Additional material, web-links, data for the lecture Sustainable Water Resources Management

Links to e-learning material

- e-learning IWRM
- IWRM (BMBF conference) 2011
- Hydrological Engineering Handbook
- Water Resources Assessment (WMO)
- Water Resources Assessment (SSM)
- IWRM programmes by UN
- UN programme water for life and IWRM
- EU Water Framework Directive
- UN Statistics Division - System of Environmental and Economic Accounting of Water
- Handbook of Irrigation and Drainage (USDA)

E-Books and Learning Material

- Whycos / WMO Guide to Hydrological Practice: Internet Link to most recent version
- WMO Guide Hydrology Vol. 1
- WMO Guide Water Management Vol. 2
- WMO Technical Guide for Water Resources Estimation

Data

- CGIR - Data sources: Rainfall, Elevation maps and time series
- NOAA data access
- Visualize Global Time Series of Rainfall
- NASA observed daily precipitation
- Tyndall Centre (link to other data sources)
- ECMWF
- Global Runoff Data Centre
- Data German Weather Service (engl.)
- FAO Climate Data
- ClimWat FAO Database of climatological data
- World Weather Database

Lectures

1. Basins and Water Balance of Basins

Lecture on basins, basin delineation and basin characteristics

- European Basins
- Small Urban Watersheds
- Hydrosheds
- How to calculate hydrosheds

Additional material, web-links, data for the first lecture on basins, GIS and watershed delineation

GIS Resources for Hydrologists

- Open Source GIS
- MapWindow - recommended for Hydrologists!
- SAGA

Other GIS Systems

- GRASS - professional, fast & complex
- GVSIG
- WhiteBox
- ILWIS
- GeoDa

2. Precipitation

2.1 Precipitation: Monitoring

Slides of lecture on precipitation, monitoring and interpolation

Exercise & Homework

1. Please read the paper of Liu et al. 2017 and the short introduction to Quantum GIS interpolation methods and answer the following questions: What is the most robust and what is the most accurate method, given that hydrological data often have errors and are highly variable?
    - Liu et al. 2017: Quantitative Evaluation of Spatial Interpolation Models
    - QGIS Rainfall Interpolation Methods
2. Use the inverse distance calculator and calculate rainfall at the point (x,y). Material: Inverse Distance Calculator

2.2 Precipitation: Extremes and Statistics

Slides of third lecture on

Precipitation: Extremes and statistics

Additional material, web-links, data for the lecture on precipitation extremes

Material

- Eu Water Statistics explained with sources of data
- NOAA Weather Statistics, Extremes
- UN Data (from WMO Standard Normals): Precipitation Averages, Monthly
- Statistics of Australian Weather Bureau: Statistical Measures

- Live US Precipitation
- Engineering Statistics, NSI and specifically for the Weibull plot

Exercise

1. Read the chapters 5.10 and 5.11 in the article of WMO on statistical analysis of time series. This article does not contain mathematics and is a pure description. How is robustness defined here?
2. You have obtained the following file with rainfall-duration statistics . The file gives the highest amount recorded in each hydrological year (Nov.-Oct) during 1, 6 and 24 hours at a station. Please calculate the rainfall-duration curves for the recurrence intervals of 2, 5 and 20 years for a 6 hour rainfall.
3. The article of Makkonen (2005) (you can also go the direct link of the Journal of Applied Meteorology) provides the full background of the formula $P=\frac{m}{N+1}$ that is also called the Weibull plotting position. It shows that a number of alternative plotting position formulae have been proposed and that there has been controversy about different types. Please summarize and conclude: Is the formula $P=\frac{m}{N+1}$ correct and safe to use regardless of the underlying frequency distribution?

Table with maximum annual rainfall amounts within 1,6 and 24 hours

Tab. *Table of rainfall data*

Duration (h)	**1**	**6**	**24**
Year	Rainfall mm	Rainfall mm	Rainfall mm
1989	85	88	91
1990	97	99	103
1991	65	72	80
1992	76	82	86
1993	66	72	75
1994	67	75	79
1995	75	81	86
1996	81	88	94
1997	88	94	99
1998	45	57	63
1999	58	67	72
2000	60	76	80
2001	66	74	81
2002	61	70	76
2003	78	84	89
2004	74	86	96
2005	49	63	69
2006	53	61	67
2007	51	60	68
2008	49	62	72

Duration (h)	**1**	**6**	**24**
2009	61	71	77
2010	64	75	81
2011	77	85	91
2012	74	77	82
2013	91	101	106
2014	59	69	75
2015	68	76	79
2016	72	77	83

3. Evaporation

Potential evaporation, actual evaporation: Measurement and Estimation

Often evaporation is - for long time periods - the largest component of the water cycle and it deserves a closer look for this reason. The

slides for lecture on evaporation

give an overview of measurement techniques, estimation approaches and formulae.

You can test how a commonly used evaporation formula works with an interactive equation plotter: You can modify wind speed, roughness and relative humidity and will get results of daily evaporation during a hydrological year with a given temperature time series.

FAO offers excellent software for the estimation of actual evaporation and for the calculation of the reference Evaporation with the Penman-Monteith method. An interactive computation sheet dev. by Prof. Kuells shows the energy balance and controlling factors of the Penman-Monteith method. The recommended software is ClIMWAT for getting climate data, CROPWAT for calculating crop water requirements and ETo Calculator for calculating the reference evaporation. Most equations are implemented in the R package evapotranspiration.

Assignments

1. Estimate evaporation: Measurements have been taken in June, temperature is 15 degrees Celsius, relative humidity is 67 percent, wind speed is 2.7 m/s and the length of the fetch of similar surface is 250 m. The incoming extra-terrestrial radiation is 480 W/m², albodeo is 0.2. The potential sunshine duration is 16.4 hours, the real and measured sunshine duration was 8.2 hours. Calculate using Haude, DVWK (Dalton-type) an Penman-Monteith and compare.
2. Small droplets evaporate slower than expected based on known physical principles, see this article. Imagine an engineered environmental hydrology application of this discovery!
3. Read this very interesting article about a new type of sustainable energy production by evaporation. It makes sense. Evaporation involves an enormous transfer of energy. Part of this energy can be re-converted by condensation or used as moist air is light and creates an upward convection force. Describe how this engine courld work and how much energy could be produced from the evaporation of lake Ratzeburg. Material: Evaporation-driven engines for sustainable power generation

Links

Additional material, links to online resources by FAO, lectures and instructional films on evaporation

1. Eddy covariance method
2. FAO Evaporation

Videos

Additional material, web-video and lecture capture on evaporation

Software

Additional material, software to estimate evaporation

1. ClimWat
2. CropWat
3. ETo Calculator
4. R-package containing programs for most evaporation equations

References

Verhoef A., Campbell C. (2006) Evaporation Measurement, Part 4. Hydrometeorology. Encyclopedia of Hydrological Sciences, DOI: 10.1002/0470848944.hsa043. John Wiley & Sons, Ltd

4. Infiltration

From Horton overland flow to modern soil physics

Slides of fourth lecture on infiltration

Assignments

1. Have a look at the films and answer the following question: You need to assess infiltration rates in a basin. Which empirical method would you use to measure infiltration rates from at least 40 different sites?
2. Calculate the infiltration rate and amount for a soil with sorptivity of $S=50 \, mm/h^{1/2}$ and hydraulic conductivity of $a=8 \, mm/hour$ during the first 5 hours using the Philip equation.
3. There is a heavy rainfall of 65 mm in Kairo. We have a permeable soil (hydrological soil group A), sandy and deep and the land use is 'industrial district'. You can use CN II. Calculate runoff from this event. First determine CN (II), then determine S [mm] and finally calculate P with an initial loss $I_a = 0.1*S$. Result must be 0 < Q < 65 in [mm]. You can try to calculte with CN - I for a dry 5-day period antecedent to the rainfall event.

Ring Infiltrometer

Tension Infiltrometer

Suction Infiltrometer

Guelph Infiltrometer

Additional material, web-links, data for the lecture on infiltration

- Computation of Infiltration - example
- Infiltration models (EPA)
- Infiltration and Entropy
- AGU (2013): Infiltration Theory for Hydrologic Applications

5. Soil Water Movement

Slides on principles of soil water movement

Pedotransfer Functions

A program and background information on the estimation of soil physical parameters for hydrological models and predicitions e.g. by Saxton (1986, USDA or here. Pedotransfer functions have been developed (and revised) for Europe by Tóth et al. (2014). In the U.S. the Rosetta model is used by USDA. A comparative study by Kluitenberg suggests that the Saxton model provides the most reliable estimates for the U.S.

6. Groundwater: MAR

Groundwater is the water that fills voids between sediments or fractures in hard-rock completley and that is moved by gravity only. When water percolating from the unsaturated zone reaches the upper boundary of the ground water, the water level, groundwater is recharged. The process of groundwater recharge is very important for the assessment of sustainable water abstraction volumnes.

The

lecture on groundwater recharge

summarizes methods to assess groundwater recharge in different climates, geologic and environmental conditions. The

fundamental terms and principles of groundwater hydrology

are introduced.

Material

- Textbook on Ground Water by Heath, 2005

7. Discharge: Measurement, Production, Concentration, Routing, Separation, Analysis, Statistics, Prediction

Measurement

The measurement of discharge in open channels, at weirs and with additional hydrometric methods (velocity measurements, ADCP and tracers) are described in the

lecture slides

. A
case study of water resources assessment with hydrometric methods in Rwanda
and of the
results obtained from a hydrometric study
are presented. Worked examples are also given for
discharge measurements with tracer methods
.

Runoff generation, runoff concentration, runoff measurement and the subsequent analysis of runoff data are key competencies of hydrologists and form the basis for water resources assessment, flood risk management, hydro-power potential assessments and any analysis of river flow data for various purposes (irrigation, ship navigation, drinking water from surface resources).

Material

- How discharge is measured (USGS)
- Manual on River Gauging, WMO, Vol. 1
- Manual on River Gauging, WMO, Vol. 2
- Lectures from OpenCourseWare at TU Delft

Production

The production of runoff - runoff production - may result from various processes: Their significance and relative contribution to overall runoff production varies with climate, soil type, geology, land-use, season and land management.

Runoff may result from intense precipitation or any other process producing liquid water (irrigation, snow melt) exceeding the infiltration capacity of soils at a given point or plot. This process is often called **Hortonian overland flow** or **infiltration excess**. This primary runoff production process can be described using infiltration formulae at a point scale. At a catchment scale, however, spatial variability of runoff production and infiltration along the flow-path - so-called runon processes - need to be taken into account. It is obvious that total runoff production at a catchment scale is the result of net infiltration of water at the end of all flow lines: Runoff produced at a more elevated point can re-infiltrate along the flow path to the river or even in the river (transmission loss). Although infiltration forumulae can give a first approximation to the process of overland flow as a result of infiltration excess, additional aspects related to basin geomoetry and hillslope processes, groundwater level and wetness of the basin need to be included to represent runoff production at catchment scale fairly.

It is evident from field observation and simple experiments that a saturated soil - such as found close to rivers and in valeys of humid regions or at the bottom of a hillslope or in wetlands - will produce more runoff than a soil with a high infiltration capacity simply because the soil cannot accomodate and store the incipient precipitation, snow melt or runon water. This process is called saturation excess runoff.

A special case is given when soils close to saturation become saturated and when a zone around surface drainage lines, rivers or valley bottoms starts developing a groundwater ridge that produces additional inflow to the lowest drainage line. This process is called **groundwater ridging**.

Some special cases of runoff production are given by rather fast or preferrential flow in the upper more permeable sub-surface part of hillslopes, often at the contact between weathered soil and bedrock or in periglacial solifluction soils in mountain areas: This fast sub-surface flow process is called **interflow**.

Finally, it should be noted that in case of hydraulic connection of the river with the groundwater system, **groundwater flow** reflecting the spatial distribution of groundwater levels with respect to the network of drainage lines will always constitute a dynamic and often substantial contribution to runoff.

Discharge in drainage networks is a result of all this processes or of some of them. There are **dominant runoff production processes**, their contribution and role may change regionally, with climate and geology, during different phases of a storm event and seasonally. The understanding of the dominant and other relevant runoff production processes is an important pre-condition and requirement for reliable runoff prediction and modeling and for other hydrological studies related to solute transport and modeling.

Concentration and routing

Runoff concentration is the process of **translation, conveyance and dispersion or convergence of runoff in the basin and its drainage networ**k. As almost all hydrological flow networks in basins are dendritic and organized hierarchically into a tree-like drainage system, runoff concentrates and forms a gamma-curve shape. Methods related to runoff concentration aim at deriving the shape of the runoff hydrograph from basin, drainage network, channel characteristics and status as well as of antecedent conditions and event parameters. **Flood routing** is the activity of predicting flood arrivial time, flood peak, duration and shape from the flood hydrograph of a measured upstream station for one or more downstream stations or continuously in the entire river network. Hydraulic routing is based on physical principles of channel hydraulics, hydrological routing relates to the application of empirical, statistical or conceptual models.

Analysis

The analysis of measured runoff data is the basis for many aspects of water resources management. The analysis includes derivation of statistical indicators such as mean discharge, variance, quantiles but also auto-correlation, correlation with other parameters, time-series analysis and the analysis of extreme values.

Prediction and modeling

Prediction and modeling are based on the understanding of how runoff and discharge change in time and in space or both and in the application of underlying statistical, physically process-based or conceptual relationships to predict or model runoff or discharge at one point or moment r(x,t), d(x,t) or for a spatial domain at a given time in future r(x,y,z,t+n) or for future time-series r(t). Prediction methods result from rainfall-runoff models or channel routing models or from any other proven and calibrated and validated relationship between relevant basin or event parameters and a hydrological target variable, here runoff or discharge.

A summary is given in the lecture slides on runoff modeling.

Engineering

Hydrological engineering is the development and implementation, planned and objective-drivent, to change runoff or discharge at one or several points in time and in space with the purpose of improving ecological status or conditions for our life and social and economic activities. Hydrological engineering includes

- flood retention, control and management
- drought management
- land drainage
- runoff harvesting

8. Application in Hydrological Engineering: Water Resources Assessment

Water Resources Assessment involves the estimation and calculation of water resources for a hydrological system. This can be a natural system, a basin or watershed, or an aquifer and groundwater body. This can also be an administrative unit, a province or state. The European Water Framwork Directive follows natural system boundaries. However, often masterplans or national W.R.A. are still needed.

As discussed in the lecture, there are four major approaches to W.R.A.

- water balance approaches, establishing a $N = E + Qs + Qgw + dS$ equation and solving it for surface runoff $Qs$and or groundwater recharge Qgw.
- discharge and baseflow analysis of existing streamflow records: The baseflow, stemming from groundwater in streamflow is identified and integrated over time. It will equal (more or less) the total inflow or recharge.
- groundwater model calibration: The recharge rate is adjusted as a variable parameter in a groundwater model with known kf and geometry until a realistic and feasible recharge rate is found that explains observed water levels.
- isotopes and age dating are used and the flow is derived from the relationship $T=V/Q$ converted to $Q=V/T$ where Q is the throughflow through the system and equals recharge and discharge V is the volume of the aquifer system taking into account porosity n_e and T is the residence time, observed and measured with isotope techniques.

For training the first approach, please download CROPWAT and CLIMWAT from the FAO webpage and install it.

Assignment

Please chose a climate station from CLIMWAT from your home country. Export climate data to be used in CROPWAT. Import climate data to CROPWAT. Calculate the daily soil water balance, without irrigation (settings/no irrigation) and analyse the results. Please establish the annual water balance consisting of rainfall, effective rainfall (minus losses, runoff because of infiltration excess and saturation), runoff which is $r-r_e$, actual evaporation, potential evaporation and recharge using the formula $N = E + Qs + Qgw + dS$ in which dS is the change in storge or difference between initial storage S_0 and final storage S_f, hence $dS=S_f-S_0$. Give the result in $mm/year$ per square meter and for training purposes also in l/s per km^2 and the available water for drinking water or irrigation for an area of 100 km^2 in million cubic meters per year.

9. Final Assignment (2 groups)

Group 1: Joel Jossy - A stormwater evaporation pond has high water losses. The city that has commissioned the pond wants to know whether the losses result from evaporation only or from evaporation and infiltration, meaning that the pond is not well sealed and that the lining is incomplete. Please judge - based on climate - data, whether the pont is actually well constructed and lined or not and if not, please indicate the magnitude of the infiltration rate in m/s.

- Assignment stormwater retention pond - water level data
- Climate data

Group 2 (5 Students): Develop a daily water balance model of the soil at the University Neighbourhood (Hochschulstadtteil). The model comprises 1 compartment of the soil that is 1 m deep and has a suface of 1 square meter (1 m^2). The soil has a porosity of 0.25 or 25 %. The model can be prepared with a spreadsheet program (Excel, Openoffice). It contains 5 different modules:

1. rainfall / snowfall and snowmelt module,
2. infiltration module (proposed a constant infiltration rate)
3. evaporation module (proposed DVWK or Dalton-Type evaporation, daily)
4. storage module (keeping the water balance of inputs (rainfall → infiltration), losses (evaporation, seepage)
5. seepage module calculating the daily seepage

The model has a daily time-step. Each day is a row. Please prepare a section with the title and a short description (1.-2. row), parameters (3.-… lines, like snow melt factor, field capacity, initial value of soil moisture etc.), some statistical summary like min., max., average, number of cells, average and then the data with heading, runits and a row for each day. It is absolutely enough to model one year.

Group 3: Groundwater recharge estimation of Hochschulstadtteil. The time series of ground water level is given (

here

). Please determine groundwater recharge from this time series using the method described in the groundwater lecture. You can assume a porosity of n=0.3 %. Prepare a table of groundwater table rises, aggregate them to a total accumulated rise and determine the corresponding recharge rate. Evaluate whether this recharge rate is possible using the water balance equation $N=E+Q_0+R+\Delta S$ with N Precipitation, E Evaporation, Q_0 surface runoff and ΔS change in storage (that can be assumed zero in this case).

Comments

Rainfall - Snowmelt

The rainfall / snowmelt module - snow is stored as water equivalent if temperature during the day is below 0 degrees Celsius. The snow store is depleted by snow-melt. Snowmelt works like

$$ snowmelt = T_{> 0} * ddf$$ in mm/day

where $T_{>0}$ are the degrees above 0 degrees per day and ddf is the day-degree factor expressing the number of mm per day that can melt per degree above 0 degrees Celsius. The ddf for this example is 4 mm/day.

Infiltration

The infiltration rate can be specified by a simple equation and we can assume that it is constant. The infltration rate can be estimated from the k_f hydraulic conductivity. It is 10^{-5} m/s (meters per second). Convert this to mm/day.

Evaporation

Evaporation can be calculated with the DVWK approach (see slides). You need to calculate E_s saturated vapour content from the Clasius-Clapeyron equation, e_a from relative humidty times E_s and take into account wind speed in m/s and a fetch factor. Please consider that evaporation stops when the soil moisture reaches the wilting point.

Storage

The soil is sandy and 1 m thick (rooting depth). Porosity is 0.25 or 25 %. You can assume a field capacity of 200 mm for this case. The wilting point is 50 mm or 5 % of the total yield/storage. I suggest that you start with 100 mm initial soil moisture.

Seepage

Seepage is only possible (in the easier version of the model), when moisture is above field capacity. When it is above field capacity, it can not exceed the hydraulic conductivity of the soil that is $10-^{-5}$ m/s. Since vertical movement usually has a conductiviy that is 1/10 of the lateral one, you should work with $10-^{-6}$ m/s as a maximum seepage rate.

Please check the water balance is met that is:

$$ N + P_{snowmelt} = E + R + Seepage + \Delta Storage$$ on a daily basis.

Data

Climate Data
provided by DWD on their website for free for a station nearbei. The parameters are explained in this file

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Template

You can use the

Word Template

for assignments showing how the title page, the figures and tables are listed, referenced and named, also giving citation style and reference list. The assignment can be short. Submit the file and a short description of what you did on < 5 pages.