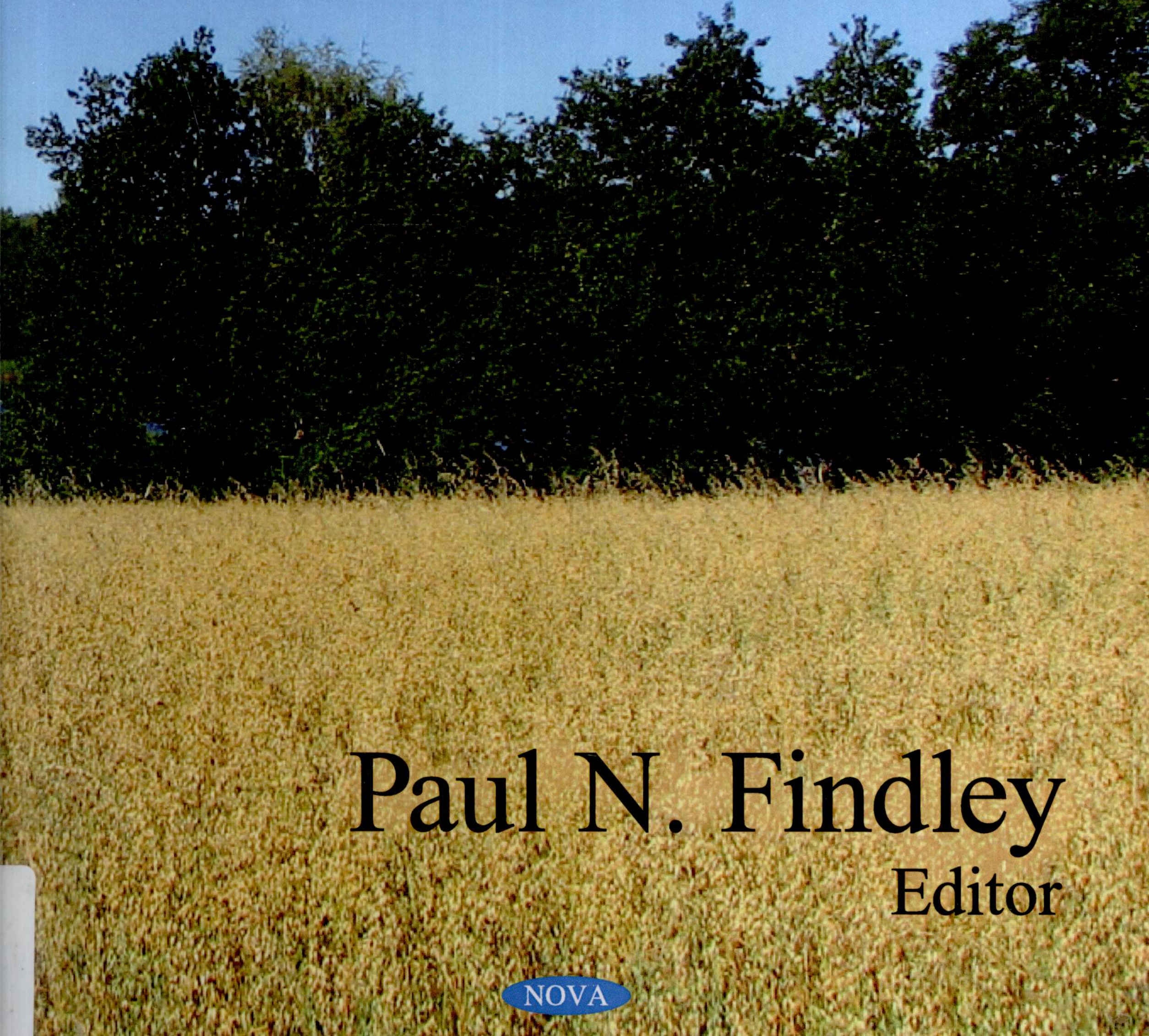
ENVIRONMENTAL MODELLING

New Research



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ENVIRONMENTAL MODELLING: NEW RESEARCH

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PREFACE

Environment models seek to re-create what occurs during some event in nature. It is much easier and practical to create computer models to run certain experiments than it is to go out and do the same experiment again and again. Computer models take equations which were usually formulated through testing under natural conditions, and put them into computer programs where they can be run quickly and easily. A model can then output the results of doing these equations into a form which can be output to a screen for the user to view. The aim is to improve the capacity to represent, understand, predict or manage the behaviour of environmental systems at all practical scales. This new book presents the latest research from around the globe.

As presented in the Expert Commentary, in recent decades, digitally georeferenced data and Geographic Information Systems (GIS) have played a growing role in human exposure assessment for environmental epidemiologic studies. Despite the increased use of GIS in exposure assessment research, spatio-temporally varying datasets, such as daily activity spaces, residential histories, and time-varying maps of environmental contaminants are poorly characterized in the GIS environment. While GIS-based methods allow for integrating datasets that contain spatial variability, until recently datasets exhibiting spatio-temporal variability have been largely unmanageable, and researchers have been forced to simplify the complicated nature of their datasets by reducing or eliminating the spatial or temporal dimension. However, recent advances in space-time technology enable exposure scientists to more fully incorporate spatial and temporal variability into human exposure assessment. Whereas traditional GIS are based on spatial data structures--the "what, where" diad that inadequately displays changes through time, space-time technology is based on space-time data structures that enable characterization of the "what, where, when" triad needed for effective representation of data used to analyze health outcomes. Space-time technology allows the user to observe and quantify how geographies change with time, thereby enabling powerful exposure reconstruction procedures that are not possible through "space only" GIS. The continual expansion of space-time databases, coupled with the recognized need to incorporate human mobility in general and residential history in particular in environmental epidemiology, has highlighted the deficiencies of GIS-based software to visualize and process space-time information. This need is most pressing in retrospective studies where collection of individual biomarkers is unattainable or prohibitively expensive, and where models and software tools are required for exposure reconstruction. Advances in new space-time technology will profoundly improve our ability to reconstruct time-resolved individual exposures to environmental contaminants.

Bayesian Belief Networks (BBNs) are graphical models that incorporate probabilistic relationships among variables. Since their development in the late 1980s, they have increasingly been employed as tools for environmental modelling. Chapter 1 provides a summary of recent progress in using the technique, based on a review of relevant literature. A total of 50 publications were identified describing the application of BBNs to environmental problems, which were examined with respect to: (i) the development of model structures, (ii) identification of the probabilistic relationships between variables, (iii) the approaches used to test or validate models, (iv) sensitivity analysis, and (v) perceptions regarding the overall value of the approach. In the environmental sector, BBNs have to date primarily been used to examine management of natural resources, especially fisheries and water resources. The approach is widely considered to be useful, particularly in modelling domains characterized by high uncertainty, and where model parameterization is strongly dependent on expert knowledge. BBNs possess a number of features that make them particularly valuable in this context, especially where there is a need for models to support decision-making. However, many of the BBN models published to date are preliminary in nature, and there is a widespread lack of rigorous model testing, hindering a full evaluation of the approach. Current trends suggest that use of BBNs is likely to increase in future, extending to a wider range of domains, and involving increased integration with other modelling approaches and analysis of spatial data. However, increased emphasis on model testing is required if the approach is to fulfill its potential as a tool for environmental modelling.

Chapter 2 describes and demonstrates a methodology for the statistical retrieval of temperature and gas species concentration that uses the spectral radiance measured by new generation of high-resolution satellite-borne infrared sensors. These include, e.g., AIRS (Atmospheric InfraRed Sounder) on AQUA satellite and IASI (Infrared Atmospheric Sounding Interferometer) on the European Meteorological Operational satellite. These spectrometers are characterized by a wide band spectral coverage (645 to 2700 cm^{-1} or 3.7 to 15.5 μm) and a spectral sampling rate in the range 0.25 to 2 cm^{-1}. The performance of the retrieval scheme has been assessed on the basis of numerical exercises. Furthermore, examples of retrievals based on real spectra measured over sea surface are given to demonstrate the ability of the scheme to obtain accurate estimation of geophysical parameters. The problem of how many principal components to retain within the regression scheme has been addressed at a length and an original procedure is presented and discussed. Furthermore, the problem of statistical interdependency of retrieval and its vertical spatial resolution has been analyzed and a new index has been designed, which is capable to quantitatively deal with such an issue. The whole methodology has been derived for a generic signal-noise model and can therefore be used to design and implement retrieval algorithms also outside the specific area of high spectral resolution infrared observations

Insect infestations have been a major driving force of landscape change, leading to severe ecological and economic consequences. The southern pine beetle (SPB), *Dendroctonus frontalis* Zimmermann, is the most destructive insect to pine forests in the U.S. South. Chapter 3 probes the spatial and temporal patterns, particularly comovement and cyclical patterns, of SPB infestations at broad scales in the Southern United States. Cluster analysis in terms of comovement shows that SPB infestations in the region can be classified into three subregions: Alabama-Florida-Louisiana-Mississippi-Virginia, Georgia-Carolinas-Tennessee, and Arkansas-Texas. SPB infestation risk has increased over time in Florida, South Carolina, and Tennessee, but decreased in Alabama. The magnitude of bi-state comovements of SPB infestations is in general quite large whereas that of regionwide comovements is small, and comovments of small outbreaks are more pronounced than those of big ones. SPB infestations in North Carolina best resemble (synchronize with) the region's median, and thus it can be used as the region's reference for monitoring and forecasting. Though regionwide cyclical outbreak patterns are not detected, statistic evidence of cyclical outbreaks for some states and especially for the identified clusters/subregions is apparent; and the sinusoidal component is commonly concentrated over a range of low frequencies. These results will be of value for monitoring and mitigating SPB outbreaks in the region.

The objective of Chapter 4 is to provide a documented discussion on modelling of radionuclides interaction with suspended particulate matter in the marine environment. Aquatic environments occupy a major portion of the earth's surface and, therefore, an understanding of the radionuclide pathways is essential for radioecology purposes. Many radionuclides within such systems exhibit non-conservative behaviour, i.e., they undergo a change in the distribution between the particulate and dissolved phases, due to sorption reactions. The first reactive transport models for non-conservative radionuclides were based upon the equilibrium distribution coefficient, kd. However, recent models are based on kinetic rates of uptake/release of radionuclides between waters and the solid phases when short timescales are involved. Recently, much experimental and modelling effort has been focused on determining those factors which affect the kinetics and the final equilibrium conditions for the uptake of pollutants in aqueous suspensions under dynamic or static situations. Some of the obtained results appear to be either surprising or contradictory and introduce some uncertainty on which parameter values are most appropriate for environmental modelling.

The kinetic box models are widely used in modelling of radionuclides dispersion in aquatic systems, and are based on reversible reactions of constant coefficients. Indeed, several models have been proposed in the literature taking account of parallel, consecutive reactions and some combinations of both depending on the uptake experimental data. Research in this field of radioecology has been stimulated by the high level of public concern over health aspects of the presence of contaminant radionuclides in the environment, which has prompted a generally anti-nuclear posture. In this paper we present a review of the most relevant mathematical models developed so far and a brief revision of the historic developments of theories on surface-electrolyte interactions. Laboratory tracing experiments to study the uptake of ^{239}Pu, ^{241}Am, ^{133}Ba and ^{85}Sr in natural aqueous suspensions from several aquatic systems (reservoir, river, estuary and sea) are also presented to illustrate the application of box models covering a large number of environmental situations and different reaction channels.

The recent broadening of agricultural policy objectives and their related policy instruments has not been mirrored to the same extent in many agricultural sector models. For example, while the Common Agricultural Policy (CAP) of the European Union is becoming more concerned with rural development (second pillar of the CAP), most agricultural sector models are not able to handle the types of policy instruments covered by the second pillar accurately. Consequently, there is a considerable gap between the demand of policy makers and the supply provided by sector models. Chapter 5 aims at contributing to narrow this gap by presenting an extension of the agricultural sector model CAPRI (Common Agricultural

Policy Regional Impact Analysis) that enables a deeper regionalization of the model and which may prove useful in extending the relevance and reliability of indicators measuring agriculture's multifunctionality.

Chapter 6 summarises the main author's contributions in the past years over environmental modelling within the framework of the methodology called ACM ('Adaptive Control Methodology'). ACM combines the instruments of System Dynamics, multi-criteria analysis and control. Ex-ante control, i.e., prior to policy implementing is called 'control by structure' because it is achieved by developing control feed-back loops in the systemic structure under focus to influence the system evolution towards sustainable long-term paths. Ex-post control takes place during the post-implementation phase in which adjustments of the policy are necessary. ACM contributions in environmental modelling are briefly introduced, and a practical environmental case is presented on the way this technique can be used in real situations.

Distributed watershed models, such as the Soil and Water Assessment Tool (SWAT), have proven to be an important means for tackling problems related to nonpoint source pollution. These models require soil data as one of the minimal inputs because soil controls the runoff mechanism of a watershed. The U.S. Department of Agriculture Natural Resources Conservation Service generated two national soil databases, namely the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases, which were designed to be used for river basin resource monitoring, planning, and management. STATSGO has a county level spatial resolution, whereas, SSURGO has a farm level resolution. These two databases have been widely used as the best alternatives for watersheds where site specific soil data are not available, which is a common case. However, in the literature, information is scarce regarding affects of using one of these two databases over another on modeling sediment processes. Thus, the objective of Chapter 7 was to evaluate affects of using STATSGO versus SSURGO as an input on SWAT simulated sediment yields at the outlet of, and sediment source areas within, a watershed. The evaluation was conducted in one North Dakota watershed and one Texas watershed. Obviously, these two watersheds have distinctly different climatic and hydrologic conditions. The results indicated that for each of the study watersheds, the predicted total sediment yields at the outlet using STATSGO might be comparable with the corresponding predicted values using SSURGO, the predicted source areas, however, could be very different. In addition, the prediction discrepancies as a result of using one dataset over another were larger in the Texas watershed. This might indicate that the simulation of a watershed with streamflows mainly generated from rainfall runoff is likely to be more sensitive to soil data resolution than the simulation of a watershed with streamflows predominantly generated by snowmelt runoff.

Because landslide generates a larger yearly loss of property than earthquake, flood, or windstorm, it is important to develop models that can measure the potential of landslide occurrence in an area. Landslide hazard models can be generally grouped into physically-based and statistical models. A physically-based model delineates areas prone to landsliding by analyzing the influence of surface topography on near-surface hydrologic response. It assumes that slope failures are caused by shallow subsurface flow convergence, increased soil saturation, and shear strength reduction. A statistical model predicts the likelihood of landslide occurrence by analyzing the relationship between past landslides and instability factors such as lithology, slope, curvature, aspect, elevation, land use, and drainage. Common statistical methods for landslide prediction include discriminant analysis and logistic regression. Model validation is the process of evaluating a landslide hazard model by comparing model predictions with observed landslides. Observed landslides are compiled from aerial photographs, satellite images, or from ground surveys. Chapter 8 covers landslide mapping, physically-based models, statistical models, model validation, and examples of models for a mountainous watershed in Taiwan.

Chapter 9 investigates the groundwater contamination by heavy metals of the industrial area of Jorf Lasfar, located on the Atlantic coast of El Jadida, Morocco. This paper describes groundwater mapping and data collection and management to be created. Water samples collected from wells near the area of the industrial installations immediately located on the coast for chemical analyses. Multivariate statistics and GIS techniques were applied to classify the elements, to facilitate interpretation of the spatial relationships among key environmental processes and to identify elements influenced by human activities.

The results show that the area in general is characterized by hard water and high salinity hazard, possibly due to its proximity and hydraulic connection with the sea. Fe, Mn, F, Cu, Pb, Ni, Cr and Cd were found to be the major contaminants in groundwater. The analysis of groundwater indicates contamination at various degrees. Spatial distribution modelling of element concentrations is produced to indicate contamination plumes from possible anthropogenic sources. It was observed that the groundwater in south-eastern of the Jorf Lasfar industrial area is contaminated due to industrial effluents in coast and predominant wind direction. Cluster analysis (CA) classified the elements into two groups: the first group being influenced by human activities, the second predominantly derived from natural sources.

CONTENTS

EXPERT COMMENTARY

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Advances in Space-Time Technology for Assessing Human Exposure to Environmental Contaminants

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Abstract

In recent decades, digitally georeferenced data and Geographic Information Systems (GIS) have played a growing role in human exposure assessment for environmental epidemiologic studies. Despite the increased use of GIS in exposure assessment research, spatio-temporally varying datasets, such as daily activity spaces, residential histories, and time-varying maps of environmental contaminants are poorly characterized in the GIS environment. While GIS-based methods allow for integrating datasets that contain spatial variability, until recently datasets exhibiting spatio-temporal variability have been largely unmanageable, and researchers have been forced to simplify the complicated nature of their datasets by reducing or eliminating the spatial or temporal dimension. However, recent advances in space-time technology enable exposure scientists to more fully incorporate spatial and temporal variability into human exposure assessment. Whereas traditional GIS are based on spatial data structures--the "what, where" diad that inadequately displays changes through time, space-time technology is based on space-time data structures that enable characterization of the "what, where, when" triad needed for effective representation of data used to analyze health outcomes. Space-time technology allows the user to observe and quantify how geographies change with time, thereby enabling powerful exposure reconstruction procedures that are not possible through "space only" GIS. The continual expansion of space-time databases, coupled with the recognized need to incorporate human mobility in general and residential history in particular in environmental epidemiology, has highlighted the deficiencies of GIS-based software to visualize and process space-time information. This need

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is most pressing in retrospective studies where collection of individual biomarkers is unattainable or prohibitively expensive, and where models and software tools are required for exposure reconstruction. Advances in new space-time technology will profoundly improve our ability to reconstruct time-resolved individual exposures to environmental contaminants.

Introduction

In recent years GIS have been adopted for reconstructing individual-level exposure to environmental contaminants in epidemiologic research [Beyea and Hatch, 1999; Nuckols et al., 2004; Ward et al., 2000]. The growing body of literature on this application most commonly includes studies that assess proximity of individuals to sources of environmental contaminants such as pesticide application on farms [Reynolds et al., 2005], landfill sites [O'Leary et al., 2004], and hazardous waste sites [Elliott et al., 2001; McNamee and Dolk, 2001]. On occasion, investigators implement environmental fate and transport models to improve the exposure assessment [Reif et al., 2003]. These studies, however, rely almost exclusively on home residence at time of interview/diagnosis as the spatial location of the individual. Yet individuals are mobile and frequently change residences, and this residential mobility information is crucial for analyses of chronic diseases with relatively long induction periods, such as cancer.

Failure to include space-time mobility in GIS-based exposure assessments is a consequence, at least in part, of the a-temporal nature of GIS. GIS operate within a static world-view which is largely incapable of representing temporal change [Goodchild, 2000]. GIS are best suited to "snapshots" of static systems [Hornsby and Egenhofer, 2000] which hinders the mapping, representation, and analysis of dynamic health, socioeconomic, and environmental information for mobile populations. In the few GIS-based exposure assessments where residential histories are included, researchers create numerous maps, or snapshots, in specified time intervals (usually annual) to assess exposure as individuals move through time [Aschengrau et al., 1996; Bellander et al., 2001; Bonner et al., 2005; Brody et al., 2002; Nyberg et al., 2000, Stellman et al., 2003; Swartz et al., 2003]. Assembling these snapshots, however, is plagued by a host of problems: (a) it is dataset-intensive, requiring a unique database and map for each time slice; (b) it is labor-intensive and as such has the potential to produce critical errors during data manipulation; (c) information about change is not available in the interval between two consecutive snapshots; (d) it is so time consuming that it typically only enables one attempt at exposure reconstruction--it does not allow for improvements in the underlying models of environmental contamination for refining and recalculating exposure in an iterative manner; and (e) dozens-to-hundreds of maps need to be created to calculate time-resolved exposure using different temporal orientations or "measures of time", such as participants' age, calendar year, and years prior to diagnosis/interview. Perhaps most problematic is the fact that the snap-shot approach implicitly involves time-averaging and the implicit assignment of values of the exposure metric over the duration of the defined snapshot. This ignores or underestimates temporal variability inherent in the exposure metric and can result in biased exposure estimates. In short, the "snap shot" approach is both difficult to implement and yields misleading results. As a result of these challenges and limitations, when conducting GIS-based exposure assessments most researchers choose to disregard residential histories, thereby implicitly assuming that individuals are immobile, and that the induction period between causative exposures and health events (e.g. diagnosis, death) is negligible [Jacquez, 2004]. These strong assumptions are typically invalid, and the resulting exposure estimates are of dubious validity and unknown accuracy. The availability of software for displaying and integrating information across space-time maps that treat time as continuous, rather than discrete, could profoundly improve our ability to reconstruct time-resolved individual exposures [AvRuskin et al., 2004; Meliker et al., 2005].

We are not alone in identifying these weaknesses in GIS-based exposure assessments. In a recent review of epidemiological methods for evaluating geographic exposures and hazards, Mather et al. [2004] lamented the scarcity of methods that account for residential histories of cases and controls. At a meeting of this nation's experts on the spatial analysis of cancer data, the need to account for latency and human mobility in cancer studies was recognized as the second most pressing issue [Pickle et al., 2005]. As Pickle and colleagues [2006] summarize from that meeting, "...few tools and methods can be applied to both space and time together... ...a data representation problem needs to be solved: how to store and retrieve integrated space-time data consisting of multiple sets of data from fundamentally different space-time frames." This problem exists because, despite modern computer technologies for storing and managing temporal or spatial datasets, surprisingly few tools are available for working with space-time datasets [Beaubroef and Breckenridge, 2000; Dragicevic and Marceau, 2000]. Without tools for visualizing and analyzing space-time datasets, participant mobility, changes in contaminant concentrations, and other forms of space-time variability are inadequately incorporated into human exposure assessments.

Space-Time Software Systems

In the past few years several new software packages have emerged for working with space-time data. To our knowledge, currently available space-time visualization software include GeoTime, TimeMap, Space Time Toolkit, Google Earth, and ArcGIS 9.2; however, analysis capabilities necessary for exposure assessment are highly limited in these software. For example, the capacity to join data between space-time datasets of mobility and environmental contaminants is not available in these software. Another software package that provides both space-time visualization and some analysis capability has yet to be released (STNexus from GeoVista), and we are unsure of its ability to join space-time datasets, either. TerraSeer's Space-Time Intelligence System or STIS software, initially released in 2004, represents the only package that we know of which allows space-time visualization, data management, and analysis, and is capable of joining information between space-time datasets for exposure assessment. STIS technology was developed over several years with funding from the National Institutes of Health, with the specific objective of developing data structures, visualization, and analysis approaches for assessing health-environment relationships using time-dynamic data. While traditional GIS are based on spatial data structures, STIS is based on space-time data structures that are essential for the effective representation of data used to analyze health outcomes. STIS allows the user to observe and quantify how geographies change with time, thereby enabling powerful exposure reconstruction procedures that are not possible through "space only" GIS. It is ideally suited to the representation, visualization and reconstruction of human exposures to environmental contaminants.

Space-Time Datasets for Exposure Assessment

Space-time datasets relevant for exposure assessment are increasingly available. These resources include mobility histories from self-report, centralized database, and location-enabled devices (e.g., global positioning system (GPS)). They also include environmental contamination histories from temporally-rich monitoring networks, space-time models of monitored data, and remotely sensed data from satellite imagery and airborne platforms. These datasets will prove immeasurably valuable for reconstructing historic exposures to environmental contaminants.

Location-enabled devices track the locations (e.g. *x, y* coordinates and sometimes altitude) of individuals and assets (e.g. appliances such as Xerox machines in buildings, trucks, packages, etc.). This may be accomplished using GPS chips in cellular phones, RFID (radio frequency identification) tags on packages and shipments, and sensing technologies within and around buildings that employ ultrasound, WI-FI, UWB (Ultra-wide bandwidth) and related sensing technologies. The latter typically involve a tag being worn on the asset or individual, a sensor that determines the position of the tag in geographic space down to 0.5m resolution, and that transmits this location data at temporal sampling intervals up to several times per minute over a local network for storage and processing.

Imagery from satellites (e.g., Landsat) and air-borne platforms are finding increased use in exposure assessment. Applications include exposures to agricultural herbicides and pesticides based on proximity of homes to agricultural fields, where the field type is classified from satellite imagery. Knowledge of the crop type may then be coupled with information on agricultural practices such as the amounts of herbicide and pesticide use for that crop type throughout the year. GIS procedures may then be used to rank exposures at residential locations based on proximity to fields. As imaging technologies have advanced they have increased temporal (return visits during flyovers), spatial (pixel size), and spectral resolution (width and number of individual bands that report the amount of reflectance in specific bandwidths). Whereas Landsat could resolve individual pixels on the order of 30 meters using 6 bands, new hyperspectral technologies can resolve pixels of 0.5 meters with 160 or more bands. This makes possible the classification of land-based features with greater precision and accuracy.

Extensive monitoring networks exist for sensing environmental parameters such as air pollutants (e.g. ozone, NOx, SOx, etc.), temperature, rainfall and acidity, stream flows, snow pack and a host of other variables. Efforts are currently underway involving governments around the world to create a "system of systems" for monitoring the earth. In February, 2005, member countries of the Group on Earth Observations agreed to a 10-year implementation plan for a Global Earth Observation System of Systems (GEOSS). The GEOSS project holds the potential to advance exposure assessment by producing and managing information in a way that makes it readily accessible to a diversity of users in common formats. At this writing it is not entirely clear how GEOSS data may best be used for exposure assessment. A pressing practical issue is the integration of data from a diversity of sources at different spatial scales, from points (e.g. monitoring station locations), to polygons (e.g. the extent of municipal water supply districts) to rasters (e.g. Landsat Imagery); at different spatial resolutions (from submeter to several kilometers); and employing different temporal sampling frequencies (from essentially static – one observation – to several times per second, as occurs for some air