Airborne Laser Remote Sensing Technology: Providing Essential Hydrologic Information in the 21st Century

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Key words: Hydrology, development, remote sensing, lasers, drainage basins, models, elevation data, mapping.

SUMMARY

Water is a cornerstone of development. With the apparent changes in climate, interest in water is growing. Hydrology is the science of the properties of the earth's water, especially its movement in relation to land. Understanding the hydrological cycle has long been a topic of interest for a number of reasons, including the need to understand water availability for human and livestock consumption, hydro-electric generation, irrigation, and industrial use. A key element of this understanding is the modeling of the hydrology of an area to better predict the availability of water at various locations in a river basin or catchment area, and water-related disasters such as floods and landslides. The building block or reporting base of a hydrological model is the river drainage basin or catchment area.

Hydrologic models are derived from information on land use or land cover (including wetlands), soil moisture, soil type (including permeability of the surface to predict water retention and run-off), stream flow, rainfall amount/intensity, local climate (including evaporation rates), digital elevation model (DEM) data, snow fall, snow density, etc. As in many other areas of scientific activity, there is an increased interest in and a capability to obtain more accurate inputs for models. The complexity of topography and land use in many areas requires high spatial resolution data over very large areas. It is clear that much of this information can only be provided by remote sensing systems. However, until recently remote sensing was not widely accepted and adopted. Part of this is a function of awareness, especially of newer systems. This paper is aimed at creating more awareness.

This paper will summarize the key hydrologic questions and variables available from remote sensing, with emphasis on the value provided by laser technology. More specifically, the paper will use operational examples to examine and demonstrate the value of new airborne laser sensing systems in providing seamless DEMs, their ability to penetrate vegetation, and their relative accuracy.

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1. INTRODUCTION

Water is one of the cornerstones of development, whether in Africa or elsewhere. With the apparent changes in climate and the growing problems associated with access to sufficient quantities of water on the one hand, and flooding and slope instability following torrential rains and changing weather patterns on the other, as well as the growing challenge of salinity, political and scientific interest in water is growing. (See http://www.ec.gc.ca/water/en/info/facts/e_contnt.htm the web site of Environment Canada, as well as the web sites of the FAO’s Land and water Development Division http://www.fao.org/ag/agl/default.stm or go to the UNDP’s Millennium Goal web page http://www.unmillenniumproject.org/reports/index.htm and search on the keyword “water”.)

This paper first examines the background to the study of water, including some of the central technical and informational challenges being faced in that study. It then discusses the remote sensing technologies now being examined and used, and closes with a detailed assessment of the important role airborne lidar (laser) technologies can play in addressing this critical issue.

2. THE CONTEXT FOR HYDROLOGY-DRIVEN GEOSPATIAL INFORMATION NEEDS

Recent analyses suggest that while water is one of the most common substances in the universe, as much as 97% of the world’s water supply, including that in the oceans, is too salty for man’s needs (Gleick, 2001). Of the remaining 35 million km^3 of fresh water, 24.4 million km^3 is in glaciers and ice, 0.102 km^3 in lakes, wetlands, and rivers, and 10.7 km^3 is estimated to be in ground water and soil moisture (Environment Canada, 2004). One of the largest and least efficient uses of water is crop irrigation which is responsible for the production of 40% of the world’s food supply. Feeding the world’s growing population will require even more irrigation – irrigation that must come from a water supply that is under threat almost everywhere (Postel, 2001). With this information as its basis, it is no wonder that the study of ground water, lakes, and rivers has taken on special importance.

Hydrology, the science of the properties of the earth’s water, especially its movement in relation to land, is said to have begun with the French pioneer Darcy in the 1850s with a report on water for the city of Dijon that characterized the subsurface flow of water through sand. In 1885, the USGS published T.C. Chamberlin's classic paper titled: "The Requisite and Qualifying Conditions of Artesian Wells" as its first report on ground water. The interest and emphasis on subsurface water had begun.

In 2002 Philips noted that "eighty years ago, pioneers … defined the region below the land surface as the new frontier of hydrogeology, but in the intervening decades, that definition has sometimes tended to turn into an intellectual prison" – the surface and its importance has often been ignored. He went on to state that "it is the land surface that is the interface that supports plants, and, in fact, most life, but we have tended to ignore that messy zone filled with roots and worms and focus on "cleaner" problems of physics and chemistry at depth. This has ultimately had the effect of distancing us from the more urgent scientific and practical problems of the present day." This realization has come at the same time as advanced remote sensing technologies make the study of the "messy" surface both possible and more complete than the early pioneers would ever have imagined.

Sophocleous (2004) in the title of his paper asks the question: "Climate change: why should water professionals care?" He then answers it by noting that "climate change will significantly impact the hydrologic cycle. A hotter climate will cause more evapotranspiration, resulting in greater amounts of moisture in the air and an increased rainfall and frequency of heavy rainfall events. Floods and droughts will likely be more severe, making future water management even more difficult." He further discusses the significant impact in more northern climates, as well as global rises in sea levels, affecting coastal aquifers. He states that "recent estimates suggest that climate change will account for ~20% of the projected increases in water scarcity." He concludes that "because climate change adds further risks and uncertainties to the management of water resources, water users and managers need to adopt integrated and adaptive management approaches based on monitoring and performance evaluation. Clearly, climate change … can also serve as a catalyst toward greater flexibility and innovation in the way we manage our water resources."

Tracking climate-change induced shifts in water availability and their impacts is an area that has long been well suited to the use of remote sensing (LeDrew et al, 1995). Recently a major climate-change related study on coastal elevations in Maryland acquired lidar airborne remote sensing data to obtain precise elevation information (See www.airborne1.com). As one seeks to better manage water resources, a critical factor will be accurate models and measurements based on better information. For example, as soil salinity becomes an increasingly serious problem associated with water movement in the soil, much better and more accurate elevation information will be required to model, understand, and combat soil salinity. This too suggests a role for the more sophisticated of the spaceborne and airborne remote sensors now available, such as the lidar used in Maryland and elsewhere.

In addition to the immediate impacts of water availability and climate-change impacts is the matter of disease related to water. Environment Canada (http://www.ec.gc.ca/water/en/info/facts/e_contnt.htm) reports that in developing countries, 80% of illnesses are water-related. Preventable water-related diseases kill an estimated 10,000 to 20,000 children every day (Postel, 2001). Some of these diseases are zoonotic – moving from insects or animals to humans (two such diseases frequently discussed in the media are malaria and avian influenza) and are often associated with specific types of drainage or wetlands.

Remote sensing has been suggested as a useful tool in predicting where the impacts of disease or its prevalence may be greatest. Required is information on subtle changes in drainage and precise elevation information related to standing water (Kaya et al, 2002; Kaya et al, 2004). Recently there has been interest among the veterinarian community in bringing together remote sensing and geospatial information in a GIS to contribute to an improved understanding, tracking and control of zoonotic diseases (Ryerson et al, 2004).

The need to better understand water and improve the measurements associated with it has exploded with the growing interest in climate change, water-related disease, scarcity of water and water-related disasters, and with the need to understand water availability for human and livestock consumption, hydro-electric generation, irrigation, and industrial use. There has also been a growing realization that harnessing water using traditional means, such as dams, does not always create benefits – in many cases they bring environmental and social problems (see Postel, 2001 for a more thorough discussion).

Water has often been the source of conflict, whether local or regional (Mathews, 2005). Some have predicted that future wars will be fought over water. Glieck (2001) has detailed a number of conflicts over water from historical times to the present. Matthews (2005) suggests that one of the major issues in trans-boundary disputes is related to definitions and water rights. It would appear that to solve such problems one requires accurate measurements and modelling of the hydrology as one crosses boundaries. Others note that conserving water and sharing resources on an equitable basis will reduce conflict. While there are many examples of how one can conserve and re-use water more efficiently (Martindale and Glieck, 2001), some of which use advanced monitoring technologies such as remote sensing, there will still be increasing demands for water. The need to predict and mitigate the availability (or lack of availability) of water has therefore resulted in a growing interest in understanding and thus accurately modelling the hydrological cycle at both the local and regional levels – the catchment area and drainage basin - the building blocks or reporting bases of a hydrological model.

A large number of hydrologic models have been developed and are well documented in literature, including in the journal ***Ground Water.*** These models are typically driven by information on land use or land cover (including wetlands), soil moisture, soil type (including permeability of the surface to predict water retention and run-off), stream flow, rainfall amount/intensity, local climate (including evaporation rates), digital elevation model (DEM) data, snow fall, snow density, etc. (See Scofield and Pultz 2002; and Jobin and Pultz for summaries that relate these models to remote sensing). Garbrecht and Martz (1999) note that DEMs provide an efficient way to represent ground surface and with them one can automatically, accurately and cost-effectively extract a number of hydrological features. This leads to clear advantages compared with traditional methods based on topographic maps, field surveys, or interpretation of aerial photographs. The creation of accurate DEMs is thus an important contribution to hydrology.

Tsang (2005) suggests that one of the key points of focus in hydrogeology is that of making long-term predictions to address the societal needs for information on water. The predictions require working, practical models. In a recent editorial on ground water, Halford (2004) notes that for some time hydrologic models were “limited alternately by analytical tools and by field measurements.” The limits imposed by analytic tools decreased 10 years ago as models became more sophisticated with greater reliance on advanced computational methods and numerical approaches. However, now he maintains that “measurement and data limitations currently constrain hydrogeologic understanding even as model complexity increases.” He concludes that “hydrogeologic understanding is limited currently by field measurements, not by a lack of models.”

With this as context Table 1 below provides a summary outline of geospatially-related information needs in hydrology.

Table 1: Geospatially-Related Information Needs in the Hydrology Context: Modeling, Floods, and Water Management[1]

- **Flooding**
- Before flooding, identification of flood risk – in the USA, Flood Insurance Risk Zones (see FEMA web site).
- Information needed shortly after the flooding event: What has happened? Where has it happened? What has been the impact of the event? Traditional methods of information collection and collation cannot always provide this. The traditional method of gathering information on the ground and communicating upwards is really not suitable during and immediately after a disaster. It is time consuming and tends to lead to micro-management.
- Flood river control in flatter areas need elevation data at 3.5 to 15 cm – will the dike be breeched or not, is the area flooded or not and thus municipalities need accurate detailed maps of elevation – elevation equates to risk…and risk to cost of insurance and damage claims.
- Five meter (or even 2 meter) contours are not very useful in flood risk assessment or planning – one small low spot a meter wide on a road could allow water to wash over the road and flood a low-lying area adjacent to a river
- Information must be accessible in the field at the time of the flood – sophisticated information systems may be neither necessary nor useful
- Need 10 cm vertical for storm surges; 10 cm to 3 meters depending on local conditions. (See FEMA web site for further details in the USA.)
- The same (or at least interoperable) information
- Comparison of post to pre-flood baseline integrated data.
- **Modeling**
- DEM data at 10 to 15 cm or better for the most demanding accuracy related to many needs, including salinity
- Land use or land cover information (including wetlands).
- Soil moisture and soil type (including permeability of the surface to predict water retention and run-off).
- Rainfall amount/intensity, local climate (including evaporation rates), snow fall, snow density, snow coverage under trees, stream-flow rates etc.
- **Management and General Needs**
- Need information across the catchment or drainage basins entire area – not just point samples or contours drawn on a map.
- Data and information fused so that visualization of the model/flood/catchment area can take place.
- Accurate water volume in reservoirs
- Location of concentrations of livestock related to stream courses and ground-water recharge areas.
- Location of construction and other sources of sediment.
- Changes in glaciers and snow pack.
- Location of sites for water harvesting (often relates to surface permeability and geological structure as well as highly accurate DEMs)
- Need versatile multipurpose data sources to meet multiple needs

for all areas affected by the flood are required. (This implies coordination far beyond today's norm, including across borders).	– Need faster data collection and quicker turn around for floods and water management
[1] The information in this table has been drawn from many sources including a number of the workshops, symposia, and papers cited in the references, as well as from files of commercial projects done by companies in Italy, Australia, New Zealand, USA and Canada. The USA's Federal Emergency Management Agency (FEMA) website on flood hazard mapping http://www.fema.gov/fhm/gs_main.shtm contains far more information on mapping standards and requirements than can be summarized here.	

As called for by Sophocleous (2004), and others cited above, it is clear that improved data are required that go beyond the traditional data collection approaches used in hydrology. It is within this setting that remote sensing enters the discussion as a source for at least some of the critical information needed in both sophisticated models as well as for practical monitoring and on-going analysis.

4. REMOTE SENSING

Miller and Gray (2002) argued that the hydrogeological community is "critically lacking in the new ideas and experimental tools needed to produce a mature level of understanding of the field." We believe that remote sensing is now in a position to provide many of the needed tools to open up a new window on hydrology.

The use of what we would call traditional[1] remote sensing in hydrology is well documented. ***The Manual of Remote Sensing*** (2nd Edition) published in 1983 had a 73- page chapter on Water Resources Assessment (Salomonson, 1983). The chapter which documented remote sensing in its infancy in hydrology included some 200 references. Since then the amount, sophistication, and importance of that use has increased dramatically. The Third Edition of ***The Manual of Remote Sensing*** (Henderson and Lewis, 1998) has 60 pages on radar applications alone. The report prepared by the Committee on Earth Observing Satellites Disaster Management Support Group (Scofield and Pultz, 2002) with a focus on floods and hydrology, provides further analysis of the information requirements of hydrology and what remote sensing tools can provide what data. What appears to be lacking in the technical literature is detail on airborne lidar or laser systems applied to hydrology. This aspect is specifically addressed in Section 5 below.

Scofield and Pultz (2002) note that "hydrologic models require several types of data as input such as land use, soil type, soil moisture, stream/river base flow, rainfall amount/intensity, snow pack characterization, digital elevation model (DEM) data, and static data such as drainage basin size. Complex terrain and land utilization in many areas result in a requirement for very high spatial resolution data over very large areas which can only be practically obtained by remote sensing systems." Indeed, several hydrologic models have been developed for use with remote sensing data. (Jobin and Pultz, 1996.)

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[1] We are defining traditional as those sensors and systems that have been in wide use for many years: aerial photography, as well as meteorological, radar, multispectral, and high resolution panchromatic satellites.

Scofield and Pultz (2002) have summarized (especially related to floods but also relevant to more general hydrological applications) what data type is required at what temporal and spatial resolution. They then show which data are available from which remote sensing system. These range from generally low resolution operational meteorological satellites to higher resolution data from the earth resources satellites such as RADARSAT and SPOT. Those uses depending upon the lower resolution meteorological satellites tend to be better developed than those dealing with land-related information. While both areas remain, as noted by Halford (2004), constrained by lack of good field information, the focus here is on the finer detailed information associated with the surface of the land, and to a lesser extent, water. It is also important to note that as the specific requirement for information within the general field of hydrology changes, so too will the type and accuracy of information change.

Scofield and Pultz (2002) have identified the minimum (or what they call threshold) and optimum image type, spatial, and temporal characteristics of remotely sensed data for several key variables. While these are discussed in the flood context, they may also provide a useful guide for hydrology in the general sense[2]. For land use information they recommend a minimum of 30 meter multispectral scanner data, with an optimum of 4-5 meters. Such data are required at a minimum of every one to three years, and ideally every six months. For vegetation data they recommend either multispectral or hyperspectral data with a minimum spatial resolution of 250 meters and optimum of 30 meters, acquired every one to three months. Chalifoux et al (2005) have suggested that Landsat TM and ETM data are useful for the characterisation and management of underground water resources. However, for more detailed modeling and site specific studies, such spatial resolution appears to be lower than has been suggested as a requirement for studies involving specific local aquifers, environmental contamination, and the like. For these, imagery at a scale of 1;60,000 or larger has been suggested (Mace, 1997).

Another important factor in hydrology is ground water recharge. Khurshid et al (2005) used a leaf area index (LAI) map as an input into a groundwater recharge assessment model in order to find its sensitivity to final water budgets. Based on a study in the Chateauguay region of Quebec (south of Montreal), Fernandes (2005) has also suggested that the degree to which the recharge region is forest covered will impact the amount of water recharged into the ground water system – "more trees = less recharge." For that reason, reforestation may not necessarily be a good thing for ground water recharge, and the ability to measure the height and extent of forest cover may be more important than has previously been understood to be the case.

Scofield and Pultz (2002) also suggest that DEMs (i.e. elevation information) are required pre and post-flood at a minimum of 1-3 meters, and ideally at 10-15 centimetres. Such data are required on a periodicity ranging from months to one to three years. Obviously the frequency will depend on the extent of local changes. It would also appear that detailed DEM information is also required for more complete and sophisticated hydrologic models and water management. Clearly the digital elevation information is not available at the more

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[2] Personal Communication, T. Pultz, December, 2005.

detailed level from satellite systems, nor can one expect to obtain such information on a wall-to-wall or total coverage basis from aerial photography.

The only practical source today for elevation data with the required accuracy, especially when combined with the requirement for multispectral or hyperspectral information and details on forest cover (including tree size), is airborne lidar combined with multispectral or hyperspectral information. The potential importance of lidar combined with the relative lack of information on its use in hydrology leads to the next section.

5. LIDAR: AN INDISPENSABLE TOOL IN HYDROLOGY

Lidar data combined with other information such as multispectral or hyperspectral imagery has been suggested for a wide range of applications including many related to hydrology. While there is considerable detail on operational use, there is a limited amount of accessible scientific and technical literature published on such use. Indeed, there have been studies conducted in the United States as to why lidar (as well as some other remote sensing data) have not been as widely used as one might expect given the value of the technology (Steering Committee on Space Applications and Commercialization, 2003).

One problem is that the use of lidar is not well documented in scientific literature, and another is that many who might use the data have historically used other data sources or have not received appropriate information on the value of lidar information. It may well be that those using it are like the official in Canada who many years ago said that they were not writing up technical papers on the subject of a specific remote sensing technology since they were "too busy using it" (Ryerson et al, 1979).

One of the goals of this paper is to help explain lidar in the context of information needs in hydrology. The fact that just one commercial website documents as many as 20 applications of lidar in hydrology (see www.airborne1.com) lends some credence to the value of the technology in water studies. There is also well documented use of the technology in more technical publications such as ***GIM International*** and ***Position Magazine***. Perhaps the clearest support for lidar in the hydrology applications context comes from the USA Federal Emergency Management Agency (FEMA) which has provided detailed specifications for the use of lidar data for mapping associated with floods. The general guidelines from that site provide a useful and unbiased introduction (see FEMA: http://www.fema.gov/fhm/lidar_4b.shtm).

The concerns expressed by Halford (2004) on the need for improved field measurements are now beginning to be answered by advanced airborne lidar systems. Airborne lidars bring the ability to rapidly produce a number of the data sets noted in previous sections as useful in hydrology. Furthermore, one might argue that lidar has more versatility and offers efficiencies such as faster data acquisition and turnaround of data. Lidar can not only produce the dense DEMs for the area of interest but also provide the series of cross sections often required by the more traditional methods of hydrological modeling. The efficiencies and versatility together explain the broad commercial interest that has developed. Lidar derived elevation data can be used for preparations for flood defence, river management, soil salinity studies, catchment management, and beach erosion. Lidars can also contribute thematic information related to surface roughness/vegetation assessments, changes in glaciers, and snow pack assessments.

In Italy, elevation data derived from lidar have been acquired for hydrologic modeling and flood control along a number of rivers with high flood potential. High-density, accurate information (3.5 cm) is required close to the river, while less dense and lower accuracy (15 cm) information can be used further away. Generally, orthophotography is required along with other data sets to capture information (for example, on forest cover) for input into the models. (Hadley and Ryerson, 2006)

Töyrä et al (2003) conclude that “the lidar DEM provided useful topographic detail in a resolution and accuracy that is acceptable for many hydrologic purposes”. Lidar data can also be used to overlay accurate DEMs on a variety of other imagery for large areas. Lidar data have been collected to help create the base map for general hydrologic studies over a number of counties in California and other states, in Panama, Canada, and many other countries where advanced lidars have been flown with vertical accuracies similar to those cited in the Italian study above - from a few centimetres to 30 centimetres as required. (The Optech lidar systems have acquired data in over 80 countries.)

Other hydrology-related applications have seen lidar data collected at 0.8 meter average. Posting for hydrologic and channel morphology research in Maryland and collected data over river-corridors in the planning of the Nacimiento Water Pipeline in California. In Ventura County, California over 700 square miles of high-resolution (18.5 cm, 30 cm horizontal) lidar data was collected for floodplain and sediment transfer studies in the Ventura, Santa Clara, and Calleguas River basins and surrounding areas.

All of Ventura County was overflown with a lidar system in early 2005. Seven hundred and forty square miles of lidar data was collected. Deliverables included a DEM of bare ground as well as extracted features. The output of the study was used for floodplain mapping and sediment transfer modeling in the river corridors for emergency planning. It was spurred on by the heavy rains in the area in early 2005 resulting in the La Conchita mudslides. Airborne 1 Corporation was responsible for the lidar data collection and processing to a bare earth surface. Data was high resolution with a spot spacing of no more than 1 meter and was suitable for mapping up to a 1 foot contour interval.

Liu et al (2005) note that soil salinity is influenced by a number of factors. One of the most important factors for salinity risk prediction is related to local elevation. They found that salinity risk prediction is less successful and typically overestimated when using a relatively low accuracy and low resolution DEM such as is commonly available. This is so because the terrain surface was flattened by derived slopes, and drainage conditions and densities were inaccurately calculated. Their results demonstrated that lidar is a “powerful tool to generate high accuracy and high resolution DEMs. Terrain and hydrological attributes derived from the lidar DEM significantly improved the salinity risk prediction."

In a flood-related project in Camden and Burlington Counties, New Jersey (USA) 1,050 square miles of lidar were collected by Airborne 1. In July 2004, southern New Jersey received 13 inches of rain in less than 24 hours. This event resulted in significant localized flooding in the two counties. Exacerbating the flooding caused by runoff was the failure of 12 dams and the partial breach of five more in Burlington County. There was an identified need to perform a riverine hydrologic and hydraulics analysis for these areas and lidar data was judged to be ideal for the purpose. Data was standard resolution with a spot spacing of no more than 1.4 meters and met FEMA specs for mapping up to a 2 foot contour interval.

Sixty-five miles of the Los Angeles River in the city of the same name was flown with a lidar on behalf of the Army Corps of Engineers for planning and mapping existing dams. Over 2500 square miles of Maryland were flown with a lidar in support of a sea-level rise project and for flood plain mapping[3]. These applications demonstrate a level of accuracy and quantity of detail across a range of needs that cannot be realized with more traditional remote sensing and photogrammetric approaches. With lidar, for example, one obtains not just a single profile of a basin acquired some distance apart, but rather a complete and accurate model of the river basin.

While traditional uses alone suggest that lidar data can play an important role in hydrology, what is more exciting are the opportunities that come with new applications that go beyond the traditional role of remote sensing in hydrology. For example, given the close inter-relationship between forest cover and hydrology, it is also useful to note that one can separate forested areas from non-forested while at the same time determining the height of the trees. Hopkinson et al (2004) have demonstrated that lidar data can be used for accurate snow depth mapping beneath different forest canopy covers (deciduous, coniferous, and mixed) by subtracting a "bare-earth" DEM from a "peak snow pack" DEM. Such snow depth estimates are most accurate in areas of minimal under-story. DEMs can also be made and data collection can be done across borders with lidars, to reduce the issues identified by Matthews (2005) that might arise from different mapping systems being used from one country to another in a shared drainage basin. Just as Zheng (2004) has found that 3D visualization underground is a very useful tool for studying and understanding groundwater, lidar can provide another useful data set by providing the ability to do the same for above the ground at both the basin and catchment level. Liu et al (2005) demonstrated that a lidar-derived DEM with high accuracy and high resolution offers the capability of improving the quality of hydrological features extracted from DEMs, especially when compared to traditional methods typically considered to be accurate topographic information, such as were available in the state of Victoria, Australia.

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[3] These are documented on the site www.airborne1.com; all used an Optech ALTM Lidar mapping System

Table 2 below brings together the demonstrated applications of lidar with the needs in Table 1, as well as some of those future needs that many in the hydrology community may not have yet recognized given the newness of lidar's use in the field.

As the use of lidar grows and as more hydrologists come to understand lidar data, it can be expected that the number and range of applications will grow dramatically from those traditional areas noted above, and the few new ones suggested here. If lidar is not yet seen as an indispensable tool in hydrology, it soon will be.

Table 2: Information Requirements Related to Hydrology Met With Lidar Data

- **Flooding**
- Provision of elevation information related to the identification of flood risk – in the USA, Flood Insurance Risk Zones (see FEMA web site).
- Provision of information needed shortly after the flooding event: What has happened? Where has it happened?
- Flood river control digital elevation model (DEM) data from 3.5 to 15 cm to reduce risk and cost of insurance and damage claims.
- Provision of information rapidly in the field at the time of the flood
- Comparison of post to pre flood baseline integrated data.
- Provision of 10 cm vertical for storm surges; and 10 cm to 3 meter elevation data depending on local conditions. (See FEMA web site for further details in the USA.)
- **Modeling**
- Lidar routinely combined with other sensors such as multispectral, digital cameras, or hyperspectral provides land cover and land use information draped on a DEM
- DEM data at 10 to 15 cm
- Accurate wall-to-wall stream profiles
- **Management and General Needs**
- Accurate wall-to-wall DEMs across the catchment or drainage basin's entire area – not just point samples or contours drawn on a map.
- Highly accurate DEMs for soil salinity risk prediction.
- Data and information fused so that visualization of the model/flood/catchment area can take place.
- Accurate water volume in reservoirs
- Location of buildings housing livestock related to stream courses and ground-water recharge areas.
- Location of construction and other sources of sediment (using other sensors combined with Lidar).
- Changes in glaciers and snow pack.
- Snow pack estimation under a forest canopy
- Multiple needs can be met by one multipurpose data source.
- Faster data collection and quicker turn around for floods and water management

[1] The information in this table has been drawn from many sources including a number of the workshops, symposia, and papers cited in the references, as well as from files of commercial projects done by companies in Italy, Australia, New Zealand, USA and Canada. The USA's Federal Emergency Management Agency (FEMA) website on flood hazard mapping http://www.fema.gov/fhm/gs_main.shtm contains far more information on mapping standards and requirements than can be summarized here.

6. CONCLUSION

We have reviewed the key information issues and needs in hydrology and summarized the key hydrologic questions and variables available from remote sensing, with emphasis on the significant value-added provided by laser technology.

Based on our analysis of hydrology literature and recent operational results of the use of lidars detailed here, lidar would appear to be a new tool that will truly change in a fundamental way how hydrologists do their work in the 21st century. They provide fast, accurate and seamless DEMs, and other useful and multipurpose information. They can penetrate vegetation, and when used with other systems, can produce thematic information that is critical in hydrology. The fact that lidars have enjoyed commercial success and government agency approval are further indications that users are increasingly recognizing the versatility and efficiency of this technology over a number of other methods, including some of the more traditional remote sensing and photogrammetric methods.

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REFERENCES

Chamberlin, T.C. (1885) "The Requisite and Qualifying Conditions of Artesian Wells" United States Geological Survey Report. Washington.

Chalifoux, S., et al (2005) "La télédétection en hydrogéologie, vers une approche intégrée" *12ème Congrès de l'Association Québecoise de Télédétection*.

Fernandes, R. (2005) "Development and Transfer of earth Observation Technologies for Groundwater Assessment" *Earth Info Days***,** Canadian Space Agency, St. Hubert, Quebec. December 12-14, 2005.

Garbrecht, J. and Martz, L. W. (1999) "Digital Elevation Model Issues In Water Resources Modeling" *19th ESRI International User Conference,* Environmental Systems Research Institute, Redlands, California.

Gleick, P.H. (2001) "Special Report: Safeguarding Our Water/Making Every Drop Count" *Scientific American* 284 (2).

Hadley, W. and R.A. Ryerson *(2006)* Disasters: Highlighting the Need for Improved Geospatial Information

Halford, K.J. (2004) "More data required" (Editorial) *Ground Water* 42 (4) (July-August 2004): 477.

Hopkinson, C., M. Sitar, L. Chasmer, and P. Treitz (2004) "Mapping Snowpack Depth Beneath Forest Canopies Using Airborne Lidar" *Photogrammetric Engineering & Remote Sensing* Vol. 70, No. 3, March 2004, pp. 323–330.

Jobin, D.I., and T.J. Pultz (1996) "Assessment of three distributed hydrological models for use with remotely sensed inputs" *Third International Workshop on Applications of Remote Sensing in Hydrology* Greenbelt, MD, October 16-18, 100-130.

Kaya, S. et al (2004) "Monitoring Environmental Indicators of Vector-borne Disease from Space: A New Opportunity for RADARSAT-2" *Canadian Journal of Remote Sensing* 30 (3), 560-565.

Kaya, S. et al (2002) “The Use of Radar Remote Sensing for Identifying Environmental Factors Associated with Malaria Risk in Coastal Kenya” *IGARSS 2002*, Toronto, Canada, June 24-28.

Khurshid, S. K. et al (2005) “Producing and Integrating Regional Leaf Area Index (LAI) Maps into Groundwater Recharge Assessment Models” *26th Canadian Symposium on Remote Sensing*. Wolfville, Nova Scotia, Canada. June 14-16, 2005

LeDrew, E. et al *The Canadian Contribution to the Understanding Global* Change Department of Geography Publication Series No. 38, Waterloo, Ontario, Canada.

Liu, X., et al (2005a) “High-Resolution DEM Generated from LiDAR Data for

Water Resource Management” In Zerger, A. and Argent, R.M. (eds) *MODSIM 2005 International Congress on Modelling and Simulation.* Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 170-176. ISBN: 0-9758400-2-9. http://www.mssanz.org.au/modsim05/papers/ascough_1.pdf

Liu, X., et al (2005) “Improving Soil Salinity Prediction with High Resolution DEM derived from LiDAR Data” *The 9th International Symposium on Physical Measurements and Signatures in Remote Sensing*, Bejing, China 17-19 October, 2005.

Mace, T. (1997) (Editor) “Environmental Monitoring” Chapter 17 in W. Philipson (ed.) *Manual of Photographic Interpretation* (2nd Ed.) American Society for Photogrammetry and Remote Sensing. Bethesda, MD. 591-612.

Martindale, D. and P. H. Gleick (2001) “Special Report: Safeguarding Our Water/How We Can Do It” *Scientific American* 284 (2).

Matthews, O.P. (2005) “Ground Water Rights, Spatial Variation, and Transboundary Conflicts” *Ground Water* 43 (5) (Sept-Oct 2005): 691.

Miller, C.T. and W.G. Gray (2002) “Hydrogeological research: just getting started” (Issue Paper). *Ground Water* 40.3 (May 2002): 224

Phillips, F.M. (2002) “Hydrogeology: time for a new beginning?” (Editorial). *Ground Water* 40.3 (May 2002): p217 (1).

Postel, Sandra (2001) “Growing more Food with less Water” *Scientific American* 284 (2), 46-49.

Ryerson, R.A., S. Kaya and D. Gregory (2004) “The Application of Remote Sensing for Human and Animal Health” Invited Keynote Paper *GISVET International Conference* Guelph, Ontario, Canada. 21-25 June 2004.

Ryerson, R.A. and R.J. Batterham (2000) “An Approach to the Development of a Sustainable National Geomatics Infrastructure” *Photogrammetric Engineering and Remote Sensing* (66) No. 1. Pp 17-28.

Ryerson, R.A. et al (1979) "Three Tests of Agricultural Remote Sensing in Eastern Canada: Results, Problems and Prospects" Canadian Journal of Remote Sensing 5 (1) May 1979. pp 53-66.

Scofield, R.A. and T. Pultz (2002) “The Use of Earth Observing Satellites for Hazard Support: Assessments and Scenarios” (2002). *Final Report of the CEOS Disaster Management Support Group.* Published by NOAA, Department of Commerce, USA.

Steering Committee on Space Applications and Commercialization (2003) *Using Remote Sensing in State and Local Government Information for Management and Decision Making*

Space Studies Board, Division on Engineering and Physical Sciences, National Academy of Sciences, Washington.

Sophocleous, M. (2004) “Climate change: why should water professionals care?” (Editorial). *Ground Water* 42.5 (Sept-Oct): p637 (1).

Töyrä, J., A. Pietroniro, C. Hopkinson, and W. Kalbfleisch (2003) “Assessment of airborne scanning laser altimetry (lidar) in a deltaic wetland environment” *Can. J. Remote Sensing*, Vol. 29, No. 6, pp. 718–728.

Tsang, C-F. (2005) “Is current hydrogeologic research addressing long-term predictions?” *Ground Water* 43 (3) (May-June 2005): 296.

Zheng, C. (2004) “Model Viewer: a three-dimensional visualization tool for ground water modellers” (Software Spotlight Article) *Ground Water* 42 (2) (March-April 2004): 164

http://www.ec.gc.ca/water/en/info/facts/e_contnt.htm Source for slide show and facts © 2004 Environment Canada

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