О некоторых общих вопросах моделирования в гидрологии речных бассейнов

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ИВП
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ИНСТИТУТ ВОДНЫХ ПРОБЛЕМ
с 1967 года

Содержание

Гидрология суши как геофизическая наука

Особенности гидрологической системы речного бассейна как физического объекта

Развитие представлений о процессах формирования речного стока

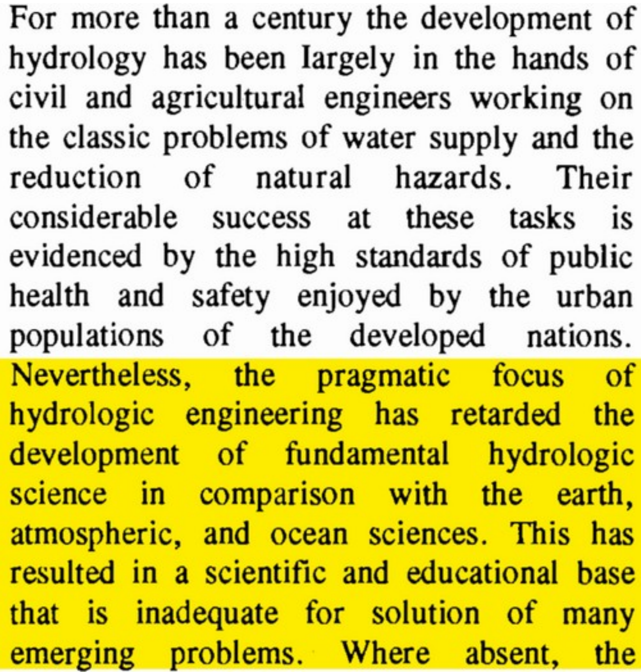
Основные типы математических моделей, применяемых в гидрологии речных бассейнов: краткий исторический экскурс

Развитие методов математического моделирования в гидрологии речных бассейнов в сравнении со смежными геофизическими дисциплинами: аналогии и расхождения (на примере метеорологии)

Гидрология как геофизическая наука

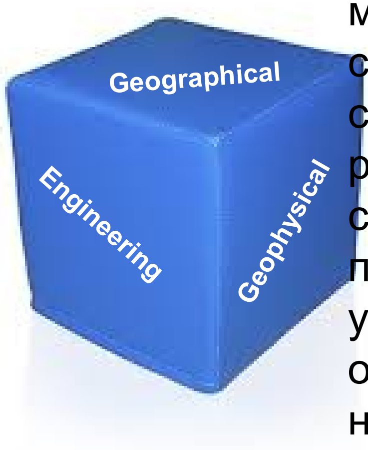
В 1937 году, в предисловии к 3-му изданию учебника «Гидрология суши», один из основоположников отечественной гидрологии Михаил Андреевич Великанов сформулировал «взгляд на гидрологию, как на основу геофизики» и определил предмет гидрологии, как «физика гидросферы» (Великанов, 1937; стр. 3, 8)

В 1987 году Рафаэль Брас и Питер Иглсон – крупнейшие гидрологи второй половины прошлого века – опубликовали статью под провокационным заголовком «Hydrology, The forgotten Earth science»



For more than a century the development of hydrology has been largely in the hands of civil and agricultural engineers working on the classic problems of water supply and the reduction of natural hazards. Their considerable success at these tasks is evidenced by the high standards of public health and safety enjoyed by the urban populations of the developed nations. Nevertheless, the pragmatic focus of hydrologic engineering has retarded the development of fundamental hydrologic science in comparison with the earth, atmospheric, and ocean sciences. This has resulted in a scientific and educational base that is inadequate for solution of many emerging problems. Where absent, the

Гидрология, как геофизическая наука



За прошедшие 35-40 лет произошли существенные изменения в методологии гидрологических исследований и во взглядах научного сообщества на место гидрологии суши в системе наук о Земле. С одной стороны, эти изменения продиктованы объективной (внутренней) логикой развития гидрологии, как естественной науки, в направлении построения собственной методологии на базовых физико-математических принципах и понятиях, единых для смежных геофизических наук. С другой стороны, указанная тенденция стимулируется субъективными, внешними по отношению к науке факторами, которые связаны с общественным запросом на расширение информационного содержания и увеличение точности гидрологических приложений в условиях растущего влияния человека на природную среду.

«Hydrology: No Longer the Forgotten Science» (Bras, 2009) – «гидрология перестала быть забытой <естественной> наукой» – результат произошедшей смены парадигмы в методологии гидрологических исследований, констатированный одним из авторов упомянутой выше статьи (Bras, Eagleson, 1987) через 22 года после ее опубликования и через 72 года после книги М.А. Великанова.

Гидрология, как геофизическая наука

Hydrology is the science, that attempts to answer the question "What happens to the rain?" Penman (1961)

Гидрология, как геофизическая наука

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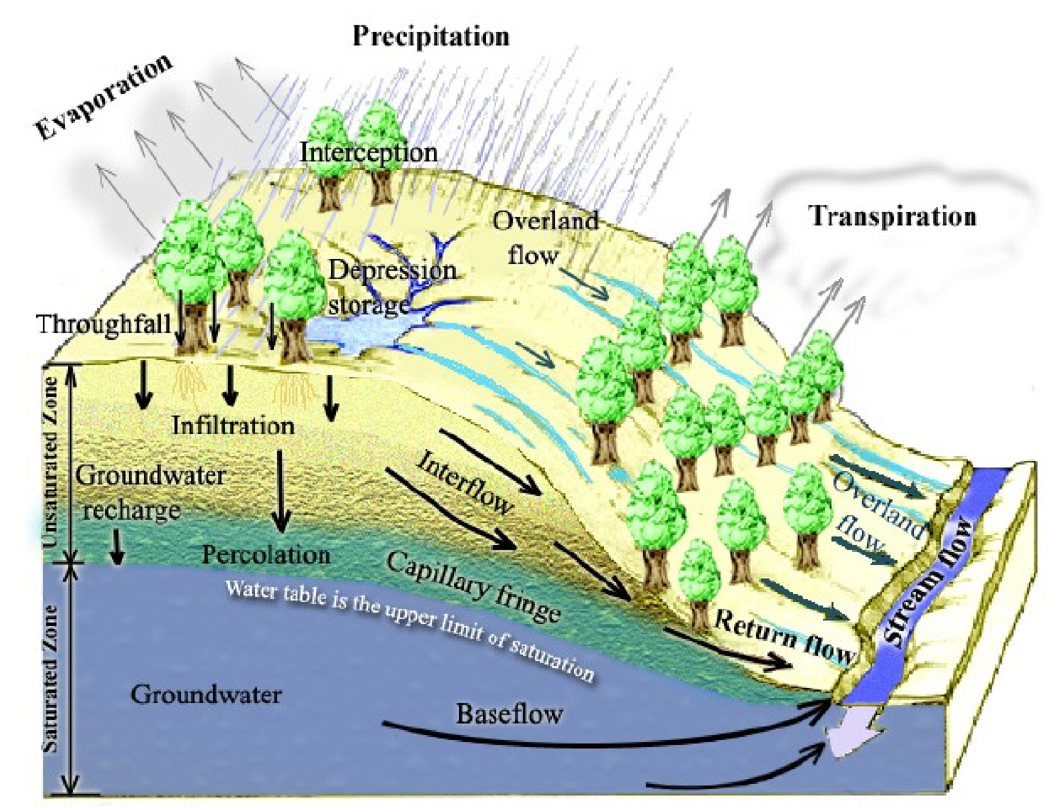
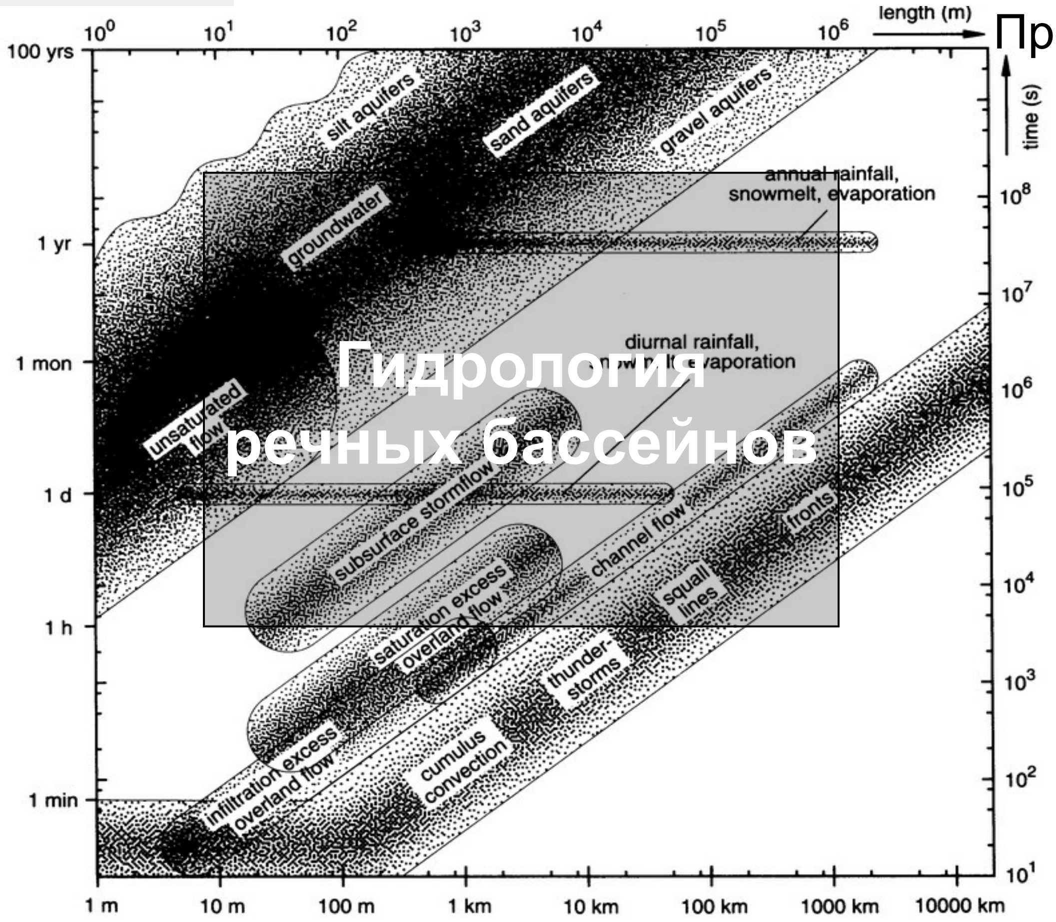


Речной бассейн, как физический объект

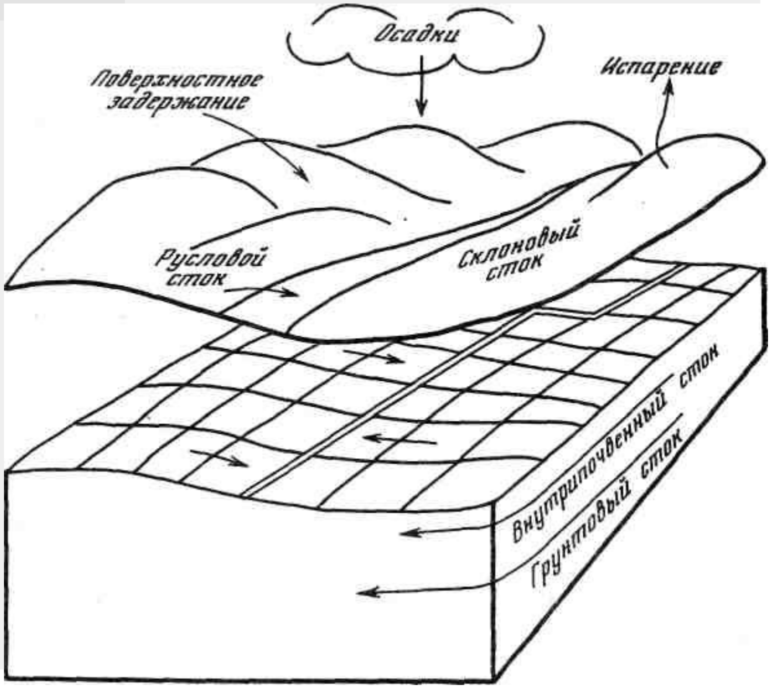


Гидрология речных бассейнов

Пространственные и временные масштабы гидрологических процессов (из Blőschl, Sivapalan, 1994)

Пространственные масштабы физических процессов, происходящих в гидрологических системах речных бассейнов, варьируют в диапазоне шести порядков – до миллионов квадратных километров, а характерные скорости горизонтального, например, движения водных масс в отдельных компонентах системы – в пределах шести-семи порядков: от десятков сантиметров в секунду (русловой сток) до метров в год (глубокий подземный сток).

Речной бассейн, как физический объект



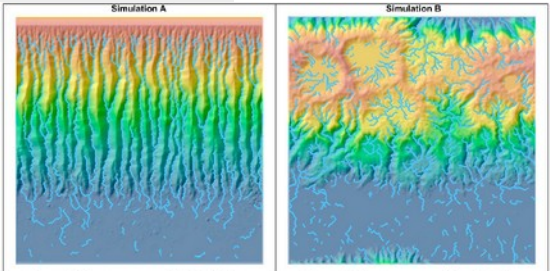
Проблемы описания динамических свойств гидрологической системы речного бассейна, физических механизмов отклика системы в целом и ее отдельных элементов на внешние воздействия, особенностей проявления этих механизмов на разных пространственных и временных масштабах, факторов, определяющих их разнообразие в зависимости от физико-географических и климатических условий – далеко не полный перечень геофизических задач, составляющих содержание современной гидрологии речных бассейнов.

Отличие в их постановке и путях решения по сравнению с традиционными подходами, развитыми в смежных геофизических дисциплинах, во многом связаны со специфическими свойствами гидрологической системы речного бассейна, как физического объекта. При всем многообразии свойств миллионов речных бассейнов Земли, их общие свойства, как физических объектов, можно сформулировать следующим образом

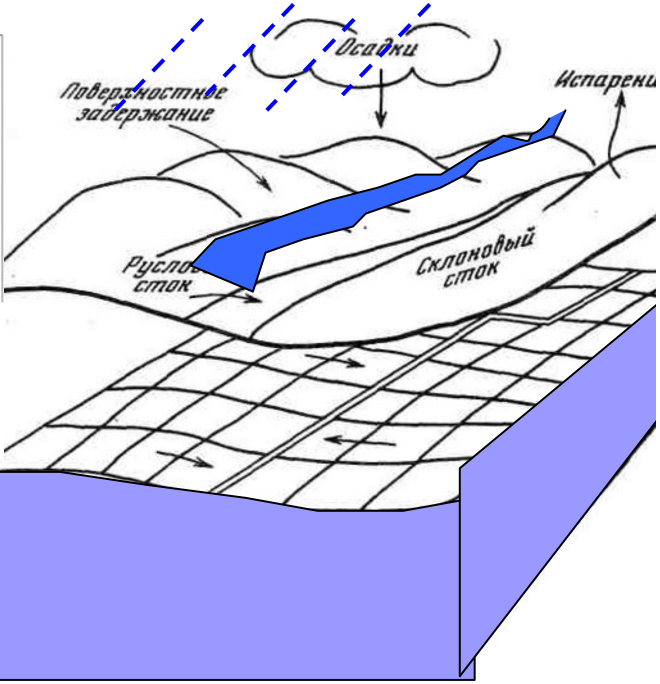
Речной бассейн, как физический объект

1. Речной бассейн – сложная динамическая система.

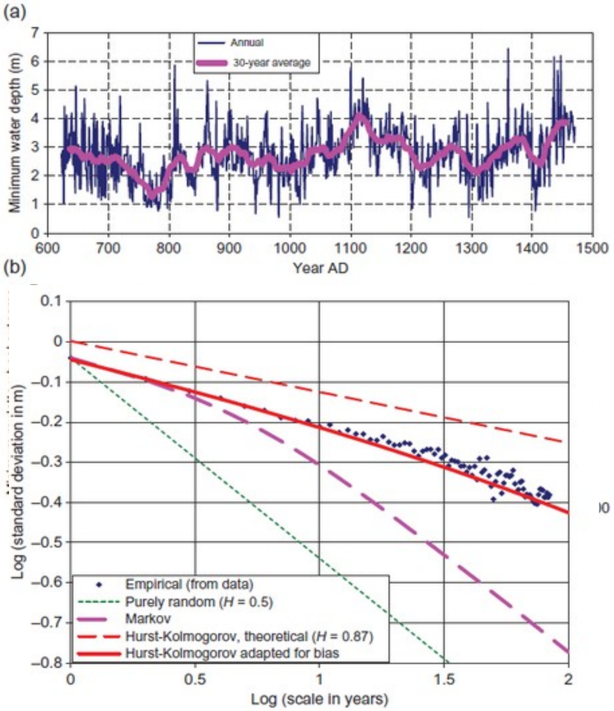
Нелинейная динамика на микромасштабах (напр., flow fingering)



«Пороговая» динамика гидрологических процессов на микро- и мезомасштабах

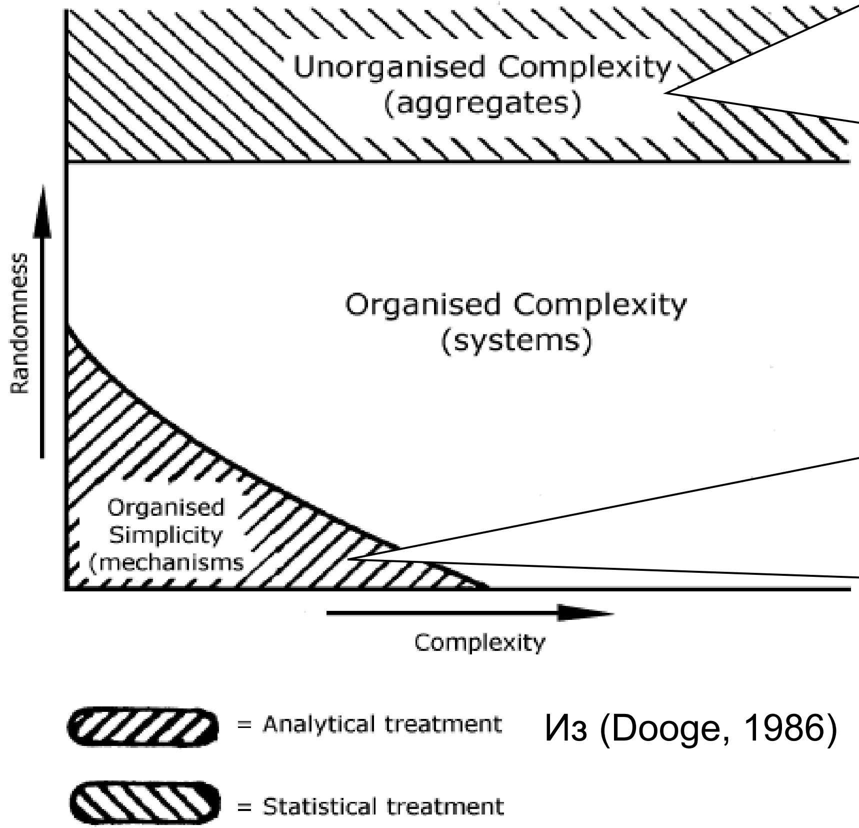


Нелинейная динамика гидрологических процессов на макромасштабах (Koutsoyiannis et al., 2009)



Речной бассейн, как физический объект

2. Речной бассейн – динамическая стохастическая система



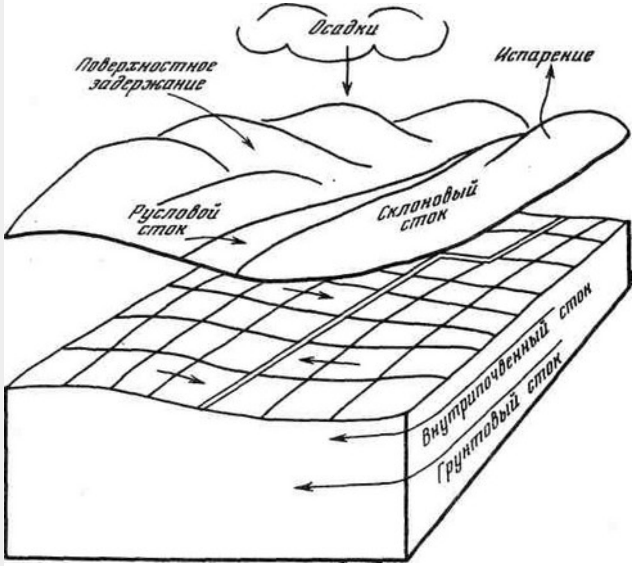
Из (Dooge, 1986)

Слабоструктурированные системы с множеством степеней свободы (агрегаты). Вероятностные свойства системы описываются методами статистической физики с учетом неопределенности параметров и/или краевых условий

Высокоорганизованные системы с малым числом степеней свободы (механизмы). Состояние системы описывается классическими методами детерминистической механики на основе точного знания ее параметров, а также начальных и граничных условий

Речной бассейн, как физический объект

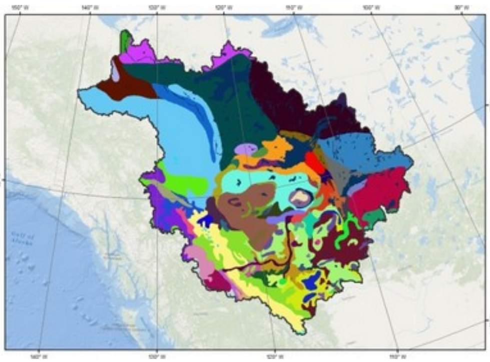
3. Речной бассейн – квазидвумерная система

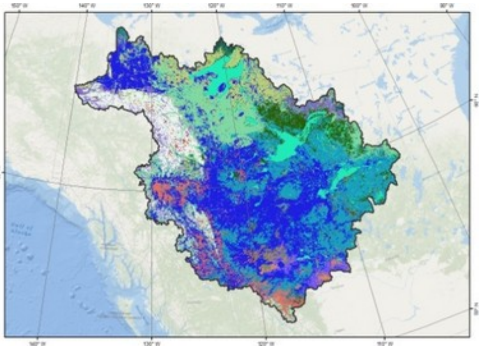


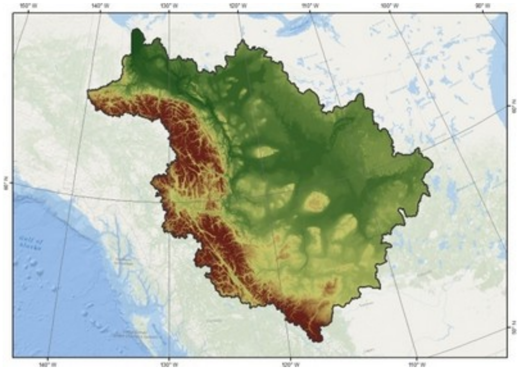
Элементы гидрологической системы речного бассейна, в которых происходят физически значимые процессы вертикального массо- и энергоомена с атмосферой (растительный покров, почвогрунты) и процессы горизонтального массо- и энергопереноса (русловая сеть, водоносные подземные горизонты), можно рассматривать как тонкие пленки, поскольку характерные вертикальные размеры этих элементов на несколько порядков меньше их горизонтальных размеров.

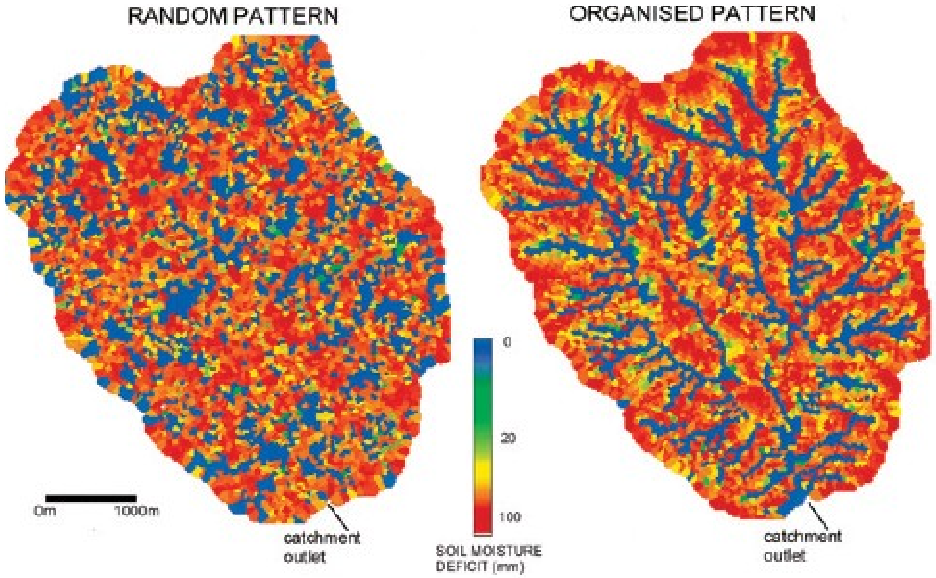
Речной бассейн, как физический объект

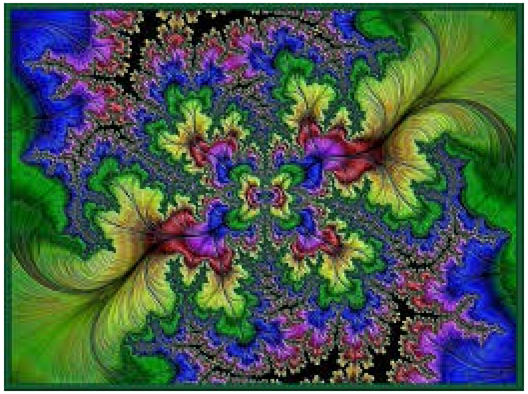
4. Речной бассейн – пространственно неоднородная система





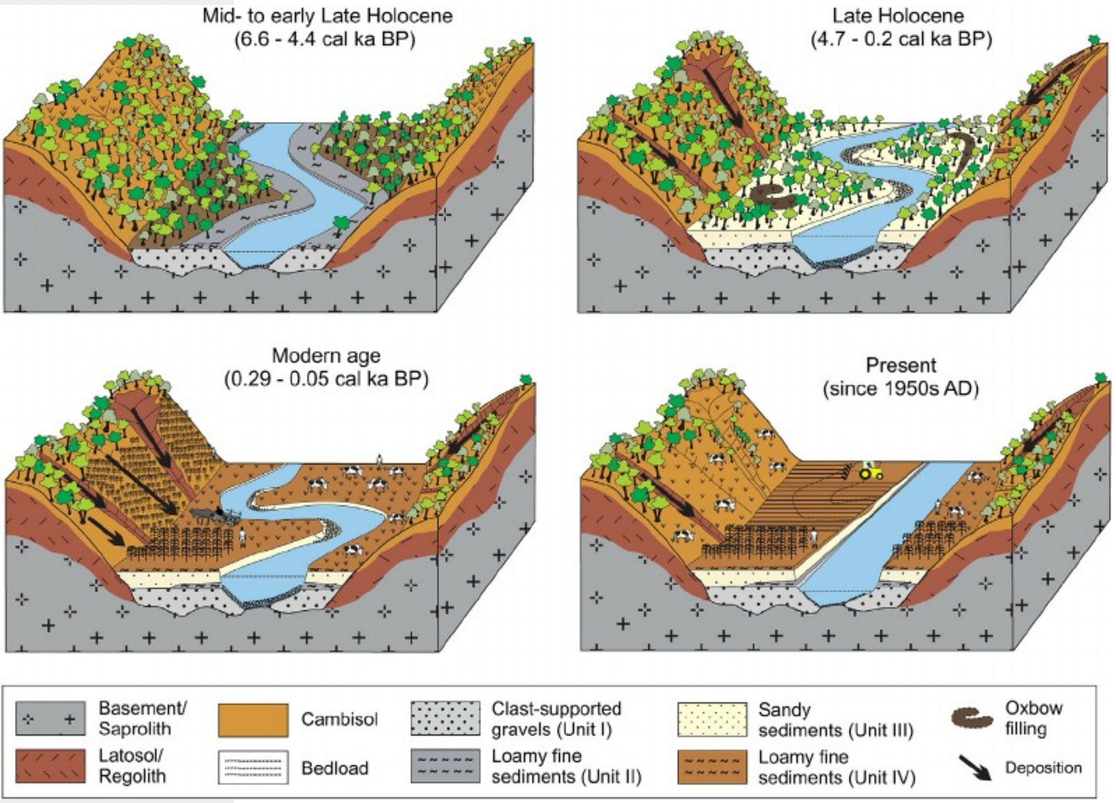






Речной бассейн, как физический объект

5. Речной бассейн – эволюционирующая система с переменными параметрам



Пространственная организация физических свойств бассейна является следствием многолетней взаимосвязанной эволюции эрозионных форм рельефа, почв, ландшафтов, в том числе, под воздействием климатических факторов и биоты, т.е. речной бассейн представляет собой эволюционирующую систему, физические параметры которой изменяются во времени. Помимо природных факторов, параметры речного бассейна могут изменяться вследствие антропогенного воздействия: урбанизация, мелиорация и др., причем скорость этих изменений обычно намного выше скорости природных изменений

Речной бассейн, как физический объект

Вывод 1:

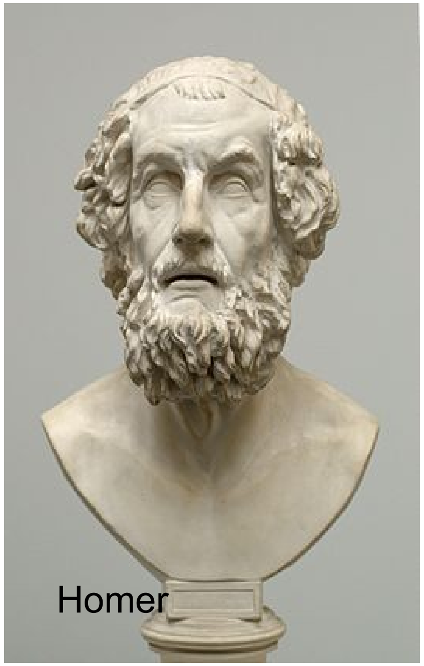
основным средством исследования гидрологической системы (более точно, изучения ее физических свойств и прогноза ее динамики) является математическое моделирование.

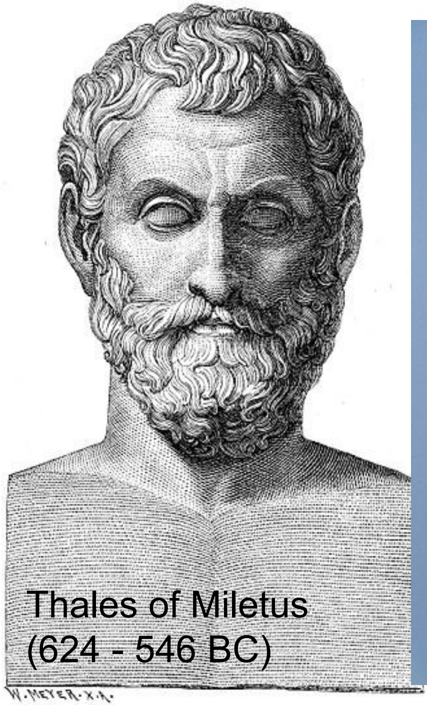
Речной бассейн, как физический объект

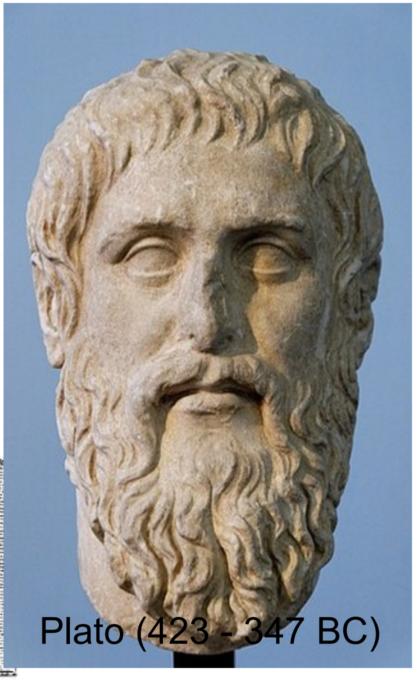
Вывод 2:
решение исследовательских и прогностических задач гидрологии речных бассейнов возможно лишь на основе численных физико-математических моделей с распределенными параметрами, которые строятся на базовых физических принципах и понятиях, единых для смежных геофизических дисциплин, и учитывают специфические свойства конкретного речного бассейна.

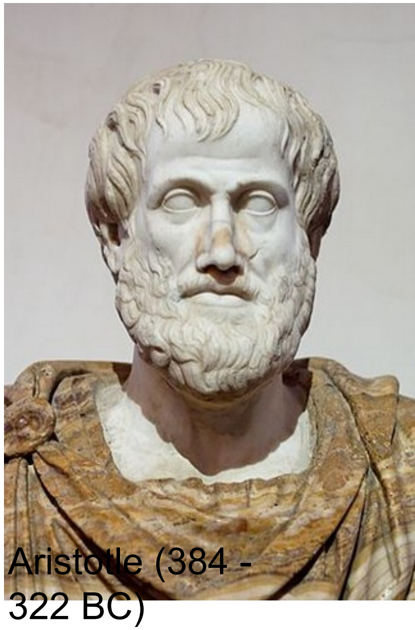
Развитие методов математического моделирования: краткий экскурс в историю

Ancient European civilization


Homer


Thales of Miletus (624 - 546 BC)

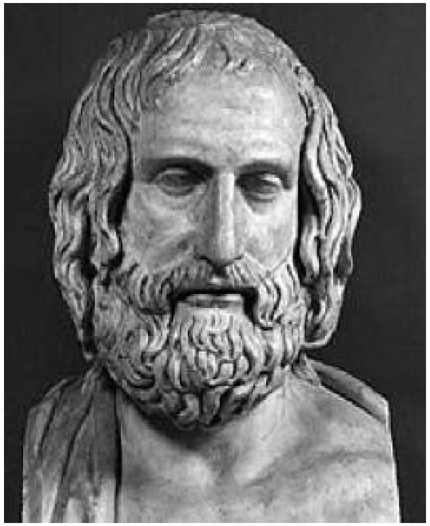

Plato (423 - 347 BC)


Aristotle (384 - 322 BC)

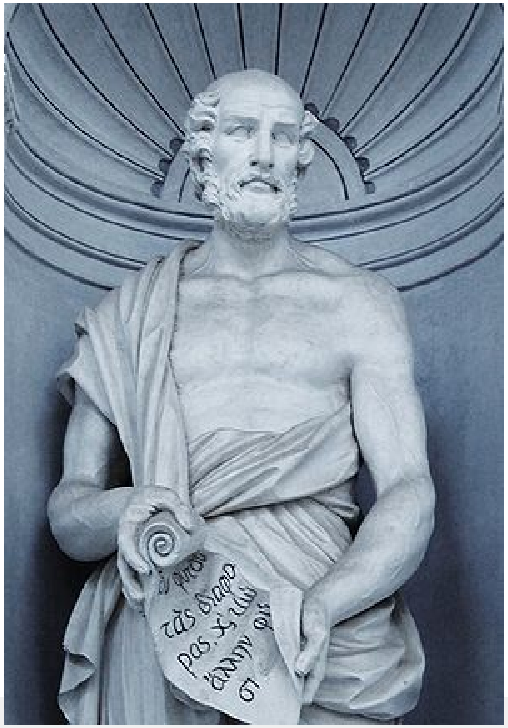
From ancient times many have speculated about the circulation of water…

Much of these speculations were scientifically unsound

Ancient European civilization



The Greek phylosopher Anaxagoras of Clazamenae (500-428 BC) formed the first primitive version of hydrologic cycle.

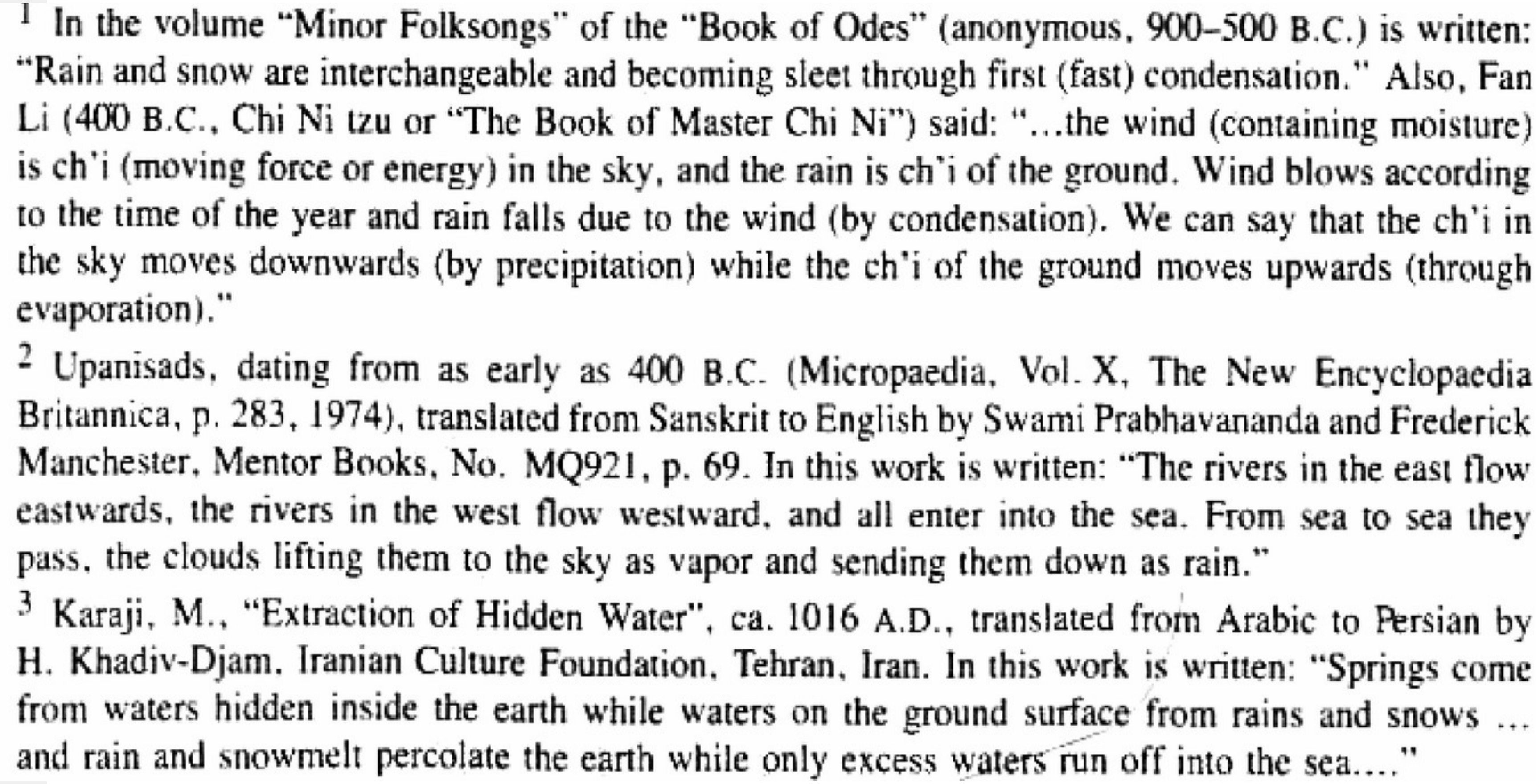


The improvement of this theory was made by another Greek phylosopher, Theophrastus, (372-287 BC) who correctly described the water cycle in the atmosphere

Ancient European civilization

After studying the works of Theophrastus, the Roman architect and engineer Marcus Vitruvius (80(70)-15 BC) conceived the theory that is now generally accepted: he extended Theophrastus’s explanation, claiming that groundwater was largely derived from rain and snow through infiltration from the ground surface. This may be considered forerunner of the modern version of hydrologic cycle.

Ancient Asian civilization



[1] In the volume "Minor Folksongs" of the "Book of Odes" (anonymous, 900–500 B.C.) is written: "Rain and snow are interchangeable and becoming sleet through first (fast) condensation." Also, Fan Li (400 B.C., Chi Ni tzu or "The Book of Master Chi Ni") said: "…the wind (containing moisture) is ch'i (moving force or energy) in the sky, and the rain is ch'i of the ground. Wind blows according to the time of the year and rain falls due to the wind (by condensation). We can say that the ch'i in the sky moves downwards (by precipitation) while the ch'i of the ground moves upwards (through evaporation)."

[2] Upanisads, dating from as early as 400 B.C. (Micropaedia, Vol. X, The New Encyclopaedia Britannica, p. 283, 1974), translated from Sanskrit to English by Swami Prabhavananda and Frederick Manchester, Mentor Books, No. MQ921, p. 69. In this work is written: "The rivers in the east flow eastwards, the rivers in the west flow westward, and all enter into the sea. From sea to sea they pass, the clouds lifting them to the sky as vapor and sending them down as rain."

[3] Karaji, M., "Extraction of Hidden Water", ca. 1016 A.D., translated from Arabic to Persian by H. Khadiv-Djam. Iranian Culture Foundation, Tehran, Iran. In this work is written: "Springs come from waters hidden inside the earth while waters on the ground surface from rains and snows … and rain and snowmelt percolate the earth while only excess waters run off into the sea.…"

Renaissance

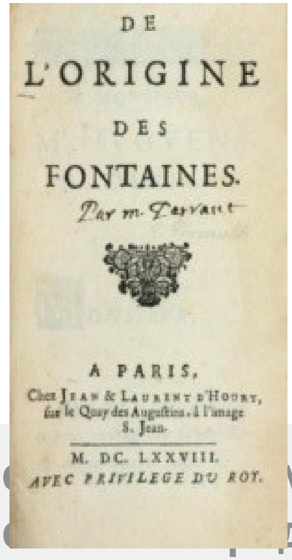
Leonardo da Vinci measured the velocity distribution across a stream section (adopted from Frazier, 1974)

Leonardo da Vinci (1452-1519) made the first systematic studies of velocity distribution in streams using a weighted rod held afloat by an inflated animal bladder. Prior to Leonardo, it was thought that water flowed more rapidly at the bottom of a stream

XVI-XVII century: beginning of scientific hydrology

Before the 17th century, many natural philosophers accepted the Greek theory (proposed by people who lived in a semiarid climate on limestone hills) that rainfall was insufficient to feed springs and rivers. It was thought that spring water was purified sea water from deep within the earth.

In 1580, Bernard Palissy proposed the theory of the hydrologic cycle. He showed that rivers originate from rainfall, thus refuting the old-age theory that streams were supplied directly by the sea.



DE
L'ORIGINE
DES
FONTAINES.
Par m. Perrault

A PARIS,
Chez Jean & Laurent d'Houry,
ſur le Quay des Auguſtins, à l'image
S. Jean.
M. DC. LXXVIII.
AVEC PRIVILEGE DU ROY.

Pierre Perrault (1608–1680) made careful observations of rainfall and streamflow in the Seine River basin, confirming Palissy's hunch and thus began the study of modern scientific hydrology. His numerical estimates demonstrated that the annual river runoff was only one-sixth of the amount of water falling as rain or snow over the drainage basin in a year.

XVIII-XIX century: flowering hydraulics

Development of Hydrology: brief historical excursion

Hydraulic measurements and experiments flourished during the 18 century. New hydraulic principles were discovered such as the Bernouli equation and Chezy formula and better instruments were developed.

Dalton – principle for evaporation (1802)

The theory of capillary flow (Hagen-Poiseuille equation, 1839)

Rational method by Malvaney (1850)

Darcy principle for porous media flow (1856)

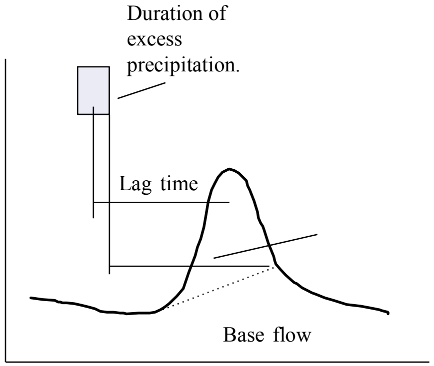
Manning’s open-channel flow (1891)

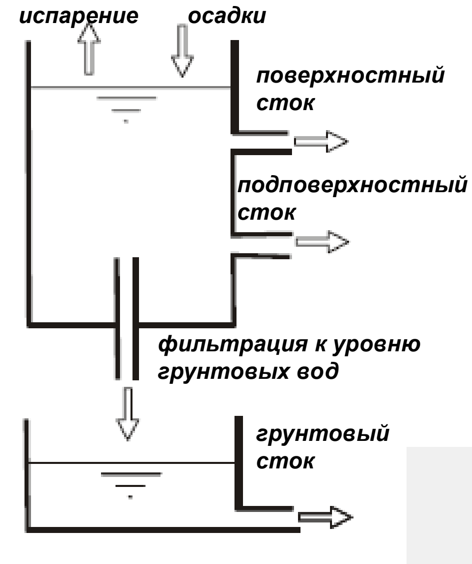
Развитие методов математического моделирования: краткий экскурс в историю

1910-1920-е годы (“Empirical Era”) : начало накопления эмпирических данных, создание первых моделей гидрологических процессов

1930-1940-е годы (“Rationalization Era”): обобщение эмпирических фактов, начало построения гидрологической теории

1950-1960-е годы (“Systems Era”): внедрение в гидрологию речных бассейнов результатов теории динамических систем, создание первых численных (концептуальных) моделей формирования речного стока, разработка первых физико-математических моделей гидрологических процессов

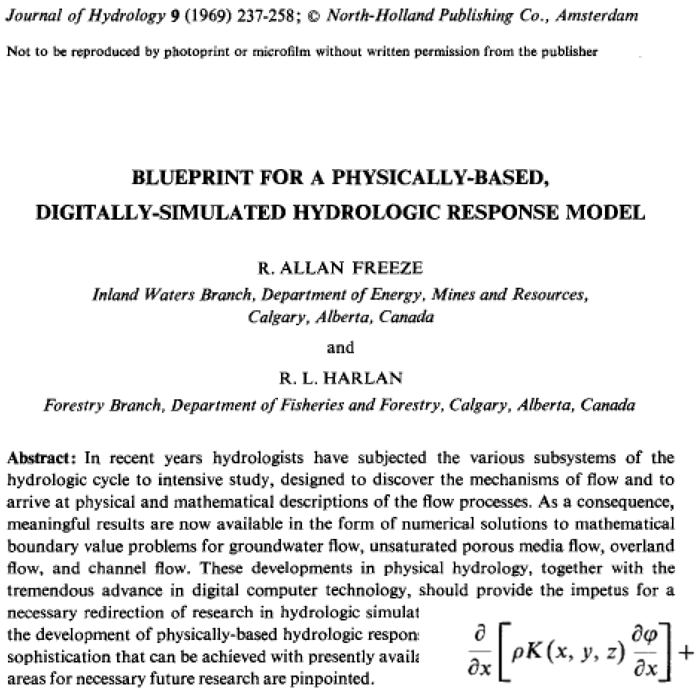




Развитие методов математического моделирования: краткий экскурс в историю

1970-1980-е годы (“Process era”): создание теории и практики физико-математического моделирования формирования речного стока

1990-2000-е годы (“Geosciences era”): становление гидрологии суши, как геофизической науки



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BLUEPRINT FOR A PHYSICALLY-BASED, DIGITALLY-SIMULATED HYDROLOGIC RESPONSE MODEL

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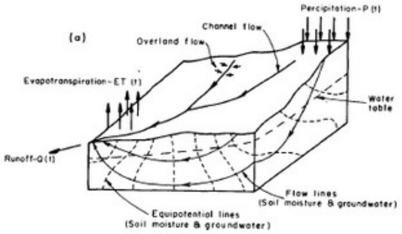
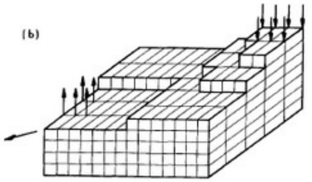
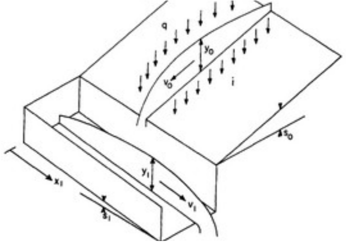
Abstract: In recent years hydrologists have subjected the various subsystems of the hydrologic cycle to intensive study, designed to discover the mechanisms of flow and to arrive at physical and mathematical descriptions of the flow processes. As a consequence, meaningful results are now available in the form of numerical solutions to mathematical boundary value problems for groundwater flow, unsaturated porous media flow, overland flow, and channel flow. These developments in physical hydrology, together with the tremendous advance in digital computer technology, should provide the impetus for a necessary redirection of research in hydrologic simulat
the development of physically-based hydrologic respon
sophistication that can be achieved with presently availa
areas for necessary future research are pinpointed.





$$\frac{\partial}{\partial x}\left[\rho K(x,y,z)\frac{\partial\varphi}{\partial x}\right]+\frac{\partial}{\partial y}\left[\rho K(x,y,z)\frac{\partial\varphi}{\partial y}\right]+\frac{\partial}{\partial z}\left[\rho K(x,y,z)\frac{\partial\varphi}{\partial z}\right]=\rho\frac{\partial\theta}{\partial t}+\theta\frac{\partial\rho}{\partial t}$$



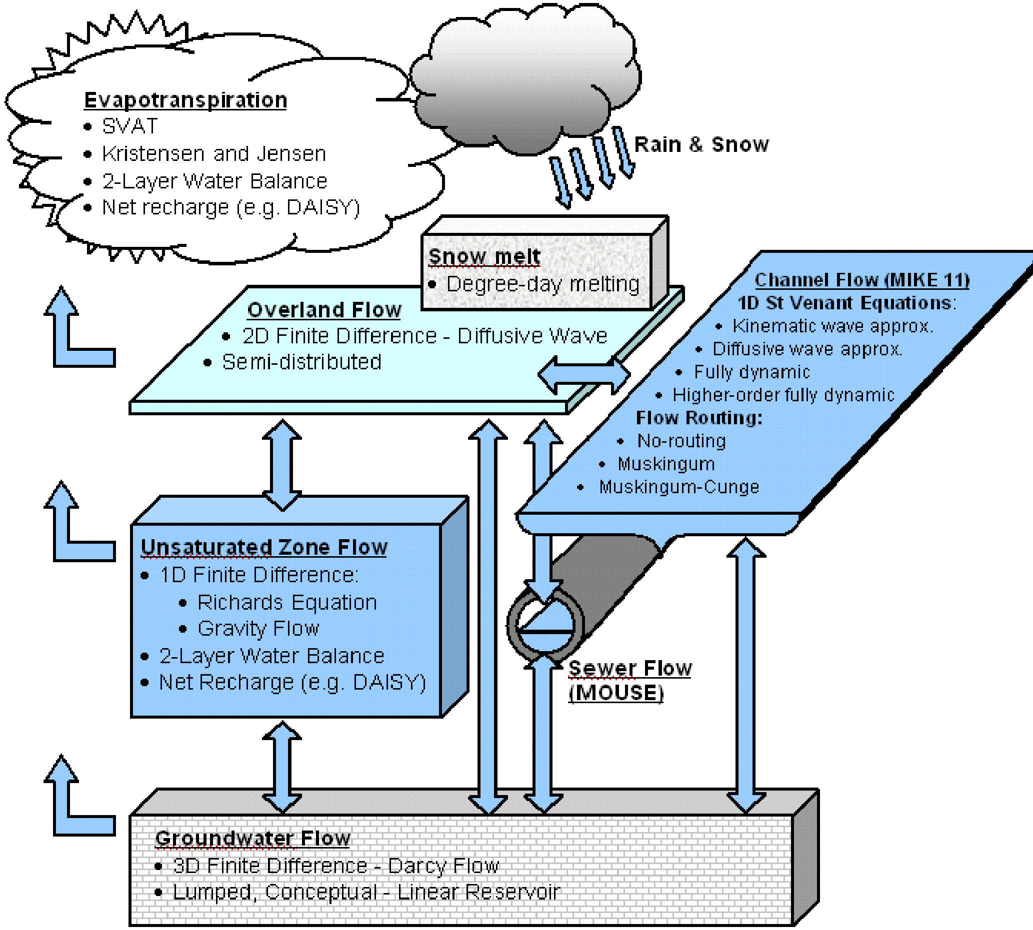
$$\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}\right)+2\rho g\beta\left[\left(\frac{\partial\varphi}{\partial x}\right)^2+\left(\frac{\partial\varphi}{\partial y}\right)^2+\left(\frac{\partial\varphi}{\partial z}\right)^2-\frac{\partial\varphi}{\partial z}\right]=\frac{\rho g}{k}\left[(1-\theta)\,\alpha+\theta\beta\right]\frac{\partial\varphi}{\partial t}.$$

Развитие методов математического моделирования: краткий экскурс в историю

Système Hydrologique Européen (SHE) –IH (UK), SOGREAH (France), DHI (Denmark) (Abbot et al., 1986)

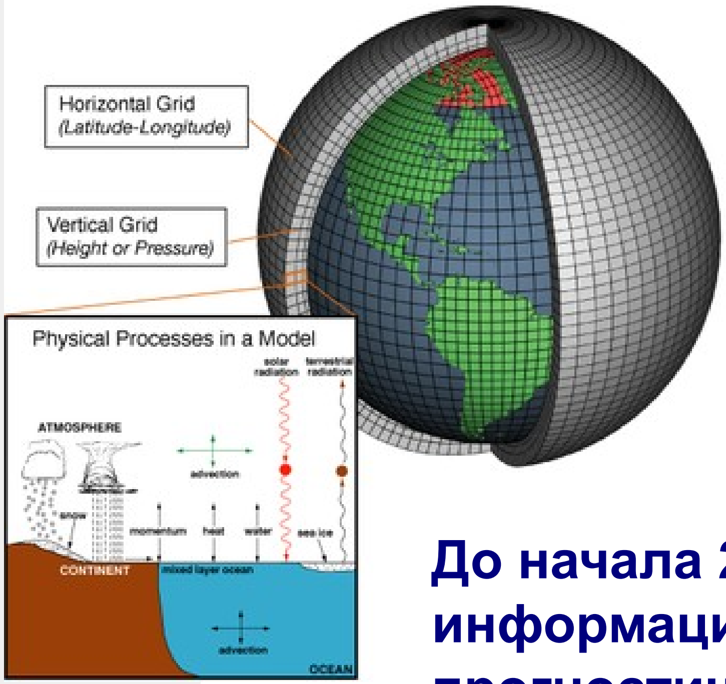
Institute of Hydrology Distributed Model (IHDM) Beven, Calver and Morris (1987)

Система физико-математических моделей ИВП РАН (Кучмент, Демидов, Мотовилов, 1983; Kuchment et al., 1986; Кучмент, Гельфан, 1993)



Thus, by the end of 1980s, hydrological society began to develop watershed modelling systems founded on basic physical principles. Hydrology began to form as geophysical science, similarly to the related scientific disciplines, such as meteorology, climatlogy, oceanology.

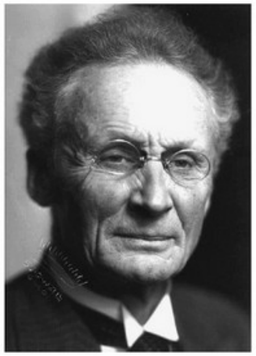
Brief retrospective of computer weather prediction and atmospheric circulation modelling



“Among the most significant scientific advances of the past century is our ability to simulate complex physical systems using numerical models and therewith to predict their evolution. One outstanding example is the development of general circulation models (GCMs) of the atmosphere and ocean” (P. Linch, 2007)

До начала 20 века – накопление метеорологической информации и попытки построения эмпирических прогностических зависимостей статистическими методами (открытие южной осцилляции). *«… mainstream meteorology had largely given up attempting to forecast the state of the atmosphere using statistical approaches based solely on data” (Nebeker 1995)*

1890: “meteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere” (Cleveland Abbe “The physical basis of long-range weather forecasting”)

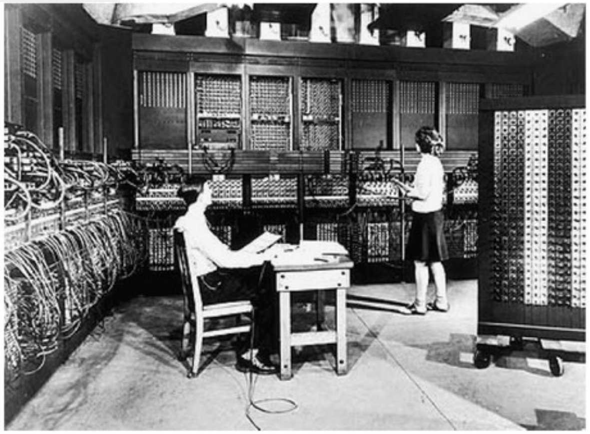


1904: Vilhelm Bjerkness предложил двухшаговую процедуру прогноза погоды: (1) диагностика (расчет начальных условий с использованием наблюдений) и (2) прогноз путем решения системы семи уравнений состояния атмосферы. Решения качественные (графические методы)

1911: Lewis Fry Richardson реализовал и развил прогностическую схему Бьеркенса. Но без компьютеров эта схема была по-прежнему нереализуема «Perhaps some day in the dim future it will be possible to advance the computations faster than the weatheradvances . . .. But that is a dream.» («Weather Prediction by Numerical Process», 1922)

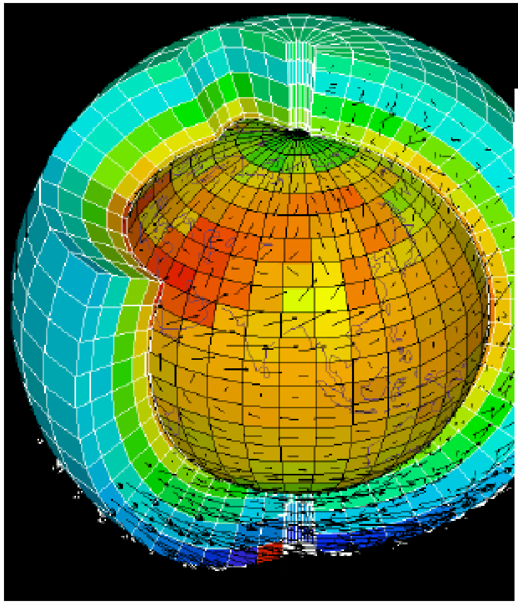
An artist's impression of the "Forecast Factory" described by Lewis F. Richardson in "Weather Prediction by Numerical Process", Section 11.2 "The Speed and Organization of Computing" (from Lynch, 2008)

The Electronic Computer Project of von Neumann

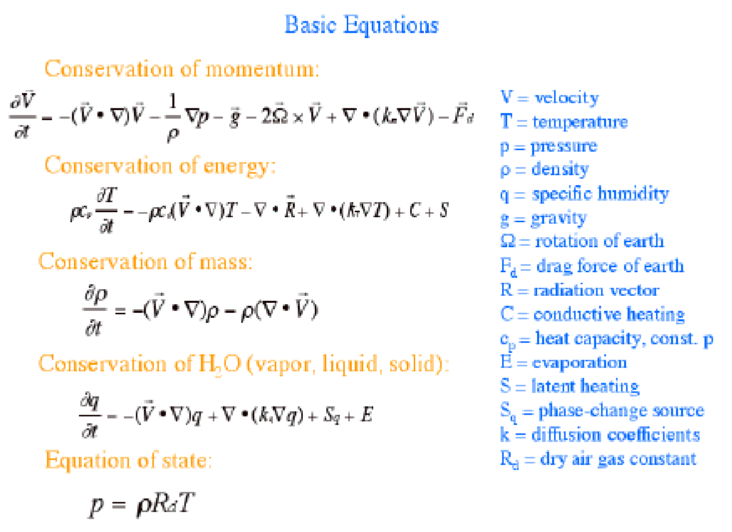


Первые прогнозы погоды, основанные на численном интегрировании гидродинамических уравнений состояния атмосферы – начало 1950-х годов

Jule Charney



Решаемая система уравнений гидротермодинамики атмосферы:



Basic Equations

Conservation of momentum:

$$\frac{\partial \vec{V}}{\partial t} = -(\vec{V} \bullet \nabla)\vec{V} - \frac{1}{\rho}\nabla p - \vec{g} - 2\vec{\Omega} \times \vec{V} + \nabla \bullet (k_m \nabla \vec{V}) - \vec{F}_d$$

Conservation of energy:

$$\rho c_v \frac{\partial T}{\partial t} = -\rho c_p (\vec{V} \bullet \nabla) T - \nabla \bullet \vec{R} + \nabla \bullet (k_T \nabla T) + C + S$$

Conservation of mass:

$$\frac{\partial \rho}{\partial t} = -(\vec{V} \bullet \nabla)\rho - \rho(\nabla \bullet \vec{V})$$

Conservation of H_2O (vapor, liquid, solid):

$$\frac{\partial q}{\partial t} = -(\vec{V} \bullet \nabla) q + \nabla \bullet (k_q \nabla q) + S_q + E$$

Equation of state:

$$p = \rho R_d T$$

V = velocity
T = temperature
p = pressure
ρ = density
q = specific humidity
g = gravity
Ω = rotation of earth
F_d = drag force of earth
R = radiation vector
C = conductive heating
c_p = heat capacity, const. p
E = evaporation
S = latent heating
S_q = phase-change source
k = diffusion coefficients
R_d = dry air gas constant

Modern GCM Genealogy

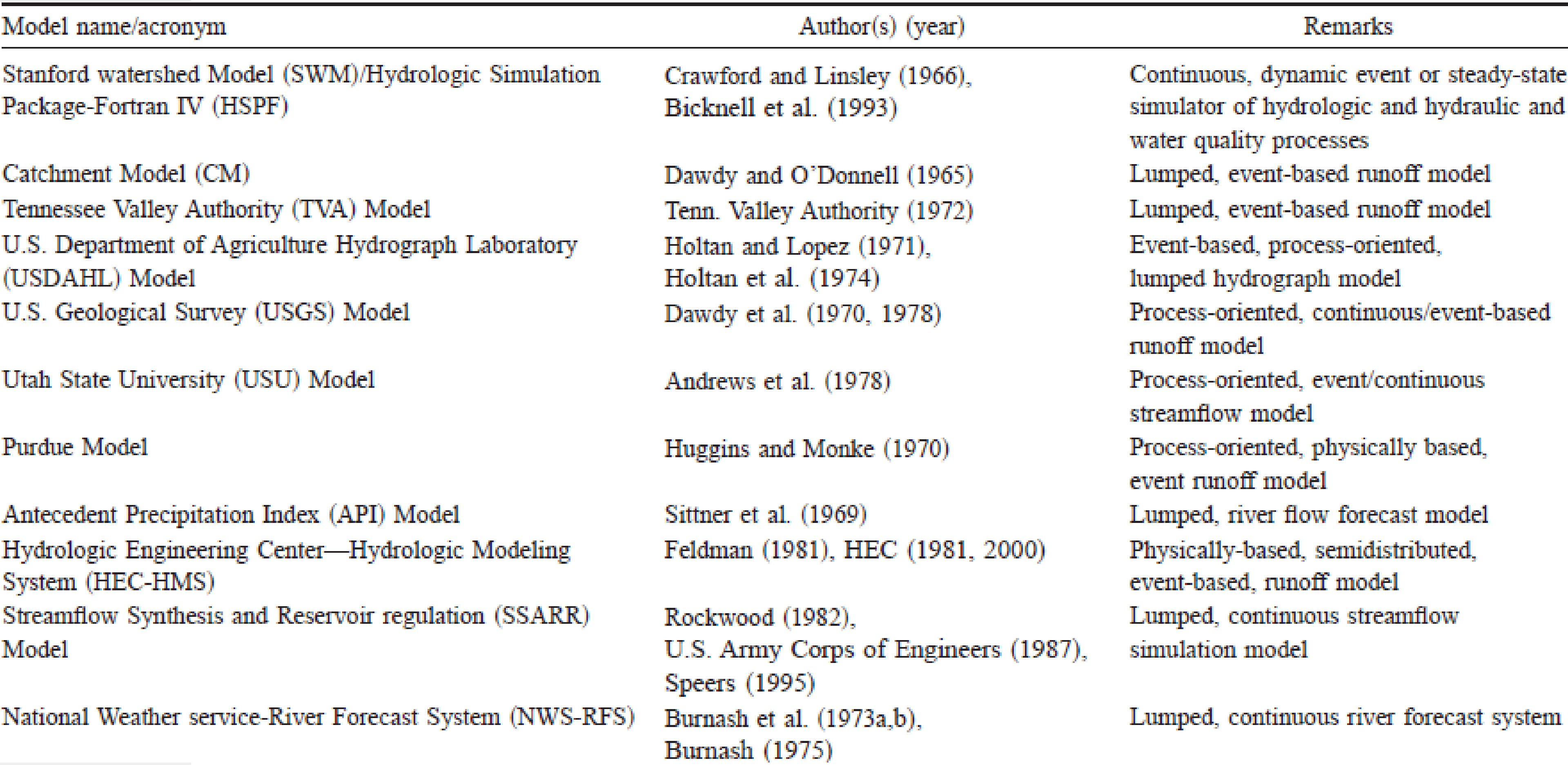
Развитие

теоретических представлений об атмосферных процессах

численных методов

технологий измерения (напр., появление радиозондов)

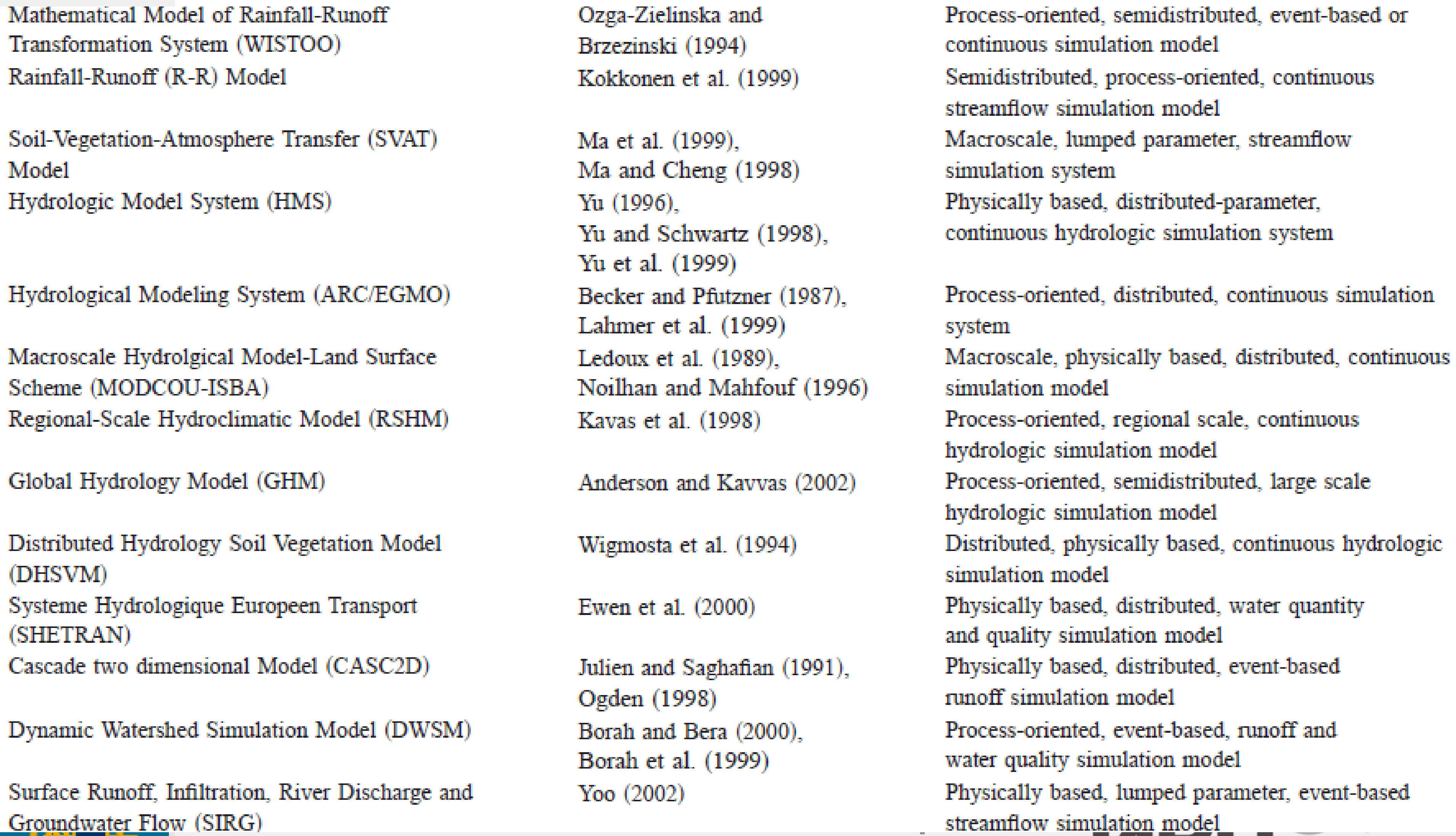
вычислительных ресурсов



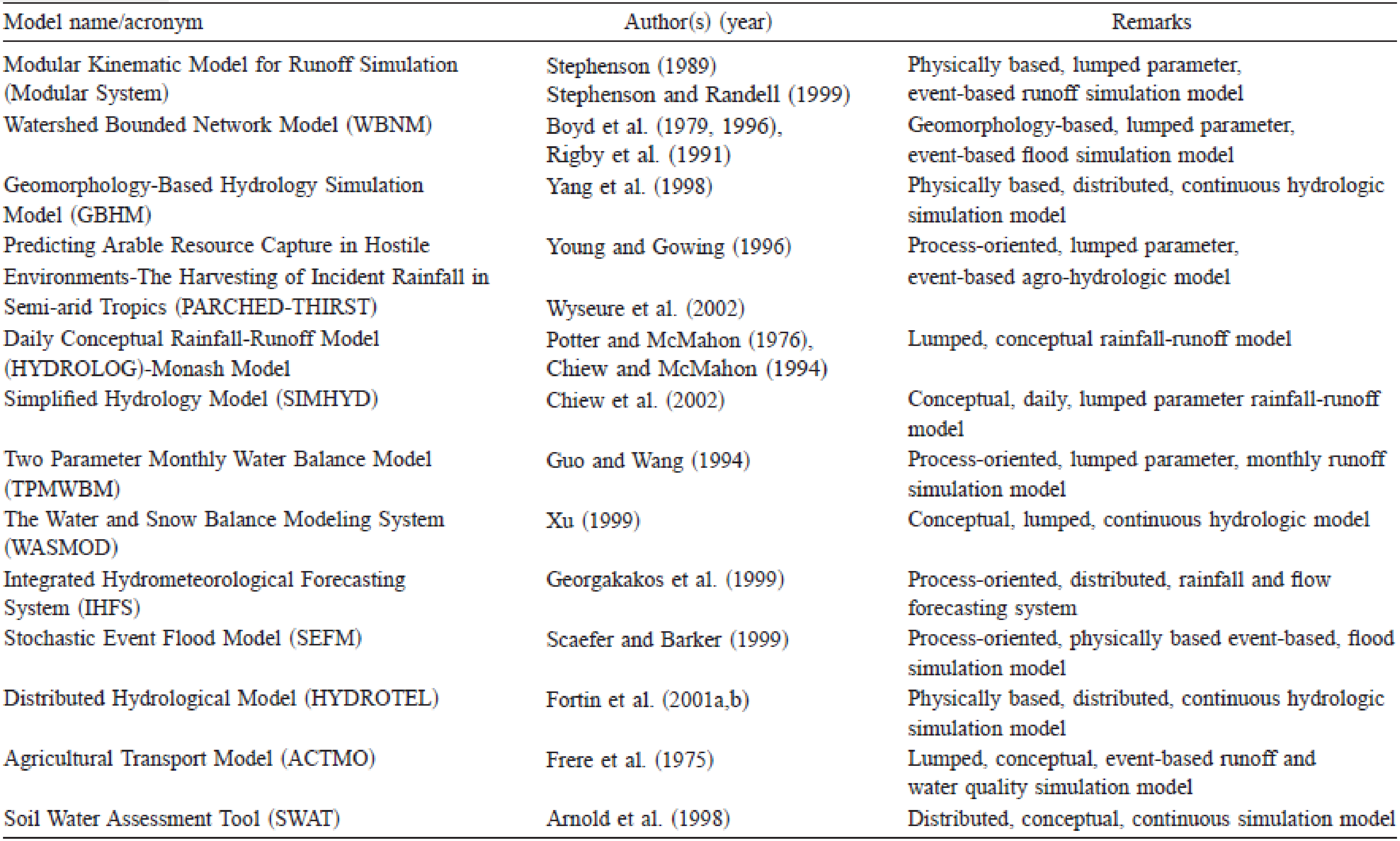
Model name/acronym	Author(s) (year)	Remarks
Stanford watershed Model (SWM)/Hydrologic Simulation Package-Fortran IV (HSPF)	Crawford and Linsley (1966), Bicknell et al. (1993)	Continuous, dynamic event or steady-state simulator of hydrologic and hydraulic and water quality processes
Catchment Model (CM)	Dawdy and O'Donnell (1965)	Lumped, event-based runoff model
Tennessee Valley Authority (TVA) Model	Tenn. Valley Authority (1972)	Lumped, event-based runoff model
U.S. Department of Agriculture Hydrograph Laboratory (USDAHL) Model	Holtan and Lopez (1971), Holtan et al. (1974)	Event-based, process-oriented, lumped hydrograph model
U.S. Geological Survey (USGS) Model	Dawdy et al. (1970, 1978)	Process-oriented, continuous/event-based runoff model
Utah State University (USU) Model	Andrews et al. (1978)	Process-oriented, event/continuous streamflow model
Purdue Model	Huggins and Monke (1970)	Process-oriented, physically based, event runoff model
Antecedent Precipitation Index (API) Model	Sittner et al. (1969)	Lumped, river flow forecast model
Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS)	Feldman (1981), HEC (1981, 2000)	Physically-based, semidistributed, event-based, runoff model
Streamflow Synthesis and Reservoir regulation (SSARR) Model	Rockwood (1982), U.S. Army Corps of Engineers (1987), Speers (1995)	Lumped, continuous streamflow simulation model
National Weather service-River Forecast System (NWS-RFS)	Burnash et al. (1973a,b), Burnash (1975)	Lumped, continuous river forecast system

University of British Columbia (UBC) Model	Quick and Pipes (1977), Quick (1195)	Process-oriented, lumped parameter, continuous simulation model
Tank Model	Sugawara et al. (1974), Sugawara (1995)	Process-oriented, semidistributed or lumped continuous simulation model
Runoff Routing Model (RORB)	Laurenson (1964), Laurenson and Mein (1993, 1995)	Lumped, event-based runoff simulation model
Agricultural Runoff Model (ARM)	Donigian et al. (1977)	Process-oriented, lumped runoff simulation model
Storm Water Management Model (SWMM)	Metcalf and Eddy et al. (1971), Huber and Dickinson (1988), Huber (1995)	Process-oriented, semidistributed, continuous stormflow model
Xinanjiang Model	Zhao et al. (1980), Zhao and Liu (1195)	Process-oriented, lumped, continuous simulation model
Hydrological Simulation (HBV) Model	Bergstrom (1976, 1992, 1995)	Process-oriented, lumped, continuous streamflow simulation model
Great Lakes Environmental Research Laboratory (GLERL) Model	Croley (1982, 1983)	Physically based, semidistributed continuous simulation model
Pennsylvania State University—Urban Runoff Model (PSU-URM)	Aron and Lakatos (1980)	Lumped, event-based urban runoff model
Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS)	USDA (1980)	Process-oriented, lumped parameter, agricultural runoff and water quality model
Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)	Beasley et al. (1977), Bouraoui et al. (2002)	Event-based or continuous, lumped parameter runoff and sediment yield simulation model
Erosion Productivity Impact Calculator (EPIC) Model	Williams et al. (1984), Williams (1995a,b)	Process-oriented, lumped-parameter, continuous water quantity and quality simulation model
Simulator for Water Resources in Rural Basins (SWRRB)	Williams et al. (1985), Williams (1995a,b)	Process-oriented, semidistributed, runoff and sediment yield simulation model
Simulation of Production and Utilization of Rangelands (SPUR)	Wight and Skiles (1987), Carlson and Thurow (1992), Carlson et al. (1995)	Physically based, lumped parameter ecosystem simulation model
National Hydrology Research Institute (NHRI) Model	Vandenberg (1989)	Physically based, lumped parameter, continuous hydrologic simulation model
Technical Report-20 (TR-20) Model	Soil Conservation Service (1965)	Lumped parameter, event based runoff simulation model

Systeme Hydrologique Europeen/Systeme Hydrologique Europeen Sediment (SHE/SHESED)	Abbott et al. (1986a,b), Bathurst et al. (1995)	Physically based, distributed, continuous streamflow and sediment simulation
Institute of Hydrology Distributed Model (IHDM)	Beven et al. (1987), Calver and Wood (1995)	Physically based, distributed, continuous rainfall-runoff modeling system
Physically Based Runoff Production Model (TOPMODEL)	Beven and Kirkby (1976, 1979), Beven (1995)	Physically based, distributed, continuous hydrologic simulation model
Agricultural Non-Point Source Model (AGNPS)	Young et al. (1989, 1995)	Distributed parameter, event-based, water quantity and quality simulation model
Kinematic Runoff and Erosion Model (KINEROS)	Woolhiser et al. (1990), Smith et al. (1995)	Physically based, semidistributed, event-based, runoff and water quality simulation model
Groundwater Loading Effects of Agricultural Management Systems (GLEAMS)	Knisel et al. (1993), Knisel and Williams (1995)	Process-oriented, lumped parameter, event-based water quantity and quality simulation model
Generalized River Modeling Package—Systeme Hydroloque Europeen (MIKE-SHE)	Refsgaard and Storm (1195)	Physically based, distributed, continuous hydrologic and hydraulic simulation model
Simple Lumped Reservoir Parametric (SLURP) Model	Kite (1995)	Process-oriented, distributed, continuous simulation model
Snowmelt Runoff Model (SRM)	Rango (1995)	Lumped, continuous snowmelt-runoff simulation model
THALES	Grayson et al. (1195)	Process-oriented, distributed-parameter, terrain analysis-based, event-based runoff simulation model
Constrained Linear Simulation (CLS)	Natale and Todini (1976a,b, 1977)	Lumped parameter, event-based or continuous runoff simulation model
ARNO (Arno River) Model	Todini (1988a,b, 1996)	Semidistributed, continuous rainfall-runoff simulation model
Waterloo Flood System (WATFLOOD)	Kouwen et al. (1993), Kouwen (2000)	Process-oriented, semidistributed continuous flow simulation model
Topgraphic Kinematic Approximation and Integration (TOPIKAPI) Model	Todini (1995)	Distributed, physically based, continuous rainfall-runoff simulation model
Hydrological (CEQUEAU) Model	Morin et al. (1995, 1998)	Distributed, process-oriented, continuous runoff simulation model
Large Scale Catchment Model (LASCAM)	Sivapalan et al. (1996a,b,c)	Conceptual, semidistributed, large scale, continuous, runoff and water quality simulation model

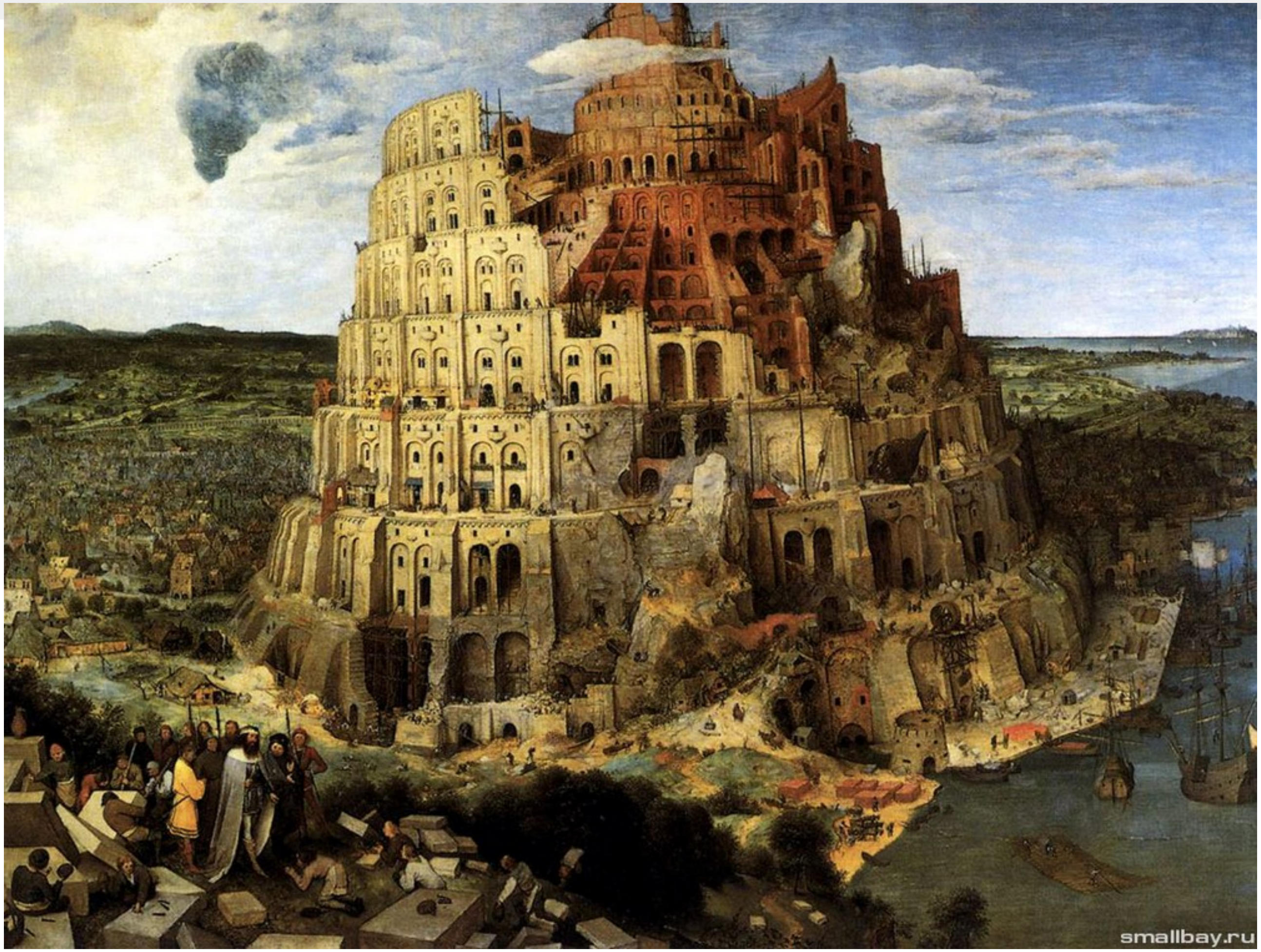


Mathematical Model of Rainfall-Runoff Transformation System (WISTOO)	Ozga-Zielinska and Brzezinski (1994)	Process-oriented, semidistributed, event-based or continuous simulation model
Rainfall-Runoff (R-R) Model	Kokkonen et al. (1999)	Semidistributed, process-oriented, continuous streamflow simulation model
Soil-Vegetation-Atmosphere Transfer (SVAT) Model	Ma et al. (1999), Ma and Cheng (1998)	Macroscale, lumped parameter, streamflow simulation system
Hydrologic Model System (HMS)	Yu (1996), Yu and Schwartz (1998), Yu et al. (1999)	Physically based, distributed-parameter, continuous hydrologic simulation system
Hydrological Modeling System (ARC/EGMO)	Becker and Pfutzner (1987), Lahmer et al. (1999)	Process-oriented, distributed, continuous simulation system
Macroscale Hydrolgical Model-Land Surface Scheme (MODCOU-ISBA)	Ledoux et al. (1989), Noilhan and Mahfouf (1996)	Macroscale, physically based, distributed, continuous simulation model
Regional-Scale Hydroclimatic Model (RSHM)	Kavas et al. (1998)	Process-oriented, regional scale, continuous hydrologic simulation model
Global Hydrology Model (GHM)	Anderson and Kavvas (2002)	Process-oriented, semidistributed, large scale hydrologic simulation model
Distributed Hydrology Soil Vegetation Model (DHSVM)	Wigmosta et al. (1994)	Distributed, physically based, continuous hydrologic simulation model
Systeme Hydrologique Europeen Transport (SHETRAN)	Ewen et al. (2000)	Physically based, distributed, water quantity and quality simulation model
Cascade two dimensional Model (CASC2D)	Julien and Saghafian (1991), Ogden (1998)	Physically based, distributed, event-based runoff simulation model
Dynamic Watershed Simulation Model (DWSM)	Borah and Bera (2000), Borah et al. (1999)	Process-oriented, event-based, runoff and water quality simulation model
Surface Runoff, Infiltration, River Discharge and Groundwater Flow (SIRG)	Yoo (2002)	Physically based, lumped parameter, event-based streamflow simulation model



Model name/acronym	Author(s) (year)	Remarks
Modular Kinematic Model for Runoff Simulation (Modular System)	Stephenson (1989) Stephenson and Randell (1999)	Physically based, lumped parameter, event-based runoff simulation model
Watershed Bounded Network Model (WBNM)	Boyd et al. (1979, 1996), Rigby et al. (1991)	Geomorphology-based, lumped parameter, event-based flood simulation model
Geomorphology-Based Hydrology Simulation Model (GBHM)	Yang et al. (1998)	Physically based, distributed, continuous hydrologic simulation model
Predicting Arable Resource Capture in Hostile Environments-The Harvesting of Incident Rainfall in Semi-arid Tropics (PARCHED-THIRST)	Young and Gowing (1996) Wyseure et al. (2002)	Process-oriented, lumped parameter, event-based agro-hydrologic model
Daily Conceptual Rainfall-Runoff Model (HYDROLOG)-Monash Model	Potter and McMahon (1976), Chiew and McMahon (1994)	Lumped, conceptual rainfall-runoff model
Simplified Hydrology Model (SIMHYD)	Chiew et al. (2002)	Conceptual, daily, lumped parameter rainfall-runoff model
Two Parameter Monthly Water Balance Model (TPMWBM)	Guo and Wang (1994)	Process-oriented, lumped parameter, monthly runoff simulation model
The Water and Snow Balance Modeling System (WASMOD)	Xu (1999)	Conceptual, lumped, continuous hydrologic model
Integrated Hydrometeorological Forecasting System (IHFS)	Georgakakos et al. (1999)	Process-oriented, distributed, rainfall and flow forecasting system
Stochastic Event Flood Model (SEFM)	Scaefer and Barker (1999)	Process-oriented, physically based event-based, flood simulation model
Distributed Hydrological Model (HYDROTEL)	Fortin et al. (2001a,b)	Physically based, distributed, continuous hydrologic simulation model
Agricultural Transport Model (ACTMO)	Frere et al. (1975)	Lumped, conceptual, event-based runoff and water quality simulation model
Soil Water Assessment Tool (SWAT)	Arnold et al. (1998)	Distributed, conceptual, continuous simulation model

«Вавилонская башня» гидрологической теории

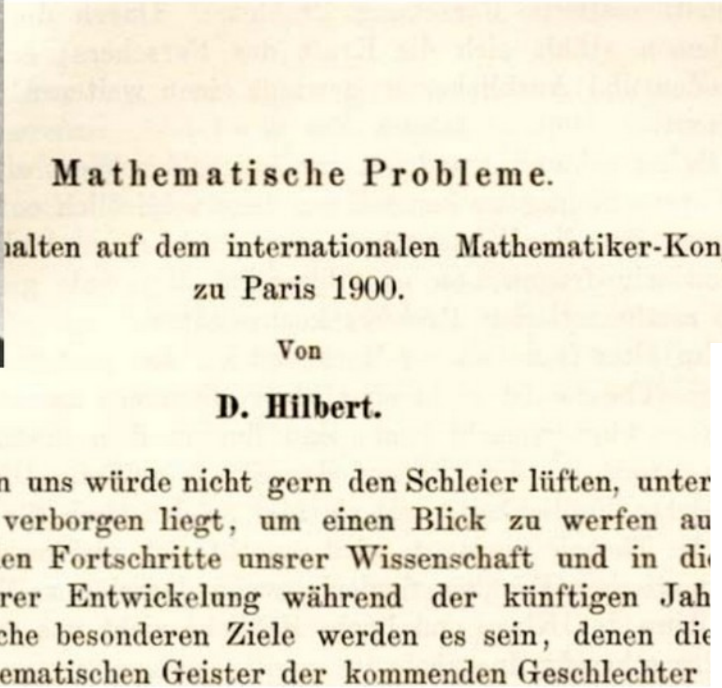


Питер Брейгель-старший «Вавилонская башня»

In 1900 David Hilbert set out

23 problems to foster mathematical research

He presented 10 of them at the Paris Congress



Mathematische Probleme.

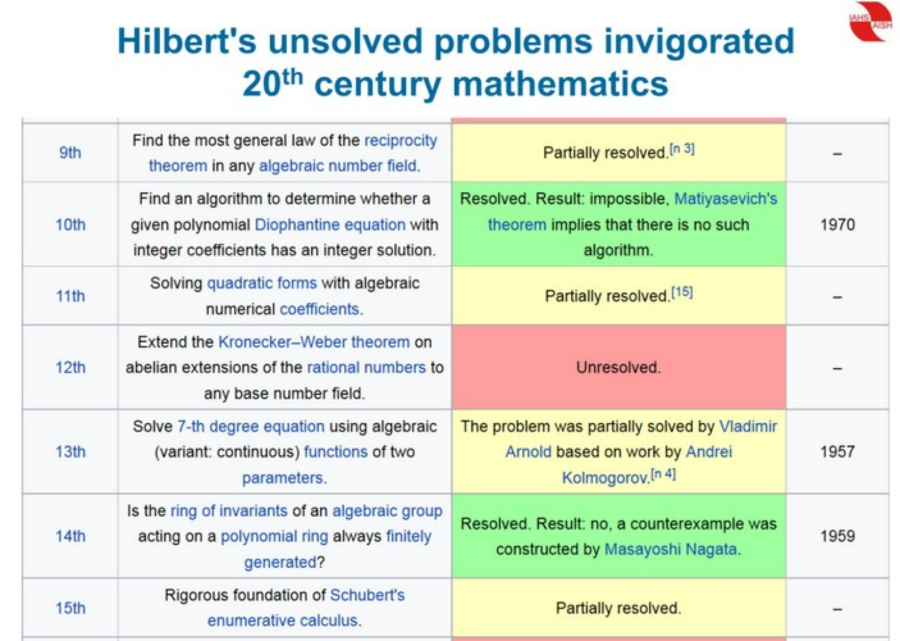
halten auf dem internationalen Mathematiker-Kongreß
zu Paris 1900.

Von

D. Hilbert.

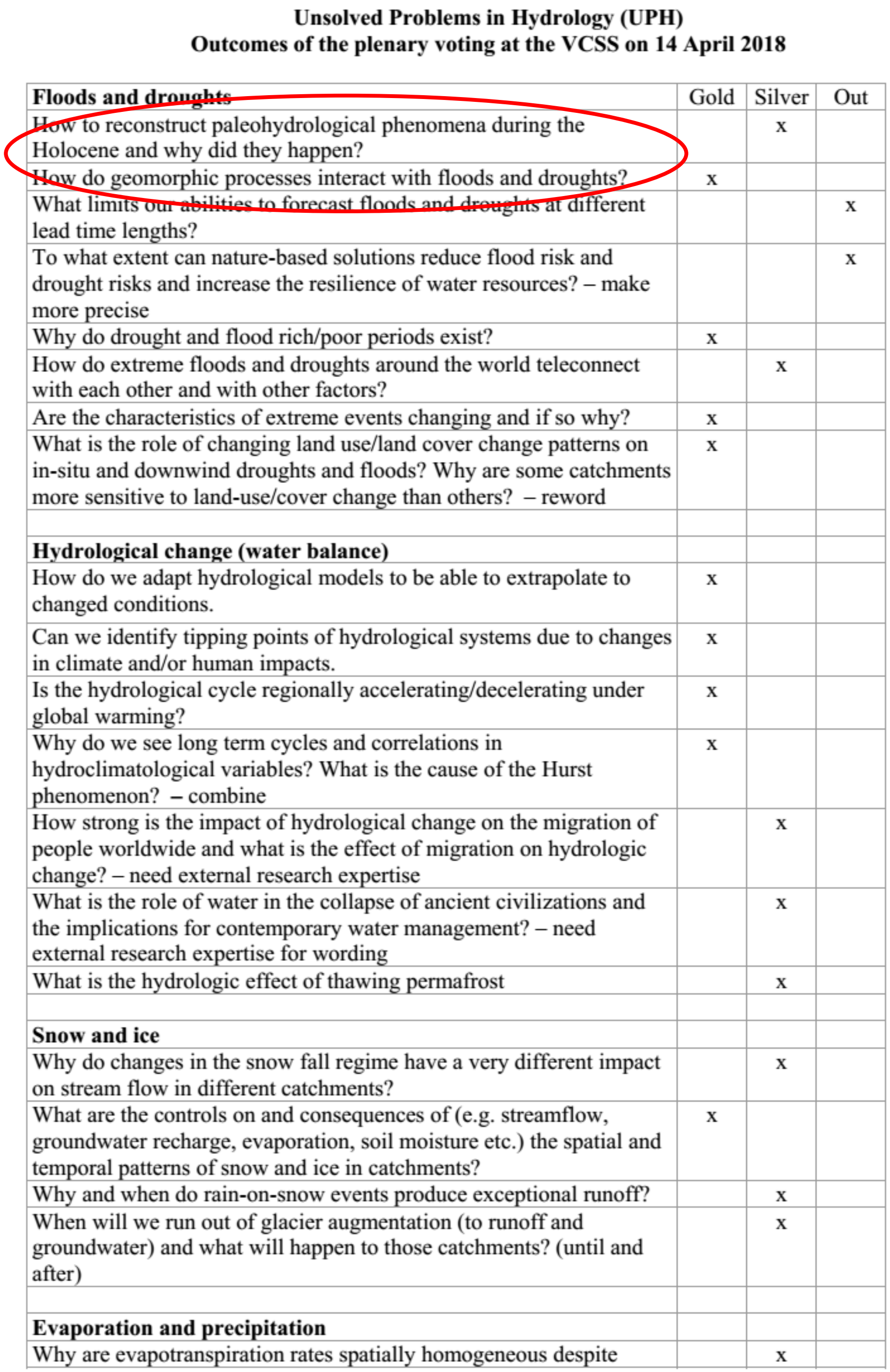
Wer von uns würde nicht gern den Schleier lüften, unter
die Zukunft verborgen liegt, um einen Blick zu werfen au
bevorstehenden Fortschritte unsrer Wissenschaft und in di
heimnisse ihrer Entwickelung während der künftigen Jah
derte! Welche besonderen Ziele werden es sein, denen die
renden mathematischen Geister der kommenden Geschlechter

16 решены Ещё 2 не являются корректными математическими проблемами (одна сформулирована слишком расплывчато, чтобы понять, решена она или нет, другая, далёкая от решения, — физическая, а не математическая). Из оставшихся пяти проблем две не решены никак, а три решены только для некоторых случаев.



Hilbert's unsolved problems invigorated 20^{th} century mathematics

9th	Find the most general law of the reciprocity theorem in any algebraic number field.	Partially resolved.[n 3]	–
10th	Find an algorithm to determine whether a given polynomial Diophantine equation with integer coefficients has an integer solution.	Resolved. Result: impossible, Matiyasevich's theorem implies that there is no such algorithm.	1970
11th	Solving quadratic forms with algebraic numerical coefficients.	Partially resolved.[15]	–
12th	Extend the Kronecker–Weber theorem on abelian extensions of the rational numbers to any base number field.	Unresolved.	–
13th	Solve 7-th degree equation using algebraic (variant: continuous) functions of two parameters.	The problem was partially solved by Vladimir Arnold based on work by Andrei Kolmogorov.[n 4]	1957
14th	Is the ring of invariants of an algebraic group acting on a polynomial ring always finitely generated?	Resolved. Result: no, a counterexample was constructed by Masayoshi Nagata.	1959
15th	Rigorous foundation of Schubert's enumerative calculus.	Partially resolved.	–



Unsolved Problems in Hydrology (UPH)
Outcomes of the plenary voting at the VCSS on 14 April 2018

Floods and droughts	Gold	Silver	Out
How to reconstruct paleohydrological phenomena during the Holocene and why did they happen?		x	
How do geomorphic processes interact with floods and droughts?	x		
What limits our abilities to forecast floods and droughts at different lead time lengths?			x
To what extent can nature-based solutions reduce flood risk and drought risks and increase the resilience of water resources? – make more precise			x
Why do drought and flood rich/poor periods exist?	x		
How do extreme floods and droughts around the world teleconnect with each other and with other factors?		x	
Are the characteristics of extreme events changing and if so why?	x		
What is the role of changing land use/land cover change patterns on in-situ and downwind droughts and floods? Why are some catchments more sensitive to land-use/cover change than others? – reword	x		
Hydrological change (water balance)			
How do we adapt hydrological models to be able to extrapolate to changed conditions.	x		
Can we identify tipping points of hydrological systems due to changes in climate and/or human impacts.	x		
Is the hydrological cycle regionally accelerating/decelerating under global warming?	x		
Why do we see long term cycles and correlations in hydroclimatological variables? What is the cause of the Hurst phenomenon? – combine	x		
How strong is the impact of hydrological change on the migration of people worldwide and what is the effect of migration on hydrologic change? – need external research expertise		x	
What is the role of water in the collapse of ancient civilizations and the implications for contemporary water management? – need external research expertise for wording		x	
What is the hydrologic effect of thawing permafrost		x	
Snow and ice			
Why do changes in the snow fall regime have a very different impact on stream flow in different catchments?		x	
What are the controls on and consequences of (e.g. streamflow, groundwater recharge, evaporation, soil moisture etc.) the spatial and temporal patterns of snow and ice in catchments?	x		
Why and when do rain-on-snow events produce exceptional runoff?		x	
When will we run out of glacier augmentation (to runoff and groundwater) and what will happen to those catchments? (until and after)		x	
Evaporation and precipitation			
Why are evapotranspiration rates spatially homogeneous despite		x	

IAHS
AISH

The Unsolved Problems in Hydrology Initiative

How to reconstruct paleohydrological phenomena during the Holocene and why did they happen?

Paleohydrological phenomena, such as paleo-floods, paleo-draughts, multi-century changes in the water cycle, happened, most likely, during the Holocene (last ~ 11650 years) both globally and regionally. There are quite a few circumstantial indicators of these phenomena, derived, for instance, from tree-ring-based reconstructions, lake-sediment, planktonic and benthic isotope analysis, glacial and geomorphological studies, etc. However, these circumstantial evidences are not only very uncertain but, more importantly, do not provide any understanding of physical causes of these phenomena. Were they caused by climate changes or happened due to post-glacial geomorphological restructuring of river network and watershed sizes or were associated with changes in permafrost, vegetation cover, etc., or with earthquakes and volcanic eruption or anything else? We do know almost nothing about the drivers of the paleohydrologal phenomena. Solving the above formulated problem can provide new insight in possible physical (natural) mechanisms of the future hydrological systems' dynamics at the geological time scales.

моделирование
ра физики моря
МГУ

ИВП
РОССИЙСКАЯ
АКАДЕМИЯ
НАУК
ИНСТИТУТ ВОДНЫХ ПРОБЛЕМ
с 1967 года


The Unsolved Problems in Hydrology Initiative

Why is aridity (according to the Budyko Curve) the main controlling factor in the partitioning between runoff and evapotranspiration?		x	
What is the fate and lifetime of evaporated water from land surfaces?		x	
Landscape processes and streamflow			
Why is stream water so young when ground water is so old?		x	
Why is most flow preferential and what are the consequences?	x		
Why is the connectivity between hillslopes and streams so heterogeneous and dynamic?	x		
Why do streams respond so quickly to rainfall, with storm flow that is so old?		x	
Scale and scaling			
Why do dominant hydrological processes emerge and disappear across scales? Why is hydrology simple at the catchment scale despite being complex at smaller scales?	x		
Under what conditions can we substitute space for time in hydrology?		x	
How do constitutive relationships and their parameters change with scale?		x	
What are the emergent hydrological "laws" at catchment scale?		x	
Modelling (general)			
How can we identify the similarities between catchments?		x	
What is the sensitivity of hydrologic models to vegetation dynamics?		x	
How to disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?		x	
What do we have to do to build a unified hydrological model?			x
How can theories and methodologies be developed to reduce equifinality?			x
How to integrate citizen science and data for the understanding and mitigation of the effects of natural disasters by risk awareness, communication and outreach activities?			x
How important is hydrology in controlling bio/geo/chemical cycles and ecology?			x
Measurements and data			
How can we accurately measure subsurface properties, states and fluxes at a range of scales in space and time?	x		
How to reduce uncertainty in large-scale hydrological fluxes using novel technologies/remote sensing?		x	
What are the consequences of choosing between a large number of less accurate observations vs a few more accurate measurements?		x	
How to extract information from available data on human and water systems in order to inform the building process of socio-hydrological models?		x	
How can we convincingly put a value to hydrological observation systems with open data to reverse the current trend of decline of observation systems?		x	
Water quality			
What are the dominant processes controlling the fate of material fluxes in catchments over different spatial and temporal scales?	x		
Why are reaction coefficients for the same process heterogeneous in time and in space across different soils, streams, lakes, catchments, groundwater bodies…?		x	
How does water quality influence human-water interactions?			x
What factors contribute to the persistence of sources affecting water-quality?			x
Groundwater and soils			
What are the impacts of climate and environmental change on aquifer recharge?	x		
What are the processes in the unsaturated zone, which have significant impacts on groundwater recharge and composition?		x	
What are the storages and fluxes of groundwater across boundaries (oceans, atmosphere and inter-catchment fluxes) at different scales?	x		
Why is soil-water content so variable in space and time?		x	
How can we precisely define groundwater pathways in karstic and fractured aquifers?			x
How can we upscale Richard's equation to the catchment scale?			x
How important is groundwater to aquatic and terrestrial surface biodiversity, and vice-versa?			x
What are the effects of natural and anthropogenic soil disturbances on heat and mass fluxes at the land-atmosphere interface?		x	
What are the processes of groundwater-surface water interactions, including the role of the hyporheic zone (e.g. in contaminant fate and transport), and the dependencies of different ecosystems?		x	
Why are microbial pathogens removed or inactivated in the subsurface?			x
Communicating and engineering in hydrology			
How to communicate (un)certainty to decision makers and general public		x	
How can we shift the culture among hydrological science to encourage collaboration with industry and stakeholders across disciplines, and improve evidence-based decision making?			x
	16	29	13