[4] http://www.marketresearchmedia.com/2009/05/23/us-federal-it-spending-forecast-2010-2015/

Mazzetti et al, 2009; Granell et al, 2012) describe how the adoption of REST principles, particularly the use of HTTP as an application protocol, may be beneficial in scenarios where ad hoc composition of geospatial services is required, something which is common among most non-expert users of SDI. In general, the realization of distributed SDI components following the REST principle enables a more generic and lightweight way of providing geographic information and are more specific and oriented towards geospatial functionality than OGC-based services (Schade et al, 2012).

3.2. Cloud Computing

Even in the first GSDI agenda in the nineties, efficiency in accessing data was identified as a main challenge; the issue of who is in charge of hosting data and tools so as to provide good performance has been a matter of discussion ever since. Efficiency may be examined from two different points of view. Firstly, the hosting of data and service execution has to be realized efficiently from an economic perspective. Service providers should avoid investing in rarely used hardware (by migrating to cloud computing platforms) and share computational resources and knowledge beyond organizational boundaries (increasing interoperability).

Cloud computing is one of the latest trends in the mainstream IT world (Driver, 2008; Buyya et al, 2009). The cloud metaphor describes an approach in which applications, services and datasets are no longer located on individuals' computers, but distributed over remote facilities operated by third party providers (Foster et al, 2008).

Cloud computing has already influenced recent research agendas such as (Craglia et al, 2008) and the Beijing declaration in 2009, which addressed the adoption of cloud computing in realising highly available and highly scalable spatial applications in order to increase an SDI's quality of service (QoS) (Baranski et al, 2011). These can range from classic web service qualities (e.g. service performance, response time and availability) to geospatial data quality (e.g. the degree of uncertainty in measured and processed data).

In cloud environments, users can allocate computational resources without requiring human interaction with a resource provider (on-demand self-service) (Mell and Grance, 2009). Examples of such resources include storage, processing, memory, network bandwidth, and virtual machines. These resources and their capabilities are available over the network via standard mechanisms and simple web-service interfaces (broad network access). The providers of resources (physical and virtual resources) have to cope with multiple users and their dynamically changing demands (resource pooling). From the user's perspective, the availability of resources in the Cloud often appears to be unlimited. They can be acquired from the resource provider in any quantity at any time, in order to scale applications, services and storage depending on use-case-specific requirements (rapid elasticity).

Resource usage in cloud environments can be monitored and reported, providing transparency for both the users and the resource providers (measured service). All these cloud characteristics are used to enable users to run their web or desktop-based applications in the cloud, without managing the hardware infrastructure (software as a service, SaaS). Resource providers can offer runtime environments in the cloud, in which users can deploy their applications created using programming languages and tools supported by the provider (Platform as a Service, PaaS). Furthermore, resource providers can offer complete access to virtual machines, in which users have control over operating systems, storage, deployed applications, etc. (Infrastructure as a Service, IaaS). However, when a resource provider makes his resources available in a pay-as-you-go manner to the general public, it is called a public cloud (Armbrust et al, 2010). When cloud technologies are used to manage an internal data centre and when such a data centre is not made available to the general public, it is called a private cloud. In a so-called hybrid cloud, a private cloud is combined with resources of a public cloud in order to handle tasks that cannot be performed in the local data centre, due to general hardware limitations and a temporarily heavy workload.

3.3. Distributed Processing and Uncertainty

While interoperability between data sources has been achieved to a degree in SDIs, the integration of geoprocessing functionality into such infrastructures, in order to provide an essential means of generating information out of basic data, is still an open challenge. Research on service granularity and the adoption of new standards-based interfaces for geoprocessing, such as the OGC Web Processing Service (WPS) (Schut, 2007), aim at facilitating the integration of distributed geoprocessing functionality in SDI applications (Granell et al, 2010; Foerster et al, 2011b). Furthermore, data provenance and tractability is a crucial issue for the distributed processing to offer information about its utility, accuracy and fitness for a particular user or use case.

Main research topics related to distributed geoprocessing, as originally outlined by Brauner et al (2009), are:

1. Service orchestration strategies for improving performance and semantic descriptions. Service orchestration deals with the question of how to combine several singular geoprocessing steps into a more complex workflow. This includes developing mechanisms to describe complex geospatial workflows in terms of, for instance, Business Process Execution Language (BPEL), but also developing mechanisms and user interfaces to discover geospatial processing functionality in the web and to integrate this functionality in geospatial workflows in an ad-hoc manner.

2. Finding the appropriate granularity with which to map workflow steps to geoprocesses (Granell et al, 2010). This also relates to the issue of performance in the geoprocessing web. Reducing a complex workflow to several small processes may increase the performance of each individual step and allow the parallelization of several steps, but it will also increase the communication overhead when transferring the inputs and outputs between the different processing steps.
3. Complex processes dealing with large data volumes. New technologies such as the distribution of processing over GRIDs or deploying it in clouds will improve performance,
4. The problem of adding semantics to geospatial workflows to allow the discovery and automation of geospatial workflows. Research projects like the ENVISION project (http://www.envision-project.eu/) aim to define common methods on how to integrate semantics. Recently, Janowicz et al (2010) proposed a mechanism for semantically enabling SDIs by using common service interfaces such as the OpenGIS catalogue service and the WPS for adding semantics. This information will handle issues such as data provenance, model uncertainty and processing fitness for a particular use.

Along with this trend of deploying distributed geoprocessing on top of an SDI, there are a number of new issues and trends to be addressed. Since users process data in a distributed form, and do not own the algorithm itself, distributed processing needs to include mechanisms for evaluating processing results. The user requires information regarding process quality to allow him to deduce the accuracy of the result. Therefore, it is not just technical integration, but the knowledge bases themselves need to be developed. This requires, for instance, defining vocabularies for simple geoprocessing functionality, such as simple topological operators, and defining common process ontologies as well as specialized ontologies for complex workflows. Finally, any geospatial information is only able to represent the universes of discourse to a degree. The difference between a discourse in some domain and the process descriptions and data representing it cannot be quantified exactly, but only propagated to a certain extent, by indicating the level of uncertainty in the data (provenance and after processed). One common way to quantify this uncertainty is by using probability distributions such as those proposed by Heuvelink (1998). Usually, neither the uncertainty in the data nor the uncertainty in the information generated from basic data is integrated in SDIs or the geoprocessing web.

The INTAMAP project recently provided an example of how to communicate uncertainty resulting from the interpolation of point measurements (Pebesma et. al, 2010). The UncertWeb project (http://www.uncertweb.org) is currently investigating how to add uncertainty propagation to complex web-based geospatial workflows, such as air-quality prediction models (Bastin et al, 2012). Questions of how uncertainty can be represented and easily added to spatial (and/or temporal) workflows deployed in the Web and how uncertainty can be propagated in web-based geospatial workflows without knowing the internals of the processing steps need to be addressed.

3.4. Participative Platforms and User-Generated content

Content provision has been traditionally associated with public administrations. Along with the evolution of SDIs and their growth in size and complexity, authors increasingly stress the need for content provision facilitators. Two factors are considered as the main challenges: firstly, SDI top-down building methodologies do not encourage or allow all stakeholders to participate and secondly, publication mechanisms are complex, provoking a lack of active user participation, and in turn, a scarcity of content (Díaz et al, 2011). On the other hand, the versatility of Web 2.0 systems, being populated with user-generated content, contrast to SDI maintenance and publication mechanisms since these Web 2.0 systems provide mechanisms that could be adopted to lower the barrier in SDI publication mechanisms (Díaz and Schade, 2011).

Providing up-to-date and full coverage of data is a requirement of any information system. Users with sensor-enabled devices can collect data and report phenomena more easily and cheaply than through other official sources. Crowd-sourced information is based on the assumption that non-expert users are able to contribute data in a specific form and for a specific purpose. This data is organized and structured in communities, which contribute to a specific task.

This emerging trend is heavily supported through improved user interfaces and ubiquitous web-access. Example applications are Mechanical Turk and Wikipedia and. Furthermore, encouraged by sensor-enabled devices, user generated content contains the information about content location, and we witness the appearance of citizen-based geographic applications such as Open Street Map[5].

The evolution of the role of the user from a pure consumer towards a provider profile has resulted in concepts such as Web 2.0, neogeography (Turner, 2006), cybercartography (Tulloch, 2007) or volunteered geographic information (VGI) (Goodchild, 2007). This trend is mainly characterized by active user participation. Ordinary citizens provide and share information (for the most part with a spatial temporal reference), for instance in the context of municipal activities (Carrera et al, 2007) or environmental monitoring (Davis et al, 2009), this new source of spatial information is increasingly being adopted by wide audiences and media (Sui and Goodchild, 2011).

Current research trends emphasize citizen-active participation to enrich official information (Craglia, 2007;Goodchild, 2010). This can be addressed in two ways, firstly by integrating available user-generated resources in the SDI context, and

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[5] http://www.openstreetmap.org/

secondly by reconceptualising the role of SDI users (Budhathoki et al, 2008), allowing SDI users to be not only consumers but assisting users to participate directly in providing content to SDI. This content, mostly geo-referenced, thanks to the smart devices currently available, allow user to provide geographic information enriched by the user context. Since we consider different user profiles to be participating more actively in data provision, SDI agendas stress the need for both mechanisms for describing and identifying users and data provenance and mechanisms for assessing data quality and consistency.

3.5. Access Dynamics: Sensor Web and the Web of Things

One of the main goals of spatial information infrastructures is to provide vast amounts of dynamic data on the current state of the Earth, at high spatiotemporal resolution, for continuous monitoring and geosensing of the world, as an aid to efficient decision making (Craglia et al, 2008). There is a need to improve data dynamics by developing technology to capture real-time and high-spatial-resolution data (Gore, 1998). Such dynamic data is provided by various geosensors, ranging from weather or water gage stations, over complex marine sensors, to unmanned aerial vehicles or satellites. To integrate such geosensors and their data with Spatial Information Infrastructures, the Sensor Web Enablement (SWE) technology can be used. SWE is a framework of web service and data encoding specifications defined by OGC and enables the interoperable discovery and tasking of sensors, as well as the access to measured sensor data and realizes eventing and alerting (Bröring et al, 2011). SWE has already found its way into practise and application, e.g., the European Environment Agency (EEA) utilizes SWE to offer air quality observations in an interoperable manner (Jirka et al, 2012).

New kinds of mobile devices not only provide users with tools to access more dynamic information, but also with sensor-enabled capabilities for capturing and providing high-resolution data. Recent trends[6] indicate that by 2014 the mobile-user community will become bigger than that of desktop users in the Internet. This will impact heavily on how web-based applications are used and put into context. Influential factors will be the limitations of display size, battery consumption and the capture of massive amounts of data by sensors in the mobile device in a constantly changing environment. The environmental context is at present mainly determined by location (measured by GPS), noise (measured by microphone), light, and velocity/attitude (measured by gyroscope). Another trend, visible in today's Web landscape, is the emergence of physical objects in the virtual space. Examples of such objects connected to the Web are intelligent household appliances, embedded and mobile devices, and networks of stationary or mobile sensors.

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[6] http://www.morganstanley.com/

This connection of real-world objects with the Internet reflects the vision of the Internet of Things (Gershenfeld et al, 2004). Possible applications in the Internet of Things are influenced by the idea of ubiquitous computing (Weiser, 1991). They range from smart shoes posting running performance online, the localization of goods in the production chain, to the calculation of car-insurance costs based on kilometres actually driven. Research topics benefiting the technical realisation of the Internet of Things, include protocol stacks for the Internet Protocol (IP) standard, optimized for smart objects (e.g., IPv6, 6LoWPAN) (Hui and Culler, 2008), naming services for objects (EPCglobal, 2008), or the unique identification of objects (e.g. RFID).

The Web of Things (Guinard and Trifa, 2009) can be seen as an evolution of the Internet of Things. It leverages existing Web protocols as a common language for real objects to interact with each other. HTTP is used as an application protocol rather than a transport protocol as is generally the case in web service infrastructures, such as OGC’s Sensor Web Enablement framework. Resources are identified by URLs, and their functionality is accessed through well-defined HTTP operations (GET, POST, PUT, etc.). Hence, Web of Things applications follow the REST paradigm (Fielding and Taylor, 2002). Specific frameworks (Pinto et al, 2010; Ostermaier et al, 2010; Bröring et al, 2012) based on REST APIs enable access to things and their properties as resources. These REST APIs can not only be used to interact with a thing via the Web, but website representations of things may also be provided to display dynamically generated visualizations of data gathered by the thing. Then, the mash-up paradigm and tools from the Web 2.0 realm can be applied to easily build new applications. An example application may use Twitter to give notification of the status of a washing machine or enable a refrigerator to post to an atom feed to state which groceries are about to run out. For such use cases, metadata descriptions of things are needed which are based on lightweight languages (e.g. Malewski et al, 2012) to also allow the exchange of those descriptions between Web-enabled things.

The user interaction generally utilizes a cell phone acting as the mediator within the triangle of human, thing, and the Web, as for example shown by Foerster et al (2011c). This emergence of physical things in the virtual world is one of the key technological changes that will shape the Web (Ackerman and Guizzo, 2011).

3.6. Open, Distributed and Linked Data

Among other authors in the nineties, the (GSDI, 1996) and Phillips et al (1999) pointed out the need to move from silos of information to open and distributed infrastructures, to enable information to be integrated from different sources. Related to this, Al Gore suggested the vision of a digital earth (DE) in 1998 and stated: 'Clearly, the Digital Earth will not happen overnight. In the first stage, we should focus on integrating the data from multiple sources that we already have (Gore, 1998). More recently, Craglia et al (2008), re-evaluating the DE vision, concluded that 'despite substantial progress, our ability to integrate geographic information from multiple sources is still quite limited'. One of the main challenges toward integrating information is to be able to search and retrieve information. One identified problem relates to the need for manual generation of resource description and cataloguing that keeps provoking the lack of metadata and the difficulties in information discovery in SDIs (Craglia et al, 2008; Díaz et al, 2007). Partial solutions have been achieved by using catalogue services that register metadata and are the key to facilitating the discovery of content available in SDIs (Nogueras-Iso et al, 2005; Díaz et al, 2007).

Today’s World Wide Web consists of myriads of documents spanning a gigantic information space. The links between these documents make them traversable with Web browsers. Search engines can analyze links to make contents discoverable and to infer relevance to search queries (Brin and Page, 1998). The research community is currently investigating the migration from the Web of documents to the Web of linked open data. This is a big move, as it not only allows data to be accessed that was not accessible before, but also to have different pieces of data linked to each other.

The Web of Data, if successfully created, will lead to an enormous data space, encompassing data relating to people, companies, publications, books, movies, music, television programmes, genes, proteins, drugs and clinical trials, online communities, and statistical and scientific data (Bizer et al, 2009) There is an increasing amount of linked spatio-temporal data on the Web. One aspect of this movement is to bring sensor data into the linked data cloud (Le-Phouc and Hauswirth, 2009). Note here that sensor observations are traditionally low level - i.e. raw data - and thus it is important to develop mechanisms of obtaining a higher-level, conceptual understanding of different phenomena (Devaraju and Kauppinen, 2011).

Some examples of how linked data are used in the context of SDIs:

1. Efficient and timely crisis management can help to reduce suffering in the aftermaths of crises such as earthquakes, tsunamis, floods or storms. To analyze the complexity of systems such as humanitarian logistics in crisis management, there is a need for integrated human data observations (Ortmann et al, 2011). Linked data technologies are capable of interconnecting different observations, and the results can be visualized online[7].
2. For analyzing processes and operations of complex systems such as environmental and societal systems, there is a need to have 1) well-interconnected data about a system and 2) techniques of statistical computing and other types of reasoning, to find new information, and 3) a

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[7] http://linkedscience.org/data/linked-haiti/

means of exploring and visualizing this information. Deforestation and its related phenomena, such as the market prices of agricultural products, together form a complex system. Linked data supports the interconnection of different pieces of data[8].

3. Identification and categorization of extreme weather events. Weather sensor data is transformed to linked data for efficient linkage. Data reasoning is used to create a higher-level conceptualization[9] of the weather events, for example the categorization of an event as a high wind, winter storm, or a blizzard (Devaraju and Kauppinen, 2011).

4. IMPACT OF IT TRENDS ON THE DEVELOPMENT OF SDIS

This section assesses the potential of the aforementioned trends in geoinformatics research and mainstream IT for the future development of SDIs. To do so, we first recall the main requirements to be addressed by SDIs, before going on to analyze the benefits to be expected from the trends described in Section 3 with respect to these requirements.

4.1. SDI Requirements

The main purpose of SDIs is to support specific specialist communities and fulfill their initial requirements. These requirements can be classified into two types. The first type addresses the user's expectations of the SDI's functional capabilities. The second is about the user's expectations of non-functional aspects relating mainly to the SDI's usability, such as performance, security and reliability, i.e., the Quality of Service (QoS).

Generally speaking, SDIs are widely known as facilitators in coordinating the exchange of geospatial information (Rajabifard, 2007) (Dessers et al, 2012). In this context, common use cases found in geospatial applications, such as geoportals, show that the main requirements of SDI users are visualization, ease of use, interoperability and mashups, and modelling and simulations (Gore 1998; Goodchild, 2008). Similar user requirements are described in the SDI cookbook (Nebert, 2004): search, visualization, features selections, download and analysis, and processing. In the same way, the GEOSS technological use cases (GEOSS, 2008) define the requirements: search, visualization and exploitation of resources. Furthermore, SDIs need regular maintenance and refinement due to their dynamic nature, the inherent complexity of standardized SDI, and the complex mechanisms of deployment, particularly as SDIs grow (Béjar, et al, 2009).

Figure 1 summarizes the common functional user requirements associated with the relevant steps in the resource life cycle (Díaz et al, 2011). Moving clockwise,

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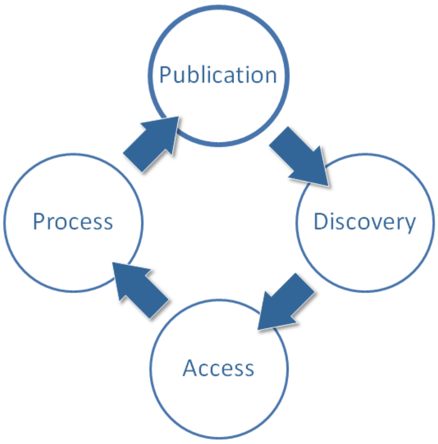
[8] See http://linkedscience.org/data/linked-brazilian-amazon-rainforest/

[9] See http://observedchange.com/ontologies/sego/

resources must first be published in the SDI, so that they are available for the other stakeholders. Then, these resources need to be searchable and discoverable in the distributed system. Key elements for increasing the visibility of the resource in the SDI, are metadata and catalogue services (Craglia et al, 2007; Nogueras-Iso et al, 2005). The third step is the ability of these resources to be accessed and visualized. In the last step, users process and exploit these resources, generating new information that should be then ready for publication in the SDI, closing the cycle.

Figure 1: SDI Resource Life Cycle



The non-functional requirements mainly address the quality and usability aspects of SDIs, which enable users to perform their workflows in a reliable, secure and effective manner. Secured access is required when exposing sensitive data, as is a certain QoS, which has to be agreed upon and guaranteed by the service providers. Another aspect from a service and content provider’s point of view is that the cost of implementing and maintaining SDI components has to be as low as possible.

Moreover, in specific application domains, such as disaster management, decision-makers have to be provided ad hoc with accurate and up-to-date information. Particularly in the first phases of an event, it is very important to provide fast access to reliable data, to understand the context of the emergency situation (Brunner et al, 2009; Mansourian et al, 2005; Rocha et al, 2005; Scholten et al, 2008, Zlatanova et al, 2006), and to efficiently disseminate the knowledge to the people involved (Almer et al, 2008; Scholten et al, 2008; Nayak and Zlatanova, 2008).

4.2. Potential Impact from Geoinformatics Research and IT Trends

Since SDIs are implemented as an integral part of the overall web based information infrastructure, most of the trends investigated in our analysis will directly or indirectly affect the future development of SDIs. Table 1 summarizes the benefits and the expected impacts on SDIs.

Table 2: Impacts on Required SDI Capabilities

Trends in Research and Mainstream IT	***Benefits to SDIs***	***Expected Impacts***
Architectural styles and interoperable interfaces	Reduced efforts and costs in integrating and maintaining SDI components	Increasing number of SDI applications, which can be chained and included in more general business models
Cloud computing	Simplified deployment and maintenance of SDI services	Increasing number of content offerings
	Reduced costs of providing content and applications with a high quality of service	Increasing quality of service
Distributed Processing and uncertainty	Increasingly easy sharing and reusing of processing capacities	Increases the number of processing tools and applications
	Improved reproducibility and interpretation of computations	Increases the quality of SDI content and its use
Participative platforms and volunteer geographic information	Low cost contribution of local knowledge and expertise	Increasing amount of data at high space-time resolution
	Private individuals form an SDI stakeholders group, which participates actively in the development of SDIs	Intensified development and use of SDI capabilities
Access dynamics: Sensor Web and the Web of Things	Improved means for collecting and accessing near real-time information	Increased demand and availability of near real-time data with high spatiotemporal resolution
Open, distributed and linked data	Simplified integration of heterogeneous data through increasingly shared vocabularies.	Increased availability of information resources
	Improved means for encoding, describing and interlinking data	Improved access to data through links and crawling mechanisms
	Homogeneous model for data and metadata	Improved descriptions of data resources and their quality

The current trend towards more lightweight protocols and data encodings eases the use and integration of technical SDI components. For instance, RESTfull interfaced services require less specialized knowledge for accessing SDI content offerings and for chaining SDI components to deploy scalable applications (Foerster et al, 2011a; Janowicz et al, 2011; Granell et al, 2012; Schade et al, 2012). This will help in coping with the inherent complexity of SDIs and reducing the costs of developing and maintaining SDI applications. Easier and more simple interfaces for spatial services or even data models might have a positive influence in all the requirements since services providing the functionality (publication, discovery, access and processing) might offer more flexible and easy ways not only to be invoked but also to be chained to complete complex workflows (Granell et al, 2012).

Public and private cloud infrastructures provide a means of automating the administration of the basic IT environment as well as SDI tools and applications deployed within this environment. This supports both the easy ad hoc deployment of SDI content offerings and high-end mission-critical solutions. The costs of achieving the level of service performance and reliability needed for the broad acceptance of SDIs will decrease significantly. Public authorities with weak IT infrastructures will be able to purchase infrastructure services tailored to their specific needs, which accelerates the process of deploying SDI content and implement applications on top of them. This trend might also have a positive impact in all the functional requirements since service providers can affordably offer a higher level of service now and spatial organizations can avoid to store and maintain hardware, which can be more efficiently managed in the cloud infrastructure.

Furthermore, the trend of deploying processing capabilities via processing services will increase the availability of functionality and decrease the need to maintain software locally. Cloud services will also support distributed processing capabilities in SDIs. This again, for simple fine-grained functions as well as for complex models, which require exceptional computational power. These processing capabilities will support the development of distributed quality-aware systems, which are capable of describing and handling the uncertainty of the information and the processing algorithms.

The publication requirement will be directly influenced by integrating user-generated content into the realm of SDIs. Web 2.0 describes the shift from a web of documents and users as passive consumers to a broader platform for communication, collaboration and business transactions, which strengthens the role of citizens as SDI stakeholders. Their demand for information and participation underpins the rationale of SDIs and hereby raises related priorities and budgets. Citizens are now able not only to consume but also to publish and contribute content to the information base of SDIs. Enabled through mobile devices, sensors and crowdsourcing platforms, they collect, publish, share and continuously improve information, thus maintaining the SDI up to date. VGI becomes a multidisciplinary and valuable massive source of information at low cost, which complements the existing authoritative data sources in SDIs (Núñez-Redó et al, 2011). The sharing and availability of VGI within SDIs may substantially improve traditional geospatial analysis and decision-support tasks (Flanagin and Metzger, 2008; Pultar et al, 2009; Núñez-Redó et al, 2011). For example, Zook et al (2010) has pointed out that VGI can provide “additional data at levels of granularity and timeliness that could not be matched by other means”. As a result, future SDIs will offer new types of geographic information, namely information including people’s experiences and perceptions. Furthermore, the timeliness of volunteered geographic information could help solve the challenge of real-time geosensor monitoring, as discussed below. Finally, since VGI enables citizens to be at the same time producers and consumers of geographic information, it is to be expected that the challenge of the “lack of awareness or importance of SDIs” identified by Williamson (2004) will no longer be an issue in future SDIs. Some authors (Budhathoki et al, 2008; Omran and van Etten, 2007) have already suggested a new SDI generation, largely influenced by these needs and the reconceptualization of the user role.

In contrast to the early days, when the development of SDIs primarily targeted G2G (Government to Governments) and G2B (Government to Businessess) communication, the changing role of individuals is creating a new set of concerns and priorities, such as improved search capabilities, open access to data, lightweight interfaces and tailored applications with adaptive and contextual user interfaces. This new group of users has its own concerns, which are extremely demanding, in terms of performance, accessibility and usability of information products. Their expectations and demands rise as offerings increase and they respond with increased attention and spending, which spurs on the further development and improvement of SDI capabilities.

Integrating the Sensor Web and the Web of Things (Section 3.5) in future SDIs requires new concepts and methodologies. The Sensor Web is already capable of making the functionality of sensing devices available within SDIs (Bröring et al, 2011). However, the integration of smart things into standardized web service architectures, such as SDIs, might be too costly and complex in practical applications (Mattern and Floerkemeier, 2010). New approaches are needed to combine the Sensor Web technology and Web 2.0 concepts to integrate aspects of the Web of Things with SDI. The technological trend and progress in sensors and mobile devices and the Web of Things might have an influence on SDI development in improving its dynamics and access to higher-resolution spatio-temporal data. However, some questions remain, such as which data (nature and scale) should be considered, which area should be sensed and how to manage dissemination and rights management (Goodchild, 2010).

The linked open data trend has the potential to be a game changer in the field of SDIs. The Web will increasingly be used to encode and interlink different kinds of information, and in turn to harmonize data models and vocabularies on-the-fly. The future web will actually be a composition of webs, where several paradigms are used to represent and process knowledge. From the author’s point of view, new patterns of the Web of Data, for providing and using spatio-temporal information, will complement and partially replace classic SDI patterns. New information resources will be integrated in the SDI by providing simple links, which can be used immediately to access information, and which employ automated crawling mechanisms to update cached views of the data and its metadata. This pattern will widely replace the traditional approach of publishing and registering content through standardized metadata catalogues, which is less flexible and more complex in terms of technical settings and workflows.

These new paradigms will also force the appearance of new and more sophisticated methods to discover and access content. Linked open data technologies will enable users to find data, enriched semantically, and access datasets which implicitly contain their descriptions, coming from different communities and linked together. These methods will allow both humans and machines to navigate through the data layer, by following links to the targeted and most appropriate data items.

One of the direct applications of the Web of Data is to increase the ubiquity of SDIs. Linked data methods facilitate the modeling and integration of information. This way, real world entities or things, can be augmented into “smart things”, being equipped with multiple capabilities, such as sensing, processing, memorizing and communicating spatio-temporal knowledge about their state and their environment. This phenomenon called the Web of Things will connect physical things such as cars, parcels, streets or buildings to SDI components. Smart sensors will be an essential part of SDIs, since they provide real-time access to live geo-information, which is needed to effectively monitor the environment.

5. CONCLUSIONS

The foregoing sections presented an analysis of the current status of SDIs, followed by a description of the main research topics in the field of geoinformatics and trends in mainstream IT. This section aggregates these findings into a set of hypotheses on the future development of SDIs.

5.1. SDIs will Continue to Evolve

On first sight, this hypothesis may seem trivial, but it addresses the recurrent discussion that SDIs may constitute a dead end, due to their complexity and slow development (Béjar et al, 2009; Díaz et al, 2011). Why bother with special SDI arrangements when the Web is already providing its own sophisticated means of sharing and integrating heterogeneous resources. One answer is that SDIs are not only about technology. Agreeing on common policies, standards and organizational structures is essential for bringing these technologies into use, and thus, realizing their potential benefits. The classic definition of SDIs being a set of policies, technologies and institutional arrangements to assist user communities in collecting, sharing and exploiting geospatial information resources (Nebert, 2004; Masser, 2005) still proposes a valid set of requirements and a general means of achieving these goals. Its scope is broad enough to embrace even major shifts in its concepts and implementations.

5.2. SDIs will Benefit from Existing IT-Trends

SDIs are an integral part of the overall Information Infrastructure, driven by experts and stakeholders from the geospatial domain. While the overall II increasingly improves its capabilities in dealing with spatio-temporal information, SDIs will benefit from these developments. This will happen without delay, as far as no SDI specific standards or agreements are affected. The use of Cloud computing for example does not require any changes to SDI policies or institutional arrangements, and is already being increasingly adopted (Schaeffer et al, 2010; Moore and Parsons, 2011; Baranski et al, 2011).

The same is true of the publishing of public sector information, published in SDIs, based on standardized open data licenses, which will immediately result in better accessibility of spatial data for many purposes.

Other advancements, such as the development towards more lightweight interfaces, data formats and protocols, require moderate changes in SDI specific standards, which hinders their immediate adoption. Nevertheless, they can be regarded as low hanging fruit, since they are in line with the core architectural concepts of SDIs.

Emerging trends, like the Web of Data or the Web Of Things, are expected to be significantly adopted in mainstream IT within the next five to ten years (Gartner IT-Trends, 2011[10];). This time is needed both for maturing the concepts and technologies and for growing the installed base. SDIs will contribute to this development, since their goals and requirements are part of the motivation that creates its momentum. The time needed for actually adopting these trends in terms of policies and technological standards depends on the adaptability of SDIs; this will be discussed in the next section.

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[10] http://www.gartner.com/it/page.jsp?id=1454221

5.3. Improving the SDIs’ Adaptability Accelerates their Development

SDIs are not driving mainstream technology, but they are unfolding their use in the geospatial domain by settling common policies, standards and institutional arrangements within certain user communities. As outlined in Section 2, this leads to a lower pace of development compared with mainstream IT.

Referring to the design principles for information infrastructures proposed by Hanseth and Lyytinen (2010), the adaptability of SDIs should be improved by employing certain strategies. The most important of these is to create choices, rather than to strictly define one stack of standards, which fixes the finest details of SDI building blocks. Choices represent degrees of freedom, and these will be used to implement variants, which have to prove their benefits in practice. The “survival of the fittest” principle will guide their further evolution, which will be more closely aligned with the development of the Geospatial Web.

5.4. Usability is the Key Driver for Leveraging the Installed Base

As stated in the first section, SDIs currently do not completely fulfill users' expectations. Often, users are not able to find offerings which meet their requirements, while existing offerings are underutilized. As a consequence, SDIs are not sufficiently attracting users to invest their effort and participate in the maintenance of the SDI and its content. A strong focus on an SDI’s usability, both for providers and consumers of spatial information resources, would create significant momentum for self-reinforcing growth.

Referring to the set of requirements outlined in Section 4.1, an action plan for improving SDI usability, heading for short- and midterm improvements, should address the following aspects:

5.4.1. Easing the publishing and discovery of information resources

This may be achieved by providing users with mechanisms to facilitate the interaction and maintenance of the deployed resources (Díaz and Schade, 2011); these mechanisms should assist users in making web services first class resources of the web, following the linked data approach. This means providing a URI, which primarily identifies the web service, and links to both the service URL and to a richer service description, for instance using RDF encoded descriptions of the resource. Publishing would mean rendering the service plus its content and metadata accessible online, and placing some links in already-existing information resources. These do not have to be, but can be, dedicated SDI registries. This concept would enable search engines to automatically collect the metadata which is needed to enable potential users to find information resources of any kind.

Since linked data provides a universal model for encoding data and metadata and for seamlessly integrating data models, this would significantly ease the integration of meta-information resources. Furthermore, it might be more attractive for commercial search engines to index geospatial content, since the resource provides human readable information.

5.4.2. Improve the accessibility of geospatial data and services

A first step should be to foster the provision of open data, since to do so would dramatically reduce transaction costs. Providers of information resources would be capable of simplifying their internal processes and technical setups. On the user side, this would enable further usages and significantly reduce the effort expended on evaluating, negotiating and contracting access conditions.

A second step should be to foster the integration of more simple service interfaces and data formats (such a REST-based interface) into SDI standards. This would reduce the cost of integrating and chaining information resources into various applications (Granell et al, 2012).

In the long run, more and more information resources should be provided in line with linked open-data methods, in which content and description are published in an integrated manner, thus increasing linkage to related resources and facilitating the navigation and discovery of the target resources. This would reduce the costs of integrating data from various sources and lead to a self-reinforcing process of harmonizing data models.

5.4.3. Improving the performance and reliability of GI services

Cloud computing should increasingly penetrate SDI environments, thus providing information resources at a high quality of service. The effect will be comparable to the effect that increasing bandwidth has on the usability of the web.

As far as information resources can be offered as open data, public commercial platforms can be used to serve data redundantly, which further increases availability and shares the costs of providing access to these resources.

5.4.4. Supporting the development of user-driven applications

The key to a broader offering of user-driven applications, which are tailored to the user's needs, is to cultivate an agile ecosystem of developers around SDIs. This can be achieved by easing access to high-quality information resources. Furthermore it should be leveraged by fostering the provision of raw data, which provides more degrees of freedom for software developers than interpreted data or map services.

Leveraging this agile ecosystem will in fact support a more user-oriented SDI, since it will accelerate the matching of demand and supply regarding the user's requirements and SDI resources.

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