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Environmental science applications with Rapid Integrated Mapping and analysis System (RIMS)

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Environmental science applications with Rapid Integrated Mapping and analysis System (RIMS)

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Abstract. The Rapid Integrated Mapping and analysis System (RIMS) has been developed at the University of New Hampshire as an online instrument for multidisciplinary data visualization, analysis and manipulation with a focus on hydrological applications. Recently it was enriched with data and tools to allow more sophisticated analysis of interdisciplinary data. Three different examples of specific scientific applications with RIMS are demonstrated and discussed. Analysis of historical changes in major components of the Eurasian pan-Arctic water budget is based on historical discharge data, gridded observational meteorological fields, and remote sensing data for sea ice area. Express analysis of the extremely hot and dry summer of 2010 across European Russia is performed using a combination of near-real time and historical data to evaluate the intensity and spatial distribution of this event and its socioeconomic impacts. Integrative analysis of hydrological, water management, and population data for Central Asia over the last 30 years provides an assessment of regional water security due to changes in climate, water use and demography. The presented case studies demonstrate the capabilities of RIMS as a powerful instrument for hydrological and coupled human-natural systems research.

1. Introduction

The Earth's environment is undergoing rapid transformations and there is alarming evidence that important tipping points, leading to irreversible changes in major ecosystems and the planetary climate system, may already have been reached or passed [1]. Wide recognition of the climate change problem by the scientific community has stimulated significant efforts in developing new monitoring [2,3], modeling, and analysis tools [4,5] to improve our understanding of ongoing environmental changes. However, in spite of a growing number of spatially and temporally coherent environmental data sets, there is a lack of user friendly systems with the capability to discover, integrate, and analyze multiple geophysical and socioeconomic data sets [6]. Because of the significant, accelerating changes, it is imperative that researchers [7], decision makers, and students [8] are equipped with appropriate data and interactive tools to identify, analyze, and communicate these changes in a rapid manner using applications.

The integration of web-based services with Earth science observational and modeling frameworks [6,9] is not new and has been previously implemented for specific projects in the fields of climatology [10], hydrology [11], oceanography [12], and global ecosystems [13], where GIS technologies are an important



part of the scientific research. The introduction of Open Geospatial Consortium-OGC standards for web-based mapping and data querying and processing [14] as well as the maturity of other web-based technologies (e.g. Open Layers) lead to further popularity of such system. However, many fundamental environmental science data needs, such as multi-layer datasets representing time series of environmental variables (e.g. temperature, precipitation, etc.), are still not implemented in the OGC standards and other related web-based technologies [15].

2. Online Rapid Integrated Mapping and analysis System (RIMS)

To facilitate operation and analysis of diverse data, researchers at the University of New Hampshire (UNH) developed RIMS (Rapid Integrated Mapping and analysis System), an online informatics tool for multidisciplinary data visualization, analysis, and manipulation with a focus on hydrological applications [16,17]. Presently, the RIMS data pool covers a variety of themes including climate, hydrology, land cover, demographics, economics, and others (see Table 1).

Table 1. Summary of RIMS data holdings.

Earth System Science Data Category	Key Sources	Examples of Major Parameters	Current Dataset Count	
			Source	Source + aggregations
Hydrology	UNH, CCNY, UAF	Discharge, runoff, evapotranspiration, river networks, irrigation, water use	650	4000
Past and Present Climate	NASA, NOAA, UDel, Princeton University	Temperature, precipitation, evapotranspiration (ET), solar radiation, pressure, wind, humidity	100	400
	NCEP, MERRA reanalysis		62	210
Future Climate and Hydrology	IPCC, UNH	Temperature, precipitation, ET, snow, runoff, discharge	800	5000
Remote Sensing	MODIS, UNH, Univ. of Oklahoma, NSIDC	Vegetation indices, soil moisture, clouds, snow, fires, temperature	88	126
Physical Geography	NASA, USGS, UNH	Elevation, bathymetry, Blue Marble, Lon/Lat	28	32
Oceanography	NOAA, NCOF	SST-sea temperature, sea ice	5	8
Land Cover	UM, NASA, USGS	Land cover, vegetation, permafrost, freeze/thaw	80	120
Sociology and Economics	CIESIN, World Bank, US CIA, UNH	Population, GDP, industry, mortality/birth/malnutrition rates, dams	50	100
Agriculture	UW-Madison, Various	Crop land, crops, fertilizer loads, greenhouse emissions	160	200
Polygon Masks	UNH	Watershed, sea/ocean catchments, continents, countries, administrative units	18	18
Station Data	UNH, USGS, NCDC	Hydrology, climate, public health	12	12
Total			~2050	~10200

Acronyms: UNH- University of New Hampshire; CCNY-City College of New York; UAF-University of Alaska at Fairbanks; NASA- National Aeronautic and Space Agency; NOAA- National Oceanic and Atmospheric Administration; UDel- University of Delaware; NCEP- National Centers for Environmental Prediction; NSIDC – National Snow and Ice Data Center; MERRA- Modern Era Retrospective-Analysis for Research and Applications; IPCC- International Panel for Climate Change; USGS- United States

Geological Survey; NCOF - National Centre for Ocean Forecasting; UM – University of Maryland; CIESIN- Center for International Earth Science Information Network; UW-Madison – University of Wisconsin, US CIA – Central Intelligence Agency; NCDC- National Climate Data Center.

It comprises over two thousand single layer (e.g. elevation) and time series (e.g. daily runoff) composite datasets as well as a number of climate and hydrology gridded and station/point network datasets. It employs a near-real-time data flow architecture where new temporal data is generated by computer clusters chained in data mining → processing → modeling → data product delivery in a similar manner described in [5]. In addition to visualization/mapping, RIMS contains web services designed for digital data content interfacing: i) A dataset search service among our data holdings, including more than 10000 raster and vector time series and single layer data (in 200+ file formats readable by the GDAL library); ii) the ability to view different temporal aggregation sub-sets of the same time series data (e.g. daily, monthly, yearly, daily climatology or long term averages, etc.) as well as their spatial aggregations (e.g. integral averages per country, per watershed, per administrative unit, etc.); iii) instant access to the raw data values for each pixel of the client-side displayed maps (WFS/WCS); iv) on-line computation and creation of new data layers via the new data calculator tool; v) tools for easy mounting and management of new vector, raster, and point/station data and metadata.

Several RIMS clones for different global, continental and regional applications (<http://earthatlas.sr.unh.edu>; <http://NEESPI.sr.unh.edu>; <http://hydroepscor.sr.unh.edu>) [16,17] have been developed at the Water Systems Analysis Group of the University of New Hampshire (WSAG UNH) to facilitate integrated analysis of multiple data sources including: gridded meteorological data from several re-analysis products, regional climate and global circulation models (GCM); gridded outputs from hydrological models; observational hydrometeorological in situ data, land cover information, vegetation indices from remote sensing, and census-based demographic and socio-economic data.

RIMS is an important resource for research and exploration in different fields of Earth science. This web-based system can be successfully applied to address multiple research problems using an extensive data archive and embedded tools for data analysis, visualization, modification, and distribution. The Water Systems Analysis Group (WSAG) at UNH widely uses the RIMS for various scientific applications and several examples of data analyses made with use of RIMS data and tools are discussed below. These examples show RIMS capabilities for integrated analysis of various data sets.

3. Research applications with RIMS

3.1. Analysis of historical, contemporary and future changes in climate, hydrology and water management

The massive RIMS archive of hydro-climatological information includes observational data, climate re-analysis products as well as outputs from many climatic and hydrological models. Temporal and spatial aggregation online tools allow estimation of historical and future trends for different regions/watersheds/administrative units/stations, construction of rasterized maps of these changes and to evaluate uncertainties of the modeled data relative to observations [18-20].

River flow is an integrated characteristic reflecting numerous environmental processes and their changes aggregated over large areas. River runoff plays a significant role in the freshwater budget of the Arctic Ocean, and ocean salinity and sea ice formation are critically affected by river input [19]. Changes in the fresh water flux to the ocean can exert significant control over global ocean circulation via the North Atlantic deep water formation [21]. Eurasia contributes 75% of the total terrestrial runoff to the Arctic Ocean [22] and contains three of the four major arctic rivers. Figure 1 demonstrates combined analysis of long-term changes in observed river discharge, major water balance components, and some climatic characteristics for Eurasian pan-Arctic drainage basin.

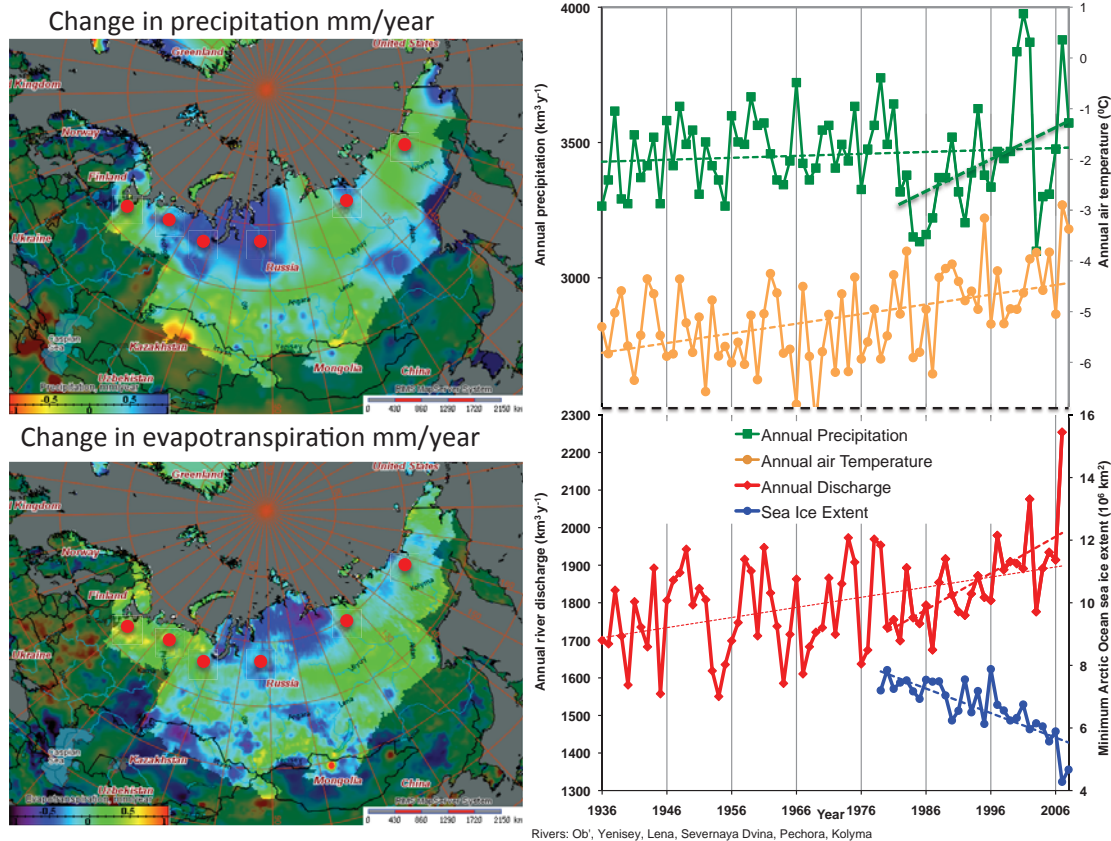


Figure 1. Analysis of changes in major water balance components for Eurasian pan-Arctic drainage basin. Upper map shows linear slope of the total annual precipitation over 1936-2010 based on monthly gridded data from University of Delaware (UDel) with 0.5° spatial resolution. Lower map demonstrates linear slope over 1936-2010 of potential evapotranspiration computed on UNH water balance model using UDel meteorological data. Blue areas represent wetter conditions or more precipitation and less evapotranspiration. Right plot shows annual time series for the total river discharge of 6 largest Eurasian rivers flowing to the Arctic Ocean - Ob, Yenisey, Lena, Kolyma, Sev. Dvina and Pechora (red line, downstream river gauges are shown as red dots on the maps), spatially aggregated annual precipitation (green line) and air temperature (brown line) for the 6 river basins based on UDel gridded data, and the total Arctic Ocean sea ice coverage in September based on remote sensing data over 1978-2008 (blue line). All these data were derived from <http://neespi.sr.unh.edu> using embedded tools.

Observations from the six largest Russian north-flowing rivers have shown an increase of 7% in combined river discharge over the period 1936-1999 [23]. More recent estimates have shown this increase has continued into the 21st Century with 2007 showing a new historical maximum (figure 1, red line; [24]). RIMS contains data sets and tools allowing exploration of possible causes of the changes in Eurasian pan-Arctic river flow. The time series of annual precipitation aggregated over 6 large Eurasian river basins has a very slight (insignificant) increasing trend overall (figure 1, green line) but much higher interannual variation and a significant positive trend of 1.2 mm/year since the 1980s. Thus, although precipitation changes cannot be the primary cause of streamflow alterations over the long-term historical period (1936-present), observed rapid increase in river discharge since 1980 can be explained by

precipitation rise. The spatial changes in precipitation (P) and evapotranspiration (ET) towards wetter conditions (more P and less ET) are most significant in the northern parts of the Ob and Yenisey watersheds and upper Lena basin. Decline in precipitation is observed in the southern parts of Ob and Yenisey river basins and in the European part. However, in some regions, especially with dry climate (Kazakhstan, Mongolia), decrease in precipitation is partly compensated with lower evapotranspiration (see maps in figure 1). The obvious long-term tendency towards wetter and colder conditions in the northern part of Kara Sea basin may be related to increasing cyclonic activities in the area [25,26] and is mainly explained by significant retreat of the Arctic sea ice during last 30 years (figure 1, blue line). The long-term variation in September sea ice area and Eurasian river discharge demonstrate a good correspondence with negative correlation ($r = -0.7$; figure 1) suggesting that (a) both rivers and sea ice were responding to changes in large-scale hemispheric climate patterns; and (b) an increasingly ice-free summer in the Arctic Ocean contributed to wetter conditions on the land via atmospheric moisture transport from open sea areas [24].

The given example of multiple historical data analysis within RIMS environment can be easily extended to monthly and daily data for historical and future time frames as well as information about changes in land cover and permafrost.

3.2. Express analysis of extreme climatic events their anomalies and impacts on socio-economic factors such as population, crops etc.

RIMS data archive and tools allow rapid scientific analysis of various anomalous phenomena. Combining regularly updated near real time data from re-analysis products and station observations with historical data on climate, hydrology, land use, fire, and population, we can evaluate characteristics and impacts of the extreme climatic and hydrological events.

The record-breaking heat wave during summer 2010 in western Russia had a significant negative impact on people (health, mortality), agricultural yield, and forestry (wild fires, tree mortality). Applying RIMS data and tools, we present an example of express analysis for this extreme climatic event (see figure 2). The analysis was made at the end of this heat wave in August 2010 using available in RIMS regularly updated near real time data and historical archives. The spatial distribution of daily maximum air temperature anomaly (figure 2a) and the long-term variation of daily maximum air temperature for meteorological station in Moscow (figure 2c) are shown along with maps highlighting the area and population significantly impacted by the heat wave (figure 2b), defined as the area where the mean daily air temperature from July 1 to August 18, 2010 was 5°C higher than the long-term mean for this period. The number of people residing this area was about 89 million or approximately 60% of total Russia population. The estimates were made in RIMS using embedded calculator tool with daily NCEP re-analysis products [27] and gridded population density data [28]. Comparison of NCEP maximum daily air temperature data with ground observations from meteorological station located in the Moscow (figure 2c) revealed that NCEP re-analysis has a tendency to underestimate the air temperature in the large city like Moscow. This is probably due to relatively coarse spatial resolution of NCEP data that cannot take into account additional heating of urban areas. The maximum daily air temperature for period from 07/05/2010 to 08/17/05 was in average 8°C higher than long-term mean and in some days the difference exceeds 11 °C. This hot period in central European Russia was also extremely dry. The total precipitation for July in Moscow region was less than 5 mm when the norm is 80 mm. Such dry and warm conditions led to extreme fire hazard conditions in many regions of the European part of Russia. The simple dryness index suggested by Ped' [29] and based on anomalies of precipitation and air temperature was estimated within RIMS environment using NCEP data aggregated for the most impacted region (figure 3b) to define anomaly of summer 2010. The index (S) is defined as:

$$S = \frac{\Delta T}{\sigma_T} - \frac{\Delta R}{\sigma_R} \quad (1)$$

where $\Delta T, \Delta R$ are deviations from the long-term mean of monthly air temperatures and precipitation over the June-August, and σ_T, σ_R - mean-square deviations of these characteristics over the long-term period. The drought conditions with this index are defined as weak ($1.0 < S_i < 2.0$), medium ($2.0 \leq S_i < 3.0$), or severe ($S_i \geq 3.0$). The summer 2010 was extremely dry ($S = 8$), reaching the highest value of the index for this area over the period 1985-2010 (figure 2d). RIMS also allows application of near-real time remote-sensing data to the express analysis. For example, land surface temperature, vegetation indices, and fire products currently available from Moderate Resolution Imaging Spectroradiometer (MODIS) can significantly enrich this analysis. The UNH Water Balance Model (WBM) integrated in RIMS can provide additional information about impacts of such conditions on hydrology and water management. Thus, RIMS can serve as a valuable tool for analysis of impacts of recent and ongoing extreme climatic events on other natural and social components.

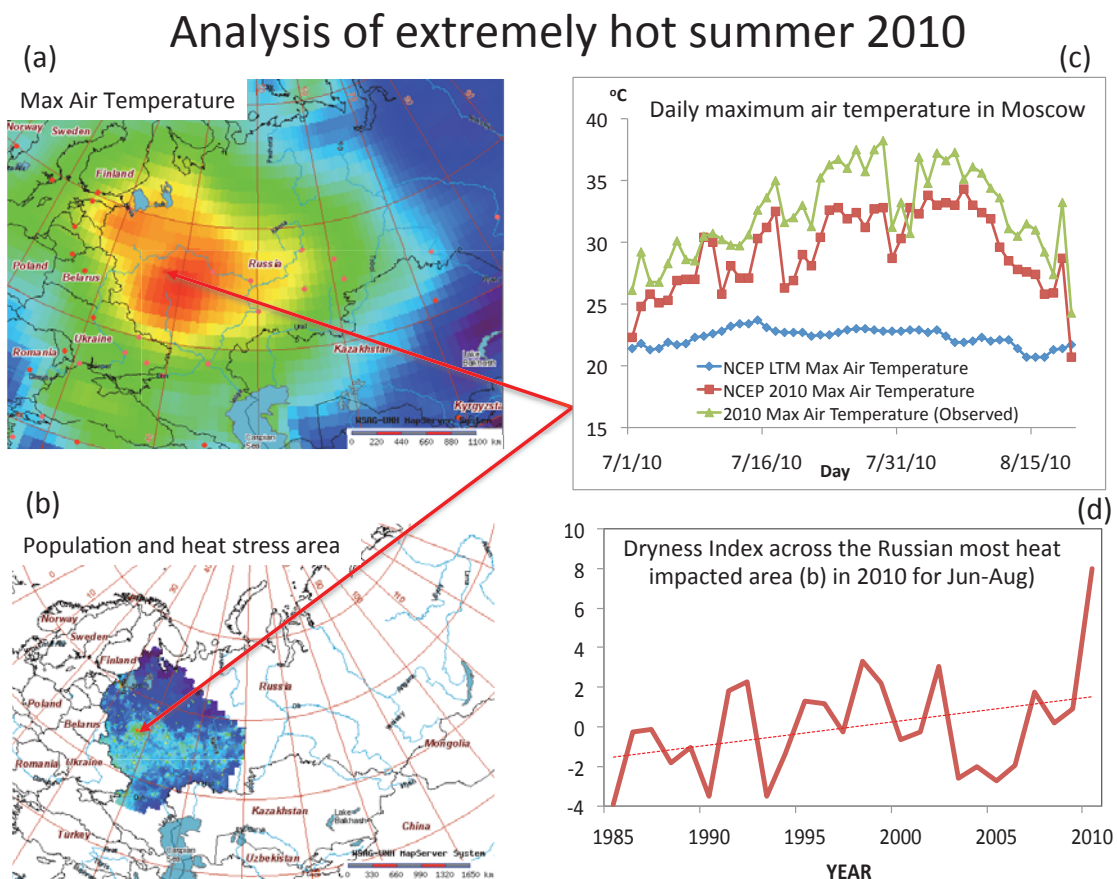


Figure 2. Deviation of mean maximum air temperature of July-August 2010 from long-term mean, based on NCEP reanalysis (a); highlighted heat stress area and population density (b); Intercomparison of in-situ and reanalysis air temperature data for Moscow city during 2010 heat wave; Time series of dryness index for June-August for area highlighted on (b).

3.3. *Creation and analysis of new data sets through integration of social and geophysical data*

RIMS capacity to produce combined geospatial fields from bio-geophysical assets and socioeconomic data has been widely used to evaluate and quantify human vulnerability through different water indicators [30]. RIMS data and tools were the core instrument in a global assessment that jointly considered human water security and biodiversity threats [31]. Thus, RIMS can be used as a research tool for combined analysis of environmental data from remote sensing, ground observations, various models, and socioeconomic data from regional censuses and models. RIMS aggregation procedures allow use of data with different spatial and temporal scales.

The analysis of climate change on some components of water security for Central Asia has been made using RIMS data collection and tools. Water is a key agent in Central Asia, ultimately determining human well-being, food security, and economic development. The University of New Hampshire - Water Balance Model - (WBM) was applied to understand the consequences of changes in climate, water use (figure 3a), demography, and economy on various variables and indices characterizing regional water security. The WBM accounts for sub-pixel land cover types, glacier and snow-pack accumulation/melt across sub-pixel elevation bands, anthropogenic water use (e.g., domestic and industrial water consumption, irrigation for most of existing crop types), and hydro-infrastructure for large inter-basin water transfer (e.g. Karakum Canal in the Central Asia) and reservoir/dam regulations [32]. The map (figure 3b) shows Central Asian countries and sub-country administrative units. The census data about land use, crops and irrigated area from 1980 to 2012 for the administrative units have been combined with gridded MIRCA2000 rainfed and irrigated crop data [33] to provide land use inputs for WBM simulations. The dynamics of water use for domestic, industrial and livestock needs have been simulated in WBM using country-based statistical socio-economic information along with spatially distributed population density. All WBM inputs and outputs parameters were integrated into RIMS to facilitate integrated data analysis.

The map (figure 3a) demonstrates change in water use (irrigation, domestic, industrial, livestock) across Central Asia between 2000-2014 and 1980-1985 based on WBM simulations. Inserted plots show annual changes in irrigation water demand over 1980-2014 for two sub-regions (pixels). Since 1980, irrigation water use significantly increased in Uzbekistan – where the highest population growth rate has been observed – and declined in East Kazakhstan (figure 3a). The barographs in figure 4b present official data about changes in areas of irrigated lands for administrative units. There are different patterns of these changes over 1980-2012, which reflect various socio-economic, demographic, and political issues. For example, significant drops in irrigated areas around 1990 in Osh region – Kyrgyzstan and Fergana-Uzbekistan – is probably related to the so-called Osh riots (conflict with numerous victims). Water Scarcity Index (WSI) [34] was estimated in the RIMS calculator based on the WBM simulations using only locally generated water resources (figure 3e,f) and total available water resources (including inflow) (figure 3c,d). The index combines information about water abstractions and water availability. It is defined by the intensity of water resource use, i.e. the gross freshwater abstractions as percentage of the total renewable water resources or as percentage of internal water resources. This indicator is defined by the ratio $WSI=W/Q$, where W are the annual freshwater abstractions and Q is the annual available water. The severity of water stress is classified in several categories (from high water stress – red to abundance of water – blue figure 3c-f). This indicator neglects temporal and spatial variations as well as water quality data. We also analyzed a number of other indexes and variables characterizing the water availability and water use in the region. There is general tendency towards significant decline in water availability by 2014 compared to 1990 (figure 3c-f). The water security situation in 2014 across the region is more stressful even despite significant political and socio-economic transformations in the region in 1990s, which led to decrease in water use. This is primarily related to change in climatic conditions and population growth.

All estimates of water stress and water availability in the Central Asia as well as computations of various water security indicators have been made within the RIMS environment using the incorporated data and tools.

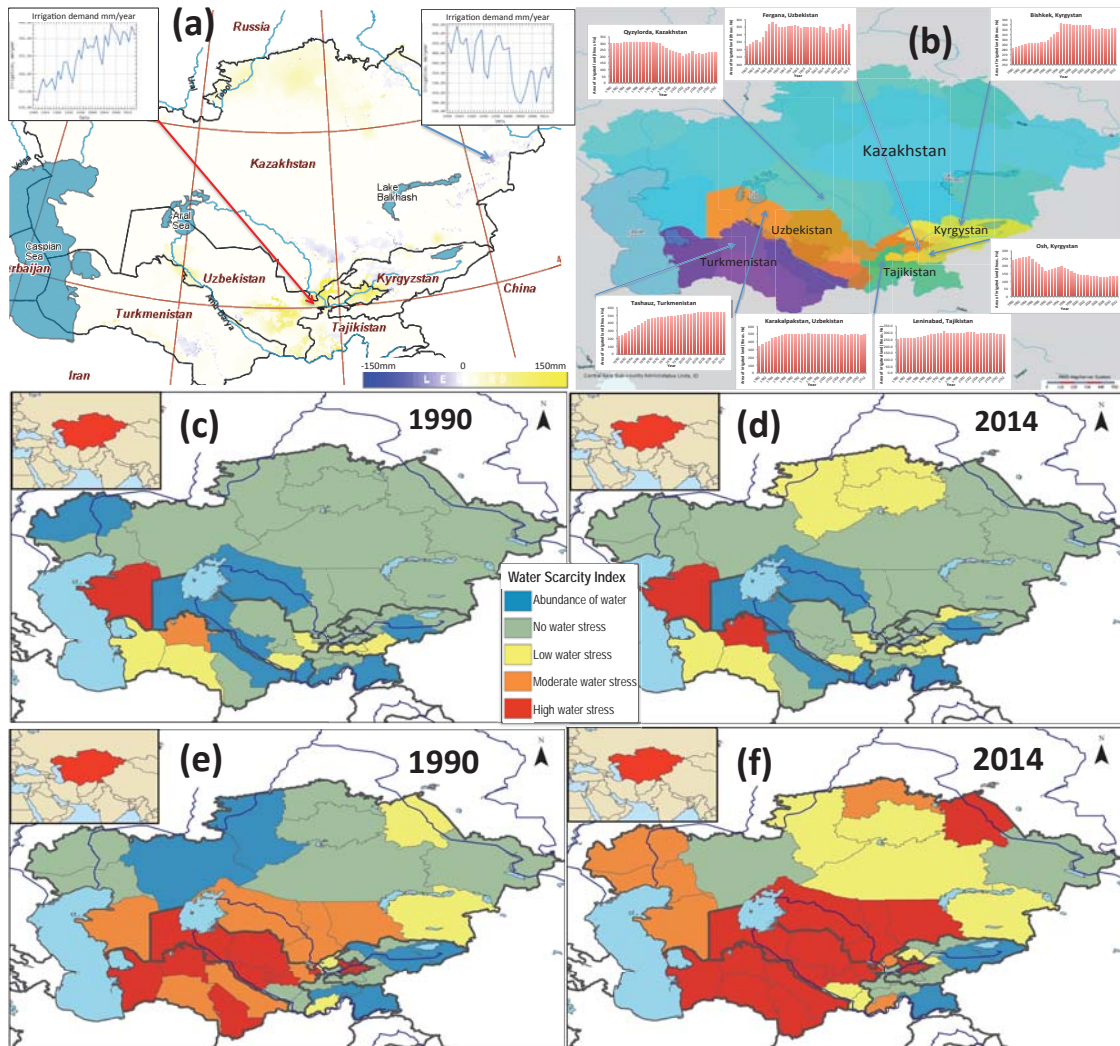


Figure 3. Deviations in water use (irrigation, domestic, industrial, livestock) between 2010-2014 and 1980-1985 for 6 minute grid cells based on WBM simulations; the embedded plots show opposite changes for two subregions (pixels) in annual water demand for irrigation (a); The map of administrative units of Central Asia and plots showing the dynamic of irrigated lands for several regions based on census data (b). Maps of Water Scarcity Index (WSI) based on only locally generated (c, d), and total available water resources including inflow from other sub-regions (e, f) for 1990 and 2014.

4. Conclusions

The Rapid Integrated Mapping and analysis System (RIMS) originally developed at UNH has an ability to acquire near-real time data and produce express analysis of changes in the state of the terrestrial water cycle. It has been significantly enriched with data and tools to allow solutions of more sophisticated

research tasks. Three different examples of specific scientific applications with RIMS have been demonstrated and discussed.

Analysis of historical changes in major components of the Eurasian pan-Arctic water budget has shown the observed increase in river flux to the Arctic Ocean. This can be partly explained by changes in precipitation and evapotranspiration primarily in the northern regions adjoining to the Arctic Ocean. The significant decline in the sea ice area during last 30 years could contribute to the wetter and colder conditions across the Arctic seacoast leading to increase in streamflow. Most noticeable changes in all major components of the terrestrial water budget in the Eurasian pan-Arctic observed since 1980 correspond to significant sea ice retreat.

Express analysis of extremely hot and dry summer of 2010 across European Russia has been made using a combination of near-real time and historical data compiled in RIMS. We found that about 60% of Russian population was impacted by this extreme event. The evaluated dryness index for summer 2010 was the highest since 1985 and its value constitutes severe drought. Thus, the climatic condition was a major contributor to extensive wildfires and decreases in vegetation and crop production (e.g. wheat yield) during 2010.

Performed integrative analysis of hydrological, water management, and population data over the last 30 years for the Central Asia was made under the RIMS. It allowed evaluating the regional water security and its dynamics due to changes in climate, water use, and demography. The water security situation from 1990 to 2014 across the study region has significantly deteriorated despite considerable decline in water use after USSR breakup. This is probably caused by fast population growth and climate change in the region.

The presented examples of the science applications demonstrate the capabilities of RIMS as a powerful instrument for various express research investigations. At the same time as it was mentioned in the Introduction the system is currently being upgraded to many modern Web server and client side features (e.g. OGC interface services, slippery maps, JQuery, etc.) that are important to be used by broader research and community. In order to facilitate the compatibility upgrade process aimed toward an increase of RIMS potential users in the science and educational fields is being carried out and discussed in another paper of this journal issue [35]. The primary goal of this project is implementation of the latest Web and GIS technologies in compliance with the Open Geospatial Consortium (OGC) standard sin RIMS codes. This effort is build on many modern solutions such as object-oriented programming, modular composition, and client-side JavaScript libraries based on the GeoExt package (<http://www.geoext.org>), ExtJS Framework (<http://www.sencha.com/products/extjs>), and OpenLayers software (<http://openlayers.org>). In particular, new approaches are used to facilitate and accelerate searching of required information on storage systems and provide users with distributed processing of large data sets [36]. The first results obtained in [35] are quite encouraging and show that after ongoing RIMS upgrade it will provides the opportunity to scientists, professionals and decision-makers to use various geographically distributed and georeferenced resources and processing services via web browser by integrating all listed above components in the single universal Geoinformatics system.

Acknowledgments

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