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System analysis to estimate subsurface flow: from global level to the State of Minnesota

Abstract.

Stream runoff data globally and in the state of Minnesota were used to estimate subsurface water flow. This system approach is based, in principal, on unity of groundwater and surface water systems, and it is in stark contrast to the traditional deterministic approach based on modeling. In coordination with methodology of system analysis, two levels of study were used to estimate subsurface flow. First, the global stream runoff data were assessed to estimate the temporal–spatial variability of surface water runoff. Factor analysis was used to study the temporal–spatial variability of global runoff for the period from 1918 to 1967. Results of these analysis demonstrate that the variability of global runoff could be represented by seven major components (factor scores) that could be grouped into seven distinct independent grouping from the total of 18 continental slopes on the Earth. Computed variance value in this analysis is 76% and supports such analysis. The global stream runoff for this period is stationary, and is more closely connected with the stream flow of Asia to the Pacific Ocean as well as with the stream runoff of North America towards the Arctic and Pacific Oceans. The second level examines the distribution of river runoff (annual and for February) for various landscapes and the hydrogeological conditions in the State of Minnesota (218,000 km^2). The annual and minimal monthly rate of stream runoff for 115 gauging stations with a period of observation of 47 years (1935–1981) were used to characterize the spatio-temporal distribution of stream runoff in Minnesota. Results of this analysis demonstrate that the annual stream runoff rate changes from 6.3, towards 3.95, and then to 2.09 $l\ s^{-1}\ km^{-2}$ (the difference is significant based on Student's criteria). These values in Minnesota correspond to ecological provinces from a mixed forest province towards the broadleaf forest and to prairie province, respectively. The distribution of minimal monthly stream runoff rate (February runoff) is controlled by hydrogeological systems in Minnesota. The difference between the two hydrogeological regions, Precambrian crystalline basement and Paleozoic artesian basin of 0.83 and 2.09 $l/s/km^2$, is statistically significant. Within these regions, the monthly minimal runoff (0.5 and 1.68, and 0.87 and 3.11 $l\ s^{-1}\ km^{-2}$ for February, respectively) is also distinctly different for delineated subregions, depending on whether or not the Quaternary cover is present. The spatio-temporal structure that emerges could thus be used to generate river runoff and subsurface flow maps at any scale – from the global level to local detail. Such analysis was carried out in Minnesota with the detailed mapping of the subsurface flow for the Twin Cities Metropolitan area.

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Original article

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Abstract Stream runoff data globally and in the state of Minnesota were used to estimate subsurface water flow. This system approach is based, in principal, on unity of groundwater and surface water systems, and it is in stark contrast to the traditional deterministic approach based on modeling. In coordination with methodology of system analysis, two levels of study were used to estimate subsurface flow. First, the global stream runoff data were assessed to estimate the temporal–spatial variability of surface water runoff. Factor analysis was used to study the temporal–spatial variability of global runoff for the period from 1918 to 1967. Results of these analysis demonstrate that the variability of global runoff could be represented by seven major components (factor scores) that could be grouped into seven distinct independent grouping from the total of 18 continental slopes on the Earth. Computed variance value in this analysis is 76% and supports such analysis. The global stream runoff for this period is stationary, and is more closely connected with the stream flow of Asia to the Pacific Ocean as well as with the stream runoff of North America towards the Arctic and Pacific Oceans. The second level examines the distribution of river runoff (annual and for February) for various landscapes and the hydrogeological conditions in the State of Minnesota (218,000 km^2). The annual and minimal monthly rate of stream runoff for 115 gauging stations with a period of observation of 47 years (1935–1981) were used to characterize the spatio-temporal distribution of stream runoff in Minnesota. Results of this analysis demonstrate that the annual stream runoff rate changes from 6.3, towards 3.95, and then to 2.09 $l\ s^{-1}\ km^{-2}$ (the difference is significant based on Student's criteria). These values in Minnesota correspond to ecological provinces from a mixed forest province towards the broadleaf forest and to prairie province, respectively. The distribution of minimal monthly stream runoff rate (February runoff) is controlled by hydrogeological systems in Minnesota. The difference between the two hydrogeological regions, Precambrian crystalline basement and Paleozoic artesian basin of 0.83 and 2.09 l/s/km^2, is statistically significant. Within these regions, the monthly minimal runoff (0.5 and 1.68, and 0.87 and 3.11 $l\ s^{-1}\ km^{-2}$ for February, respectively) is also distinctly different for delineated subregions, depending on whether or not the Quaternary cover is present. The spatio-temporal structure that emerges could thus be used to generate river runoff and subsurface flow maps at any scale – from the global level to local detail. Such analysis was carried out in Minnesota with the detailed mapping of the subsurface flow for the Twin Cities Metropolitan area.

Keywords Groundwater runoff · Hierarchical hydrogeological flow fields · Hydrological databases of regions and continents · Subsurface flow mapping

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Introduction

Recently published, the "World map of hydrogeological conditions and groundwater flow" (Dzhamalov and Zektser 1999), is a result of many decades of mapping groundwater resources in the world. At the same time, it is appropriate to analyze the results retrospectively and revisit some regions (in our case Minnesota) with new available data.
The territory of the former Soviet Union, covering about one-sixth of the Earth's surface, is mapped with such maps at scales of 1:5,000,000 and 1:2,500,000. The series of hydrogeology of USSR contains the regional maps at a scale from 1:2,500,000 to 1:500,000 (Shmagin and Kanivetsky 1997). The same methodology was applied in a compilation of groundwater flow maps for Central and Eastern

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Europe at a scale of 1:1,500,000 (Konoplyantsev 1984) and maps for the northern European part of Russia (non-Chernozem zone) at a scale of 1:1,500,000 (Vsevolozhsky and others 1984). This novel approach of quantitative regional mapping of water resources began and was successfully developed in the former Soviet Union.

Here is what Daene McKinney and David Maidment (1998) from Center for Research in Water Resources University of Texas at Austin wrote: "The adequacy of the world's water resources to support the sustainable development of the Earth is a subject of significant current interest. Central to this debate is an accurate assessment of water availability in precipitation, surface water, and groundwater as a function of space and time for entire Earth. An improved understanding of the effects of climate change and variability in space- and time-distribution of regional water resources is also needed because it is at the regional level that most water resource decisions are made. The most comprehensive assessment made to date of the world's water resources was done in the Soviet Union during the 1960s and 1970s as part of the International Hydrological Decade. This effort resulted in publication by UNESCO of an "Atlas of the world water balance" (1978), and a landmark book "World water balance and water resources of the Earth" (1978). The UNESCO atlas contains 65 maps covering nine geographic regions of the world with information about the annual amount and monthly distribution of precipitation, potential evaporation, and runoff. This information has been updated in Russia for UNESCO as part of its current water resource activities, but no updated atlas of the world water balance was produced".

The published UNESCO atlas in 1978 stimulated Daene McKinney and David Maidment to compile their version of the atlas in GIS (McKinney and Maidment 1998). Thanks to the effort of American scientists, who used as a basis the previous works of scientists from the Soviet Union, the new version is available on the Internet. This is an example of cooperation in this new globalized information age, without actually working together. More productive cooperation is occurring as scientists from different countries develop personal contacts. Such collaboration between American and former Soviet Union scientists dramatically increased during the last decade, thanks to the American Institute of Hydrology's collaborative initiative (Shmagin and others 1996; Shmagin and Kanivetsky 1997).

The map of groundwater runoff of the world (Dzhamalov and Zektser 1999) is not the final word in studying groundwater resources. In the last decade, a new, so-called, system approach has been developed to study stream runoff. The system analysis to study the stream runoff components (annual and monthly minimal) represents a new direction in estimating and mapping fresh groundwater resources. This approach includes three phases: (1) system analysis of the geosphere (Earth landscapes), (2) groundwater flow field classification, and (3) spatial mapping of river runoff.

System analysis is a well-know approach in science, including the study of Earth systems (Schellnhuber and Wenzel 1998). During the period from 1968 to 1990, the system approach to investigate Earth landscapes was developed (Krcho 1990). The development of system (cybernetic) models for landscapes (Krcho 1990) allowed for shared investigations between landscape and hydrosphere of the Earth and components of the hydrosphere for various types of watersheds (Shmagin 1997).

The fundamental premise of the system analysis is the consideration that the stream runoff hydrosphere can be investigated at many levels (planetary, global, regional, basin; Shmagin 1997). This model is based on the "geological sphere" by V.I. Vernadsky (and logic-multiple form (Krcho 1990). This model of hydrosphere runoff could be determined for any territory as well as for all Earth surface for two intercrossed systems: systems of landscape and systems of stream basins. Such a model allows for the quantification of the spatio-temporal structure of stream runoff, The system analysis is an approach that unifies all streamflow characteristics for any area of interest, in our case for the State of Minnesota.

This paper present the results for two statistical models solved for two levels of stream runoff. The temporal–spatial variability of global stream runoff (global level) is discussed first, and then the spatio-temporal structure of stream runoff in Minnesota (regional level) is presented with an individual record for that site.

Previous studies and data

Lins (1985) investigated interannual streamflow variation at 106 locations in the United States to attempt to assess temporal and spatial patterns. For the period from 1931 to 1978, statistical analyses was carried out using five principal components of factor loading. These five components, reflecting 56% of the total streamflow variance, permitted us to understand, in general, the multi-annual variability of stream runoff for the United States. The author compiled the maps to depict the factor-loading isolines for each component. The result of this analysis demonstrated the tendencies of spatial–temporal variabilities, but could not define the geographical boundaries of these variabilities. These isoline maps of factor loading could be interpreted in a few ways and differently than that of Lins.

Saco and Kumar (2000) tried to identify the coherent regions using the characteristics of streamflow variability. To address this issue, the authors used wavelet spectral analysis. Vogel and others (1998) demonstrated a purely procedural technique to analyze regional data. This study documented that regional average streamflow statistics usually contain much more information about the variability and persistence of streamflow at a particular site than does the individual streamflow record for that site. In comparison with the work by Lins (1985), these two works used a more sophisticated technique, but the results did not improve the understanding of geographical distribution of stream variability.

Previous studies in Minnesota on minimal streamflow include investigations by Ackroyd and others (1967) and

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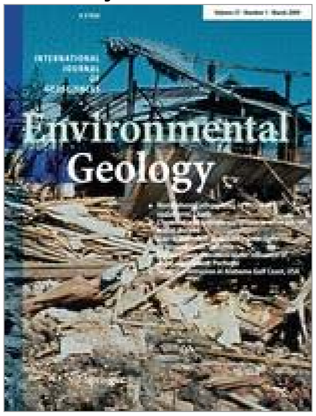

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