United Nations Educational, Scientific and Cultural Organization (UNESCO)

Role of Groundwater in Water Resources Planning for Coping with Scarcity and Adapting to Changes

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Outline of the presentation

- Groundwater recharge – distribution, sources and affecting factors
- Particularities of arid and semi-arid areas
- Groundwater-surface water interactions
- Examples of impacts of climate variability affecting groundwater conditions
- Approaches to coping with water scarcity using groundwater: non-renewable groundwater and managed aquifer recharge
- Implications of climate variability and change to management of water resources

Groundwater and Climate: Some Key Scientific Questions

Climate Impacts on Groundwater & Adaptive Strategies

- How can climate prediction better inform climate-driven impacts on groundwater resources - integrated versus offline impact models?
- Are potential increases in groundwater recharge from changing rainfall distributions offset by increased ET?
- Can we define sustainable groundwater abstraction under non-stationary hydrological conditions?

Groundwater & Advancing Climate Prediction

- What are the key constraints to the representation of groundwater flow and storage in climate models?
- What aspects of groundwater flow and storage are most important to hydrological simulations and where?
- On the basis of currently available information, what methodologies can be used to improve the next generation of climate models?

UNESCO GRAPHIC project

Recharge & groundwater resources

Long-term average groundwater recharge

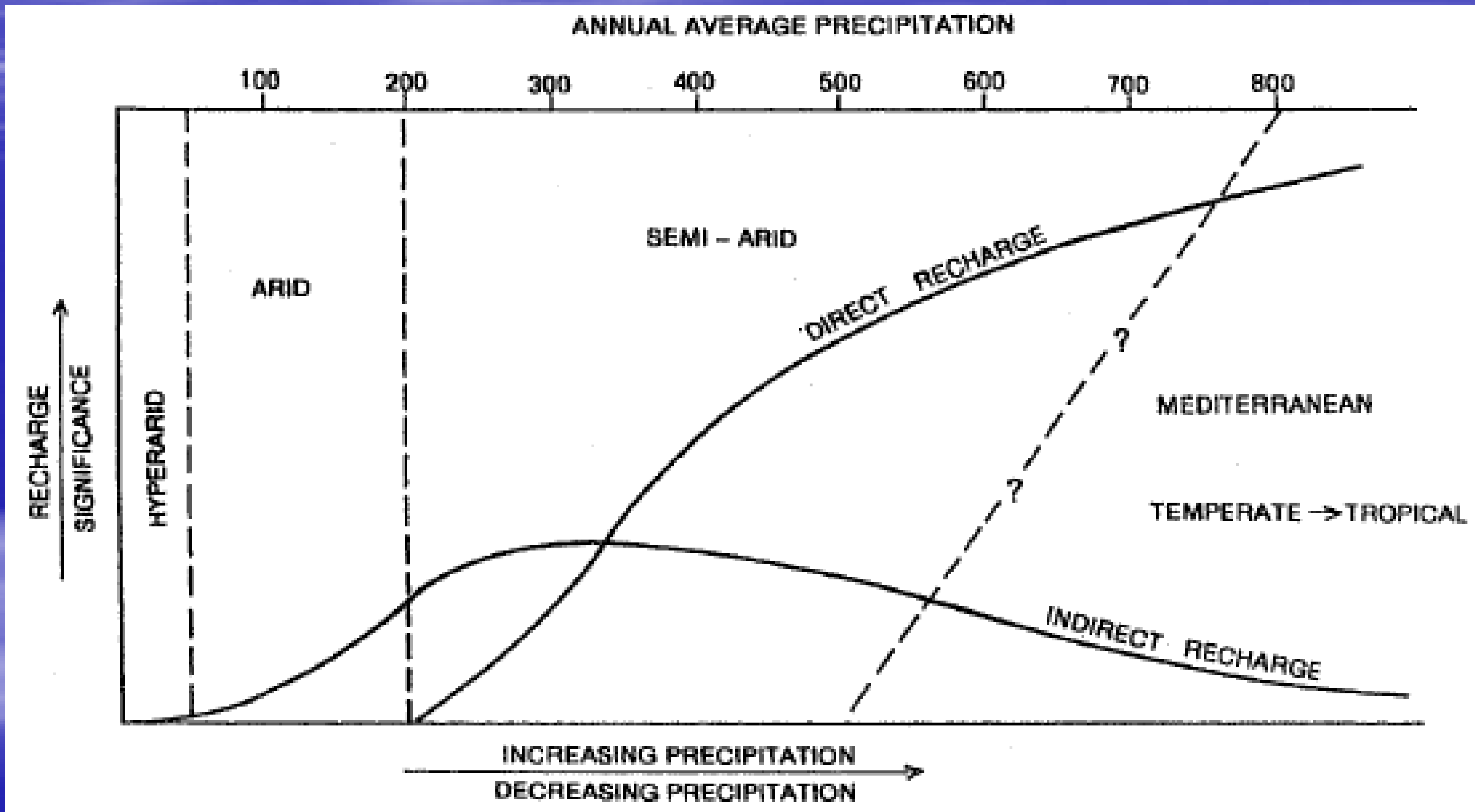
Is commonly used as an estimate of renewable groundwater resources.

This is also the (theoretical) maximum amount of groundwater that may be withdrawn without irreversibly depleting the resource.

Recharge in arid and semi-arid areas – general features

- Arid and semi-arid areas are particularly vulnerable to climatic changes: recharge to maintain groundwater resources of utmost importance
- Recharge occurs to some extent even in the most arid areas
- Recharge in (semi-)arid areas is much more susceptible to near-surface conditions than in more humid regions
- Interaction of climate, geology, morphology, soil condition, and vegetation determines the recharge process
- In general, as aridity increases, direct recharge becomes less important than localized and indirect recharge for total aquifer plenishment

Relative importance of direct and indirect recharge in different climate zones

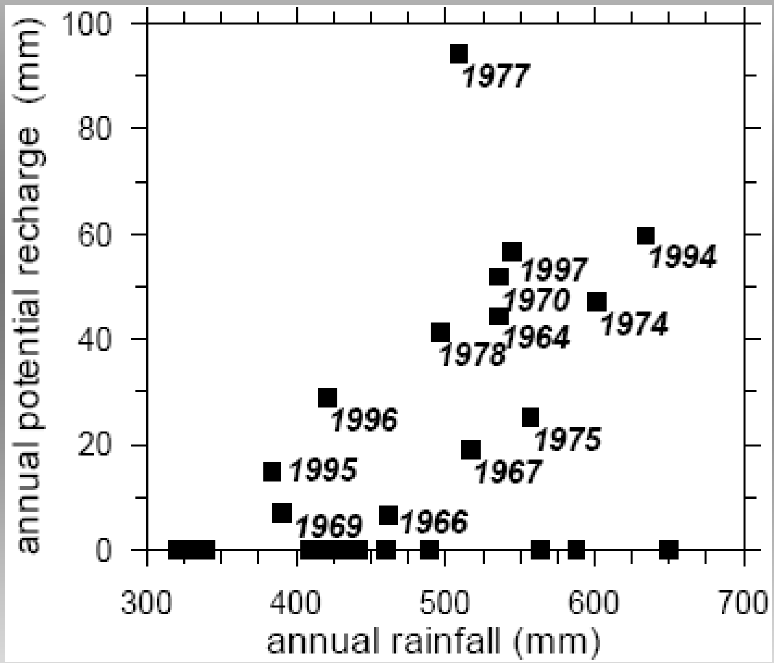


Sources of recharge

- Precipitation
- Rivers (perennial, seasonal & ephemeral)
- Irrigation losses, both from canals and fields
- Interaquifer flows, and
- Urban recharge

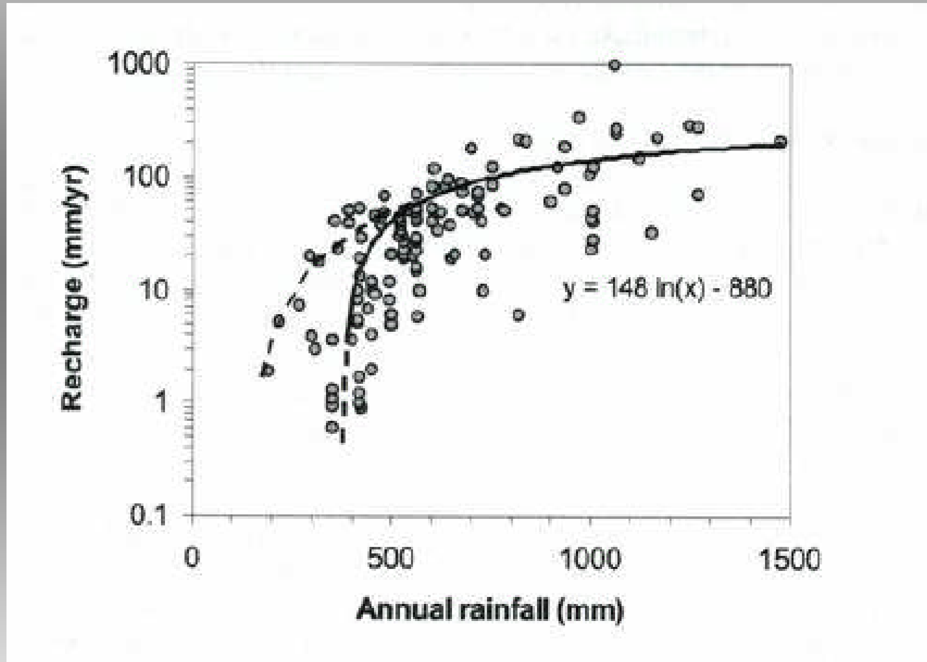
Variability of groundwater recharge

One location, soil water balance, 36 years.



Eilers, 2002, Estimation of groundwater recharge from soil water balance in semi-arid regions (data for Nguru, NE Nigeria)

"Many disparate locations", multiple methods.



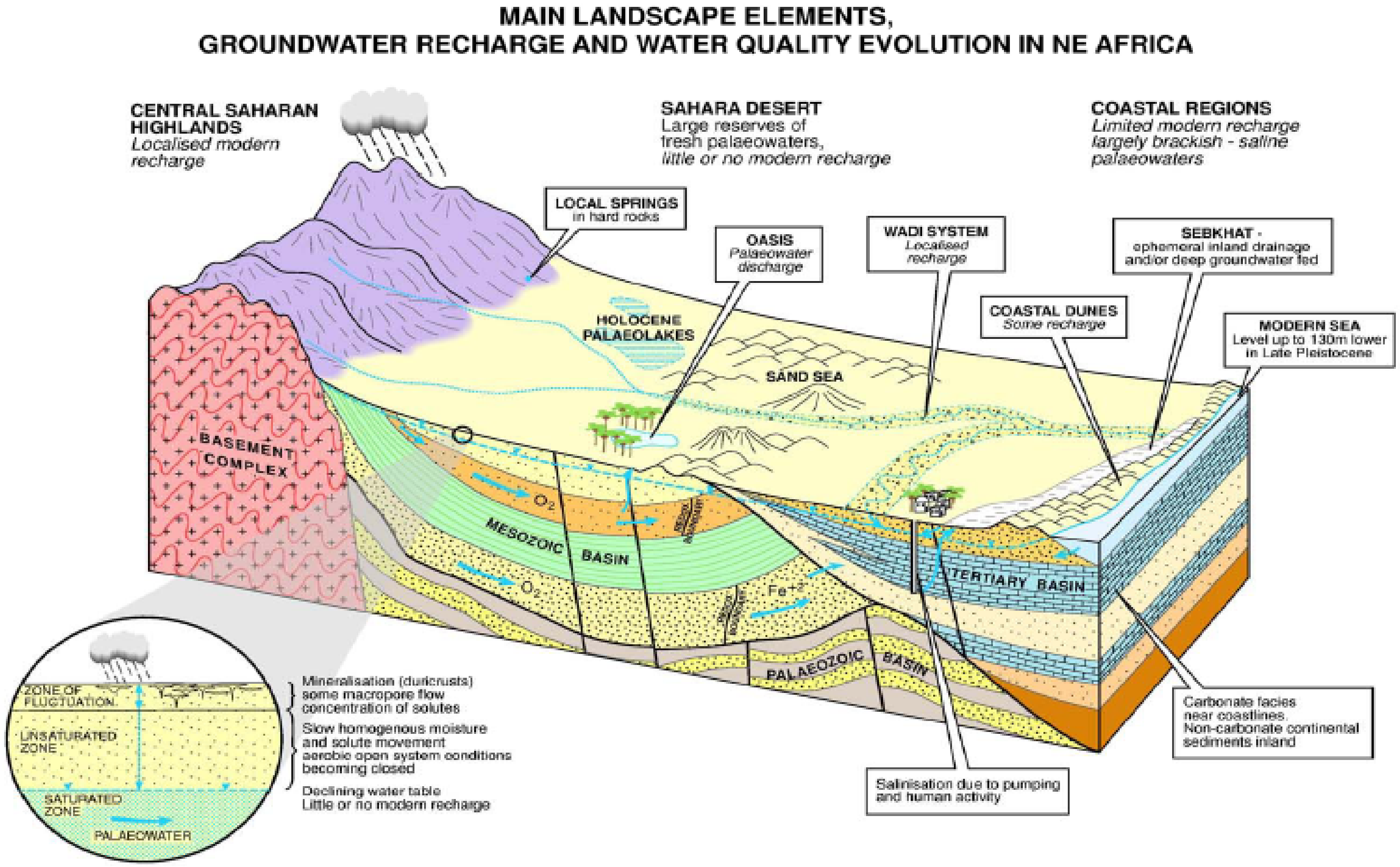
Cavé, Beekman and Weaver, 2003, Groundwater recharge estimation in southern Africa (data from Botswana, South Africa and Zimbabwe)

R.C. Carter 2008

Recharge estimation for estimating water resources: factors that play a role

- The objective of the recharge estimation has got implications for space & time scales: Water resource evaluations require information at large spatial and temporal scales; aquifer vulnerability studies more detailed
- Important to describe the location, timing and probable mechanisms of recharge soundly upon conceptualization
- Initial estimates of recharge rates to be provided based on climate, topography; land use and land cover; soil and vegetation types; geomorphologic and (hydro) geological data
- Useful checks for soundness of the estimate: 1) What is the infiltration capacity of the surface/interface?; 2) Capacity of the aquifer to receive recharge?; 3) Volume available from the source?

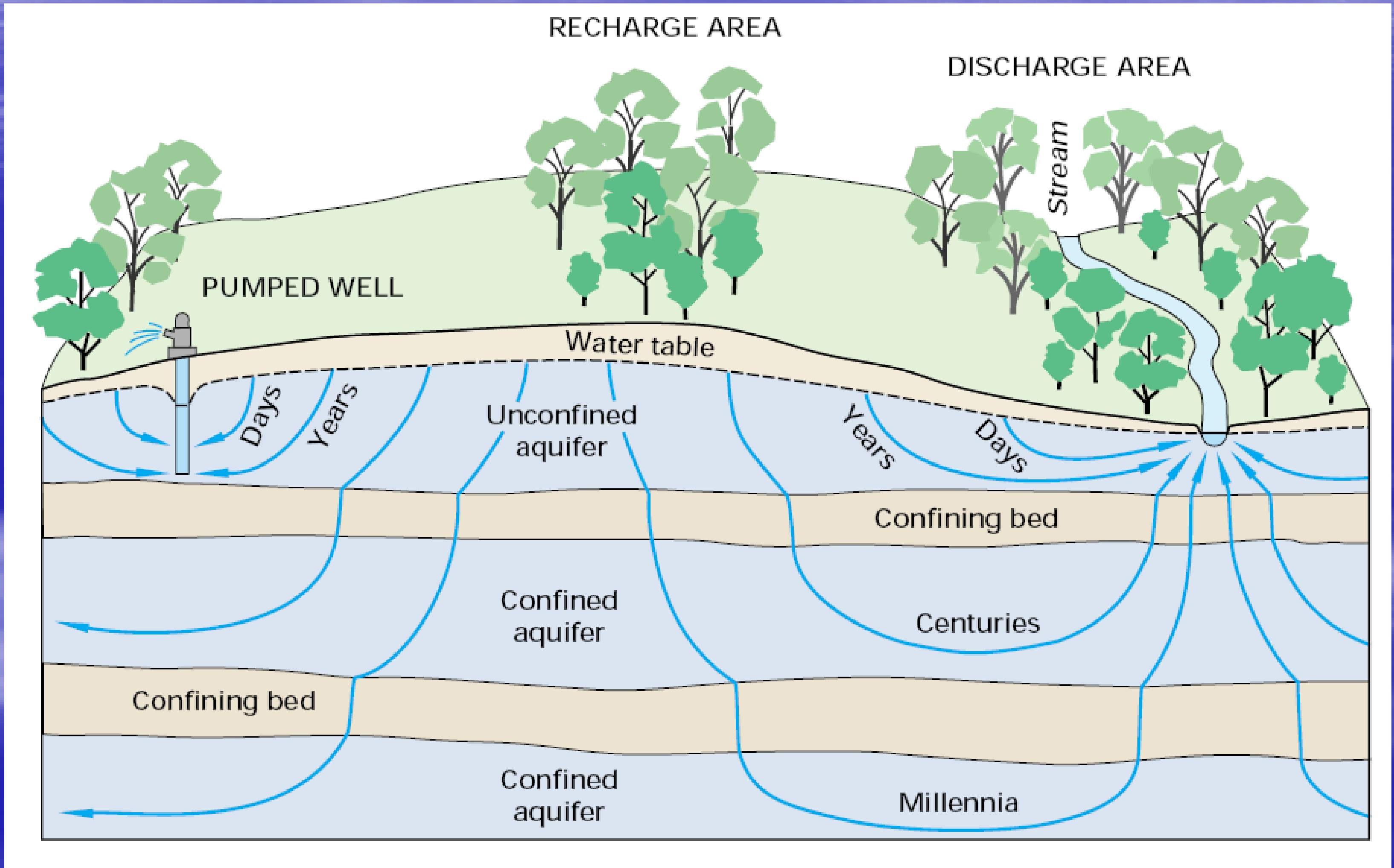
Conceptualising recharge in arid and semi-arid regions



Variations in variables that affect recharge (1): Aquifer types & hydraulic/recharge properties

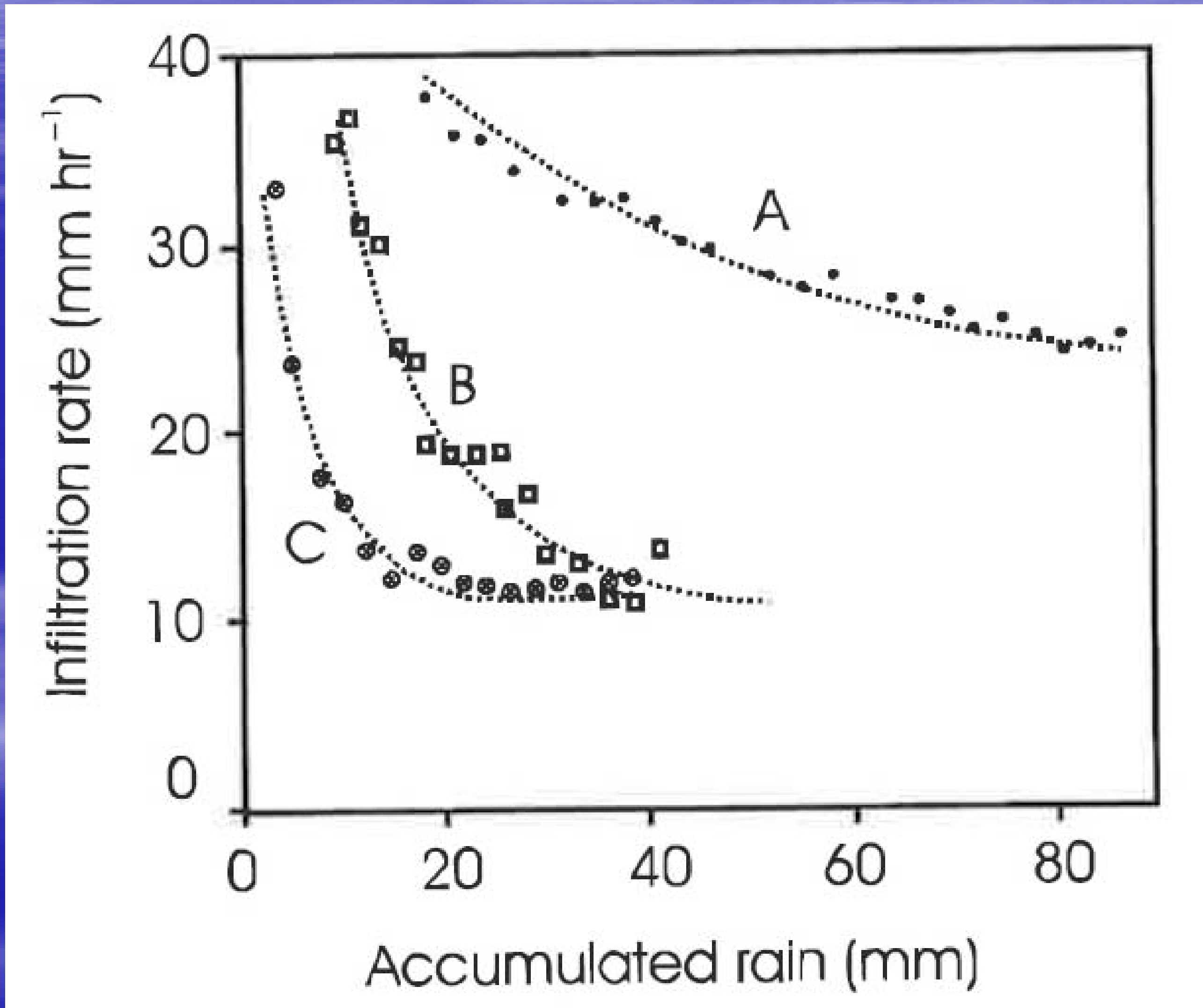
- Unconsolidated sediments (streambed deposits, alluvial fans etc.)
  - Hydraulic characteristics mainly determined by grain size distribution and sorting
  - In arid areas, ephemeral (wadi) stream beds: recharge along main drainage channels
- Bedrock aquifers
  - Receptiveness depends on the degree of fracturing
  - some direct recharge (difficult to quantify), but most recharge where major fracture zone catch overland or stream flow or are fed through overlying alluvium
- Volcanic rocks
  - Columnar fracture systems facilitate percolation; intercalated buried sediment and weathered lava layers, pores provide storage space

Ground-water flow paths varying in length, depth, and traveltime from points of recharge to points of discharge



U.S. Geological Survey Circular 1139 (1998)

Typical infiltration rates for Mediterranean (A), semi-arid (B) and arid sites (C) along a climatic transect



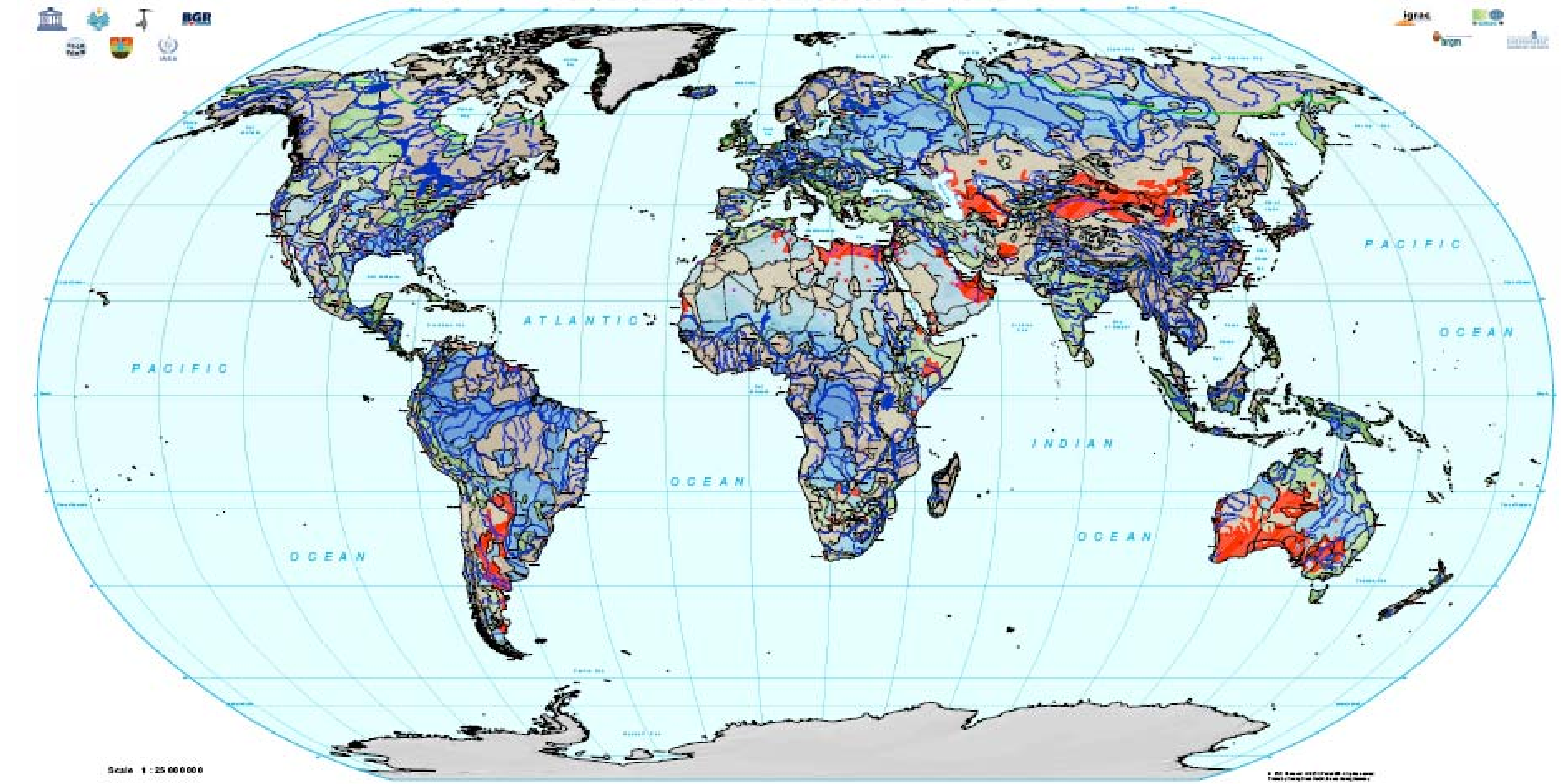
Lavee *et al.* 1998

Examples of indications of implications to recharge as a result of varying climate conditions - vegetation

Single-Site (Subtropical) Results from simulations by Bryson Bates, Steven Charles, Mick Fleming & Timothy Green

- Vegetation type affected the transpiration and resulting recharge more than soil type, but both played a significant role.
- Simulated net recharge consistently increased by absolute amounts approaching or exceeding the change in total rainfall.
- Recharge could more than double (1.74 to 5.09) under simulated climate change (37 percent increase in mean annual rainfall).
- Temporal persistence in annual recharge may by a factor between 2 and 5.
- The above were *indicated* by the simulations under these conditions, but are not considered robust predictions.

Groundwater Resources of the World: WHYMAP

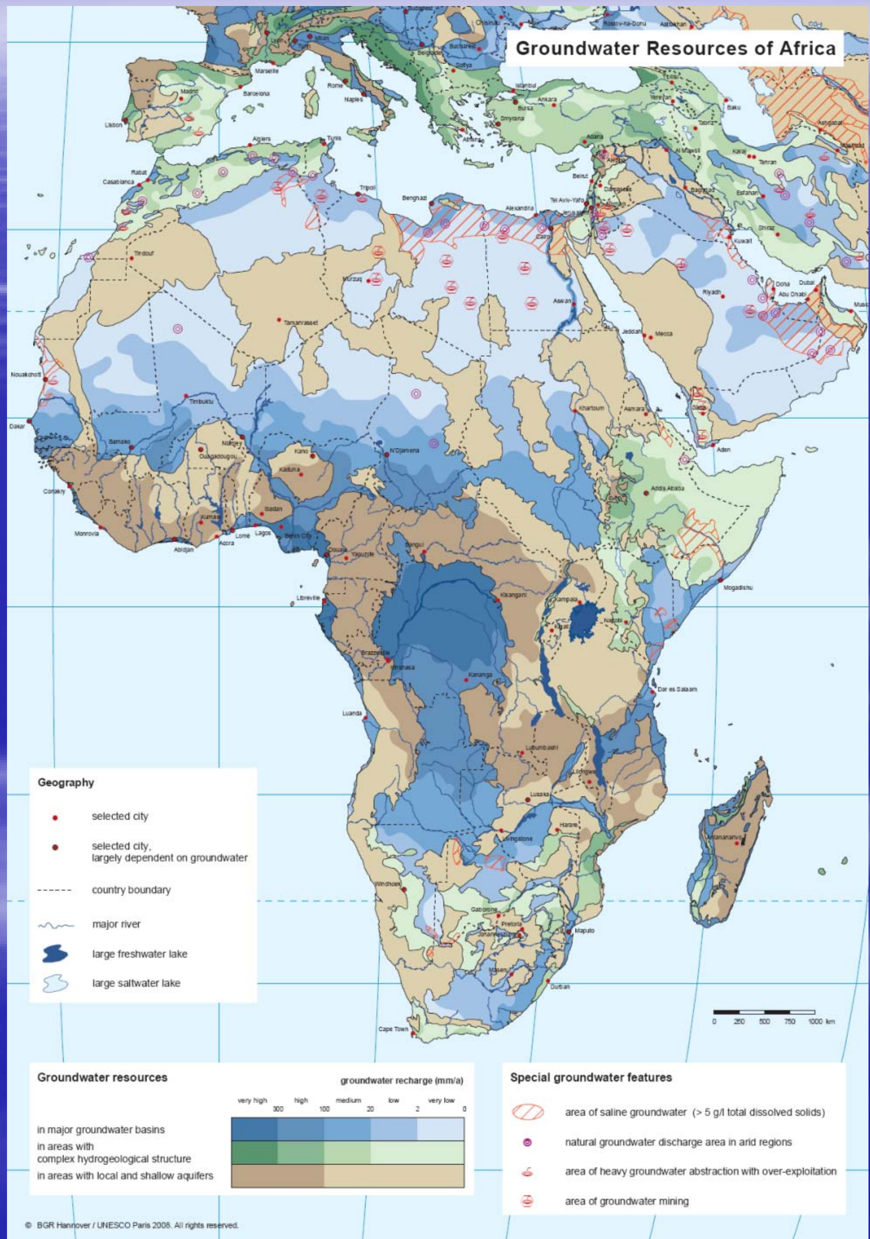


Groundwater resources and recharge (mm/year)

very high	high	medium	low	very low	
300	100	20	2	0	
					in major groundwater basins
					in areas with complex hydrogeological structure
					in areas with local and shallow aquifers

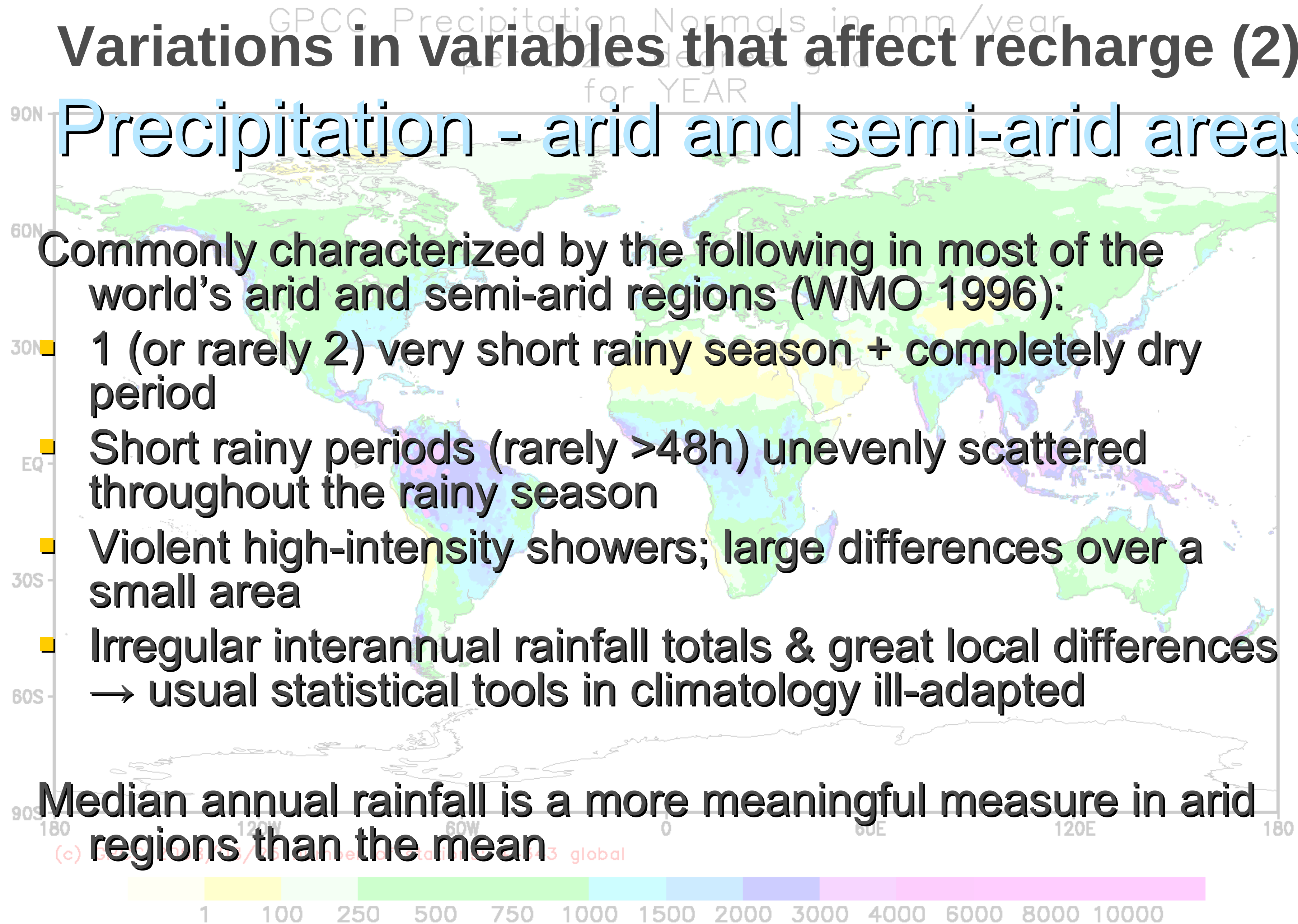
area of saline groundwater (> 5 g/l total dissolved solids (TDS))

Groundwater resources/recharge: Africa



Variations in variables that affect recharge (2):

Precipitation - arid and semi-arid areas

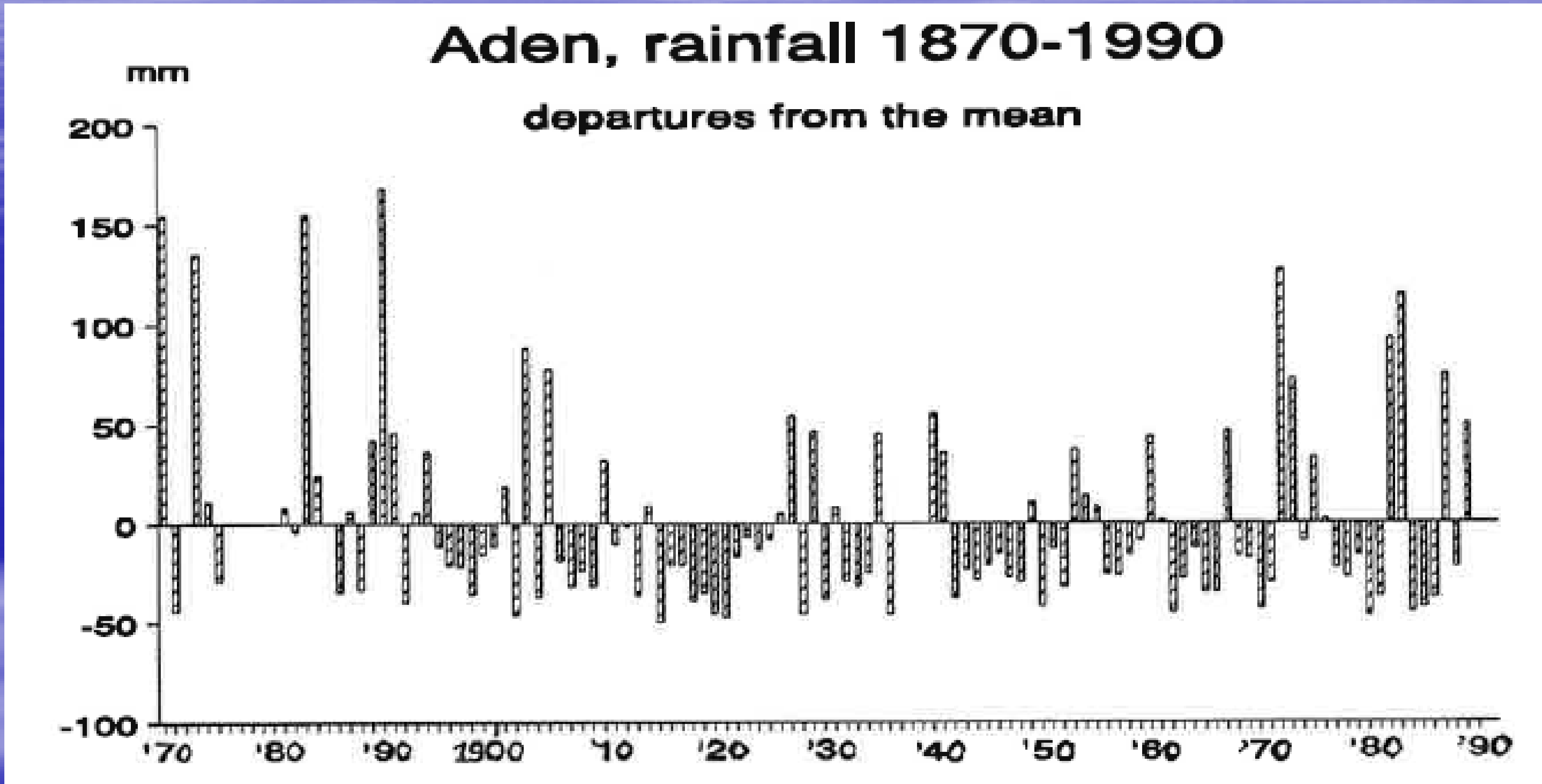


Commonly characterized by the following in most of the world's arid and semi-arid regions (WMO 1996):

- 1 (or rarely 2) very short rainy season + completely dry period
- Short rainy periods (rarely >48h) unevenly scattered throughout the rainy season
- Violent high-intensity showers; large differences over a small area
- Irregular interannual rainfall totals & great local differences → usual statistical tools in climatology ill-adapted

Median annual rainfall is a more meaningful measure in arid regions than the mean

Rainfall in Aden, Yemen

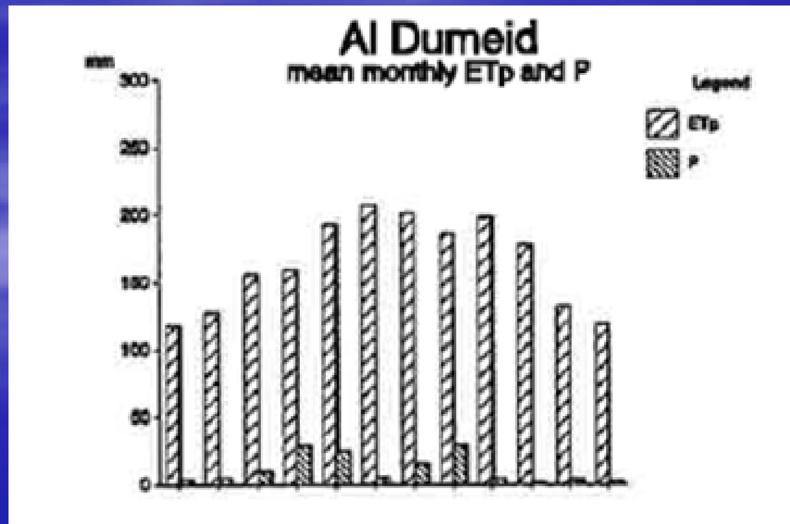


Due to the temporal variability of water regimes in arid zones, the value of a short-term data set of field measurements is rather limited.

Variations in variables that affect recharge (3): Evapotranspiration

- Strongly dependent on the depth of groundwater level; the closer the groundwater to the surface, the higher the ET
- Depends also on soil moisture salinity and root zone of the riparian vegetation
- ET can only be controlled

by management of the groundwater table and the vegetation

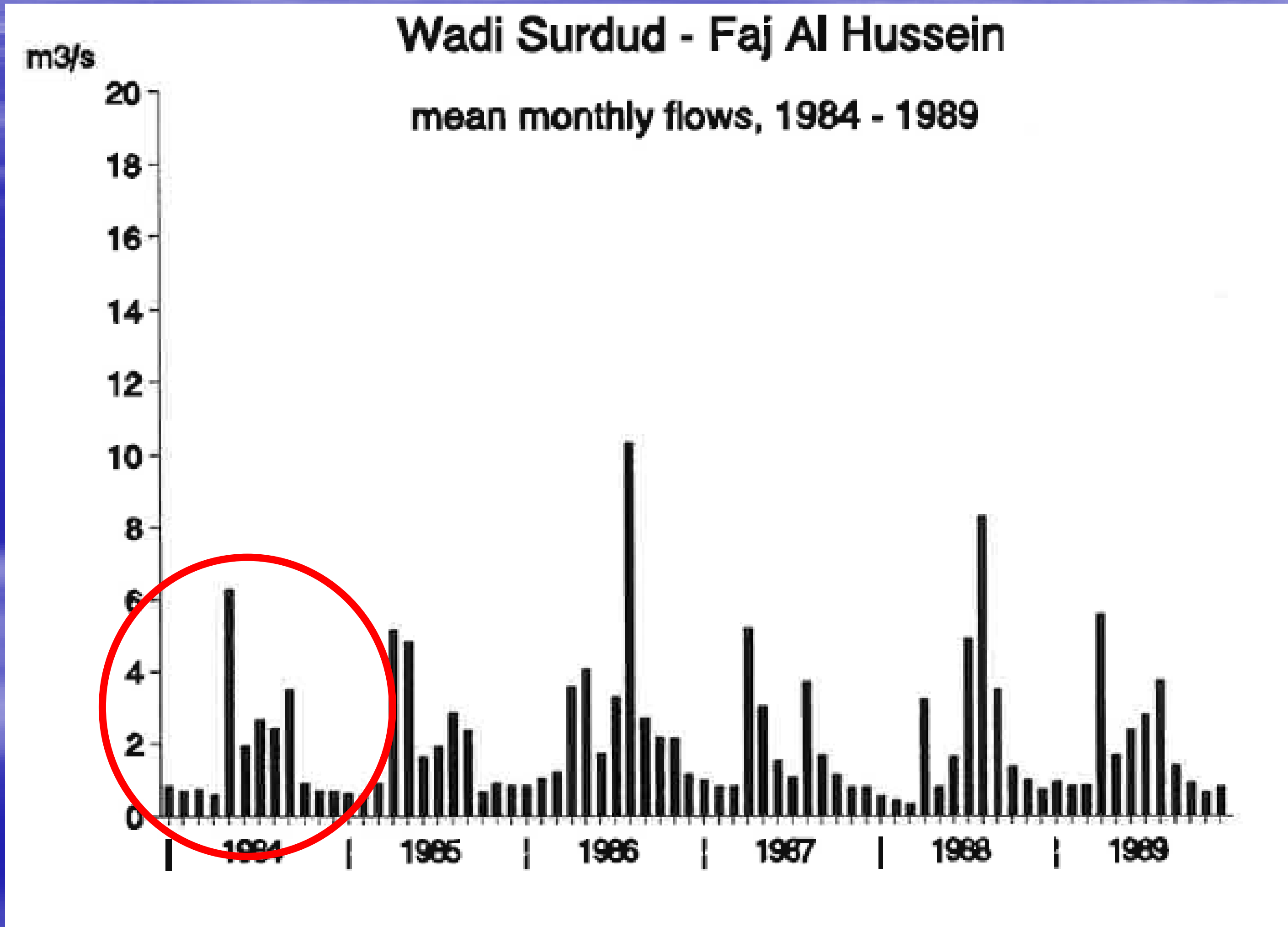


Mean monthly potential evapotranspiration (ET_P) and precipitation (P) in Al Dumeid in Yemen

See Hendrickx, Phillips & Harrison (2003) for an arid/semi-arid areas focused review

Variations in variables that affect recharge (4): runoff

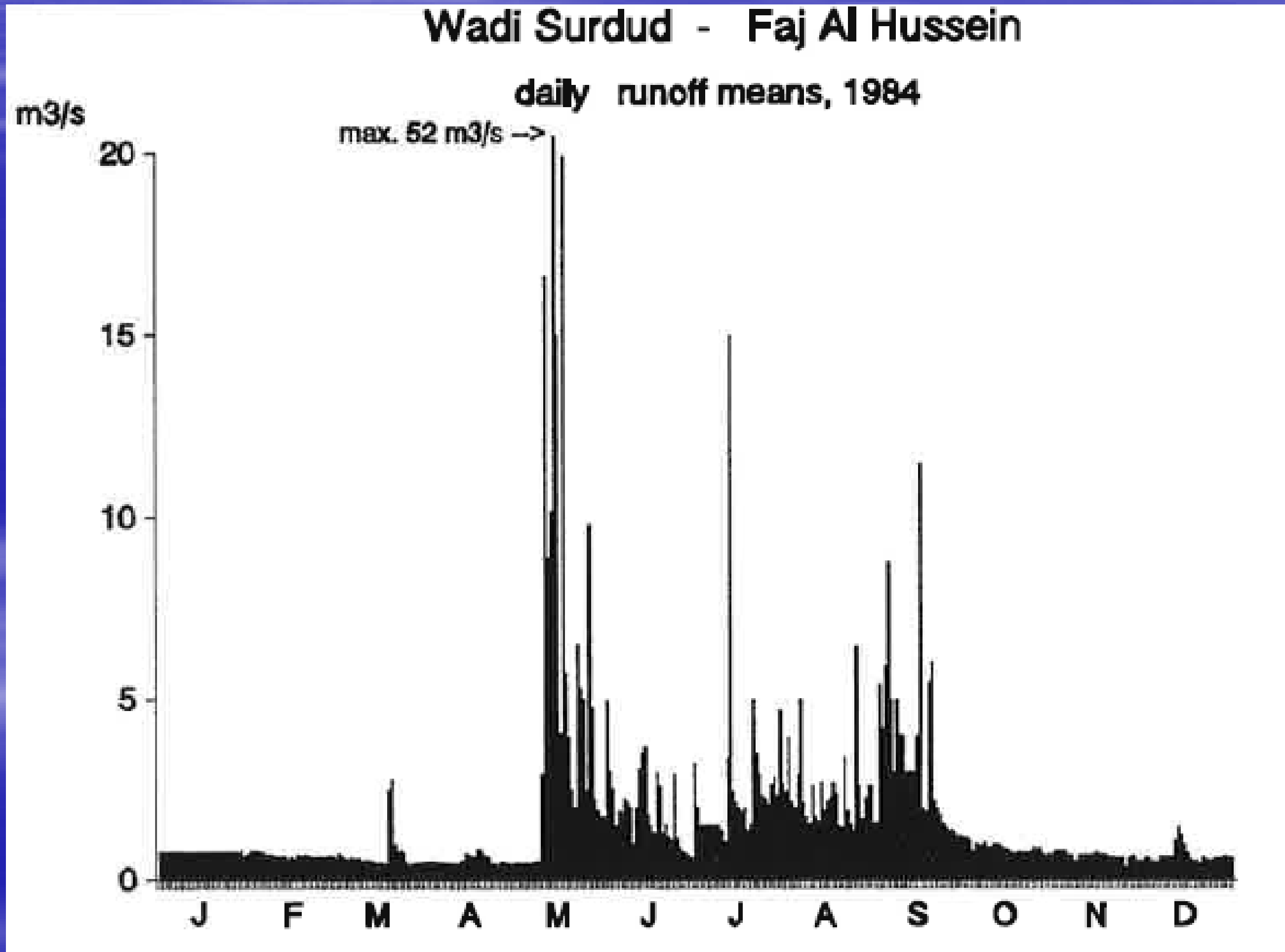
Mean monthly flows: Wadi Surdud, Yemen



TNO

Variations in variables that affect recharge (4): runoff

Mean monthly flows: Wadi Surdud, Yemen



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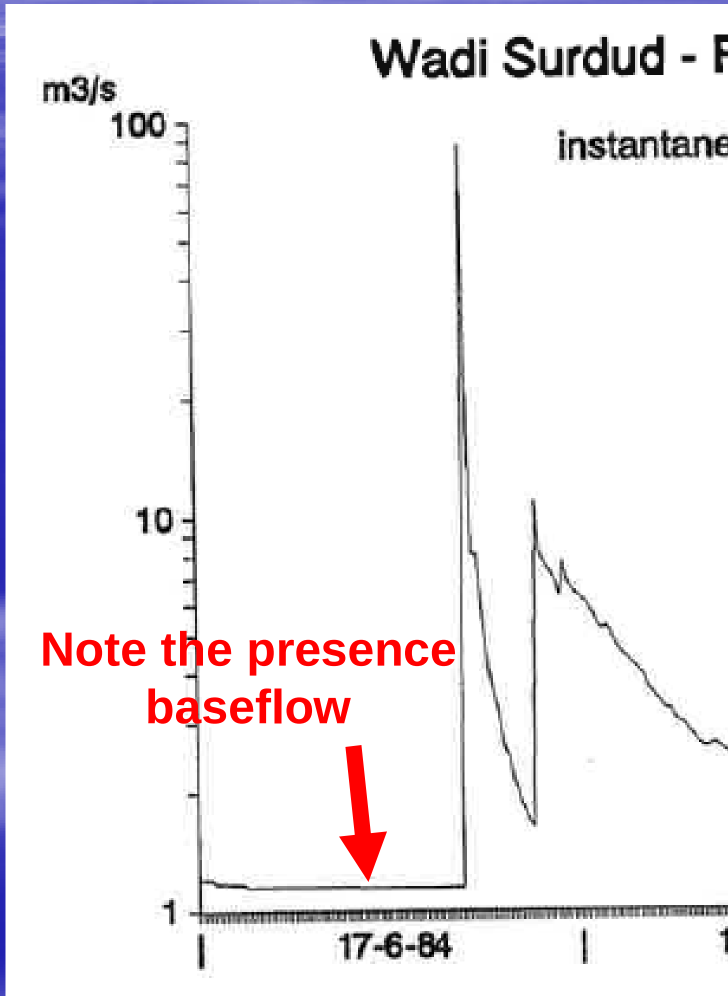
Instantaneous flow: Wadi Surdud, Yemen

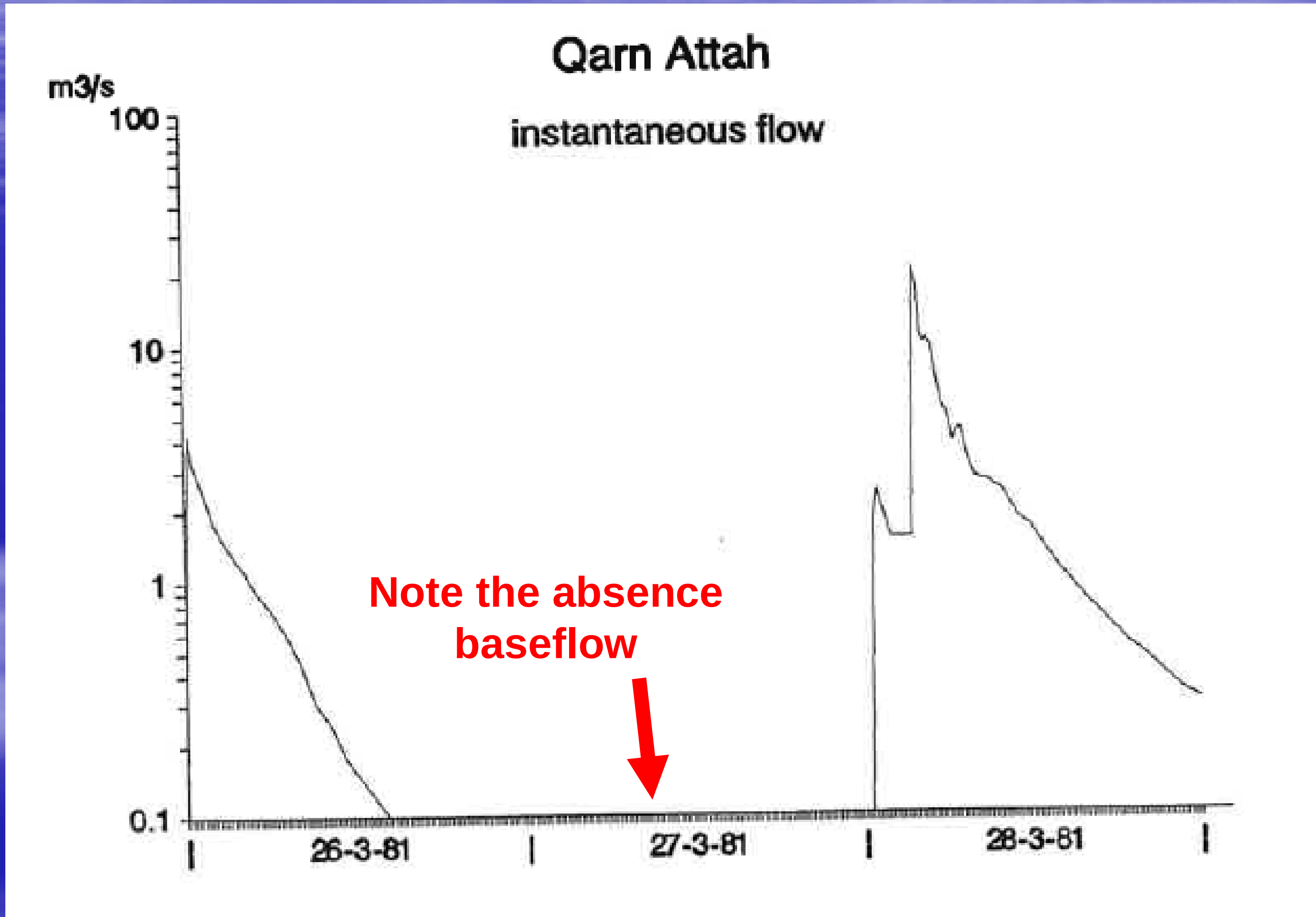


Typical

- Short time to peak & sharp peak (10-30 mins in)
- Short duration
- Less steep recession limb

TNO

Instantaneous flow: Qarn Attah, Yemen



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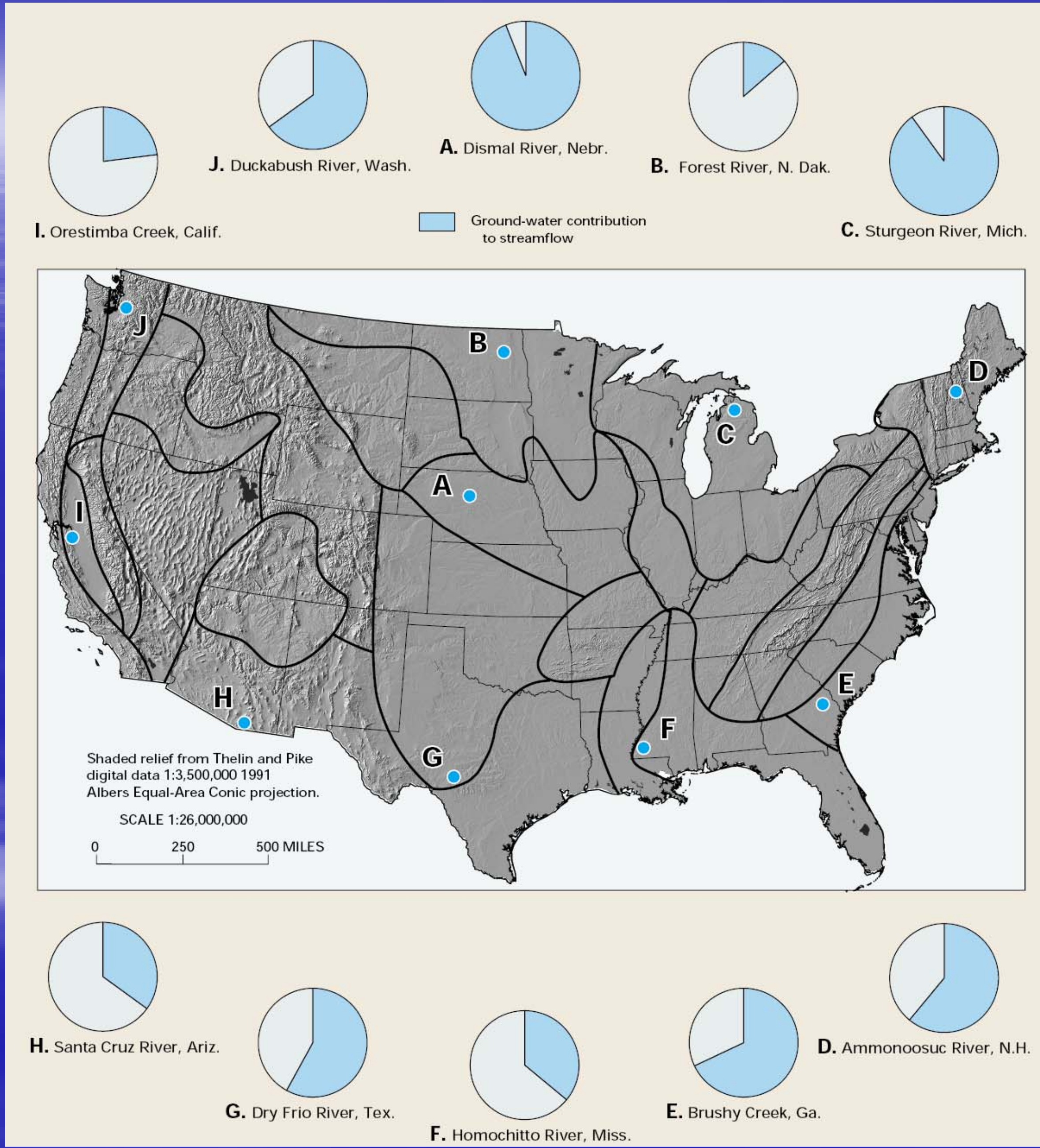
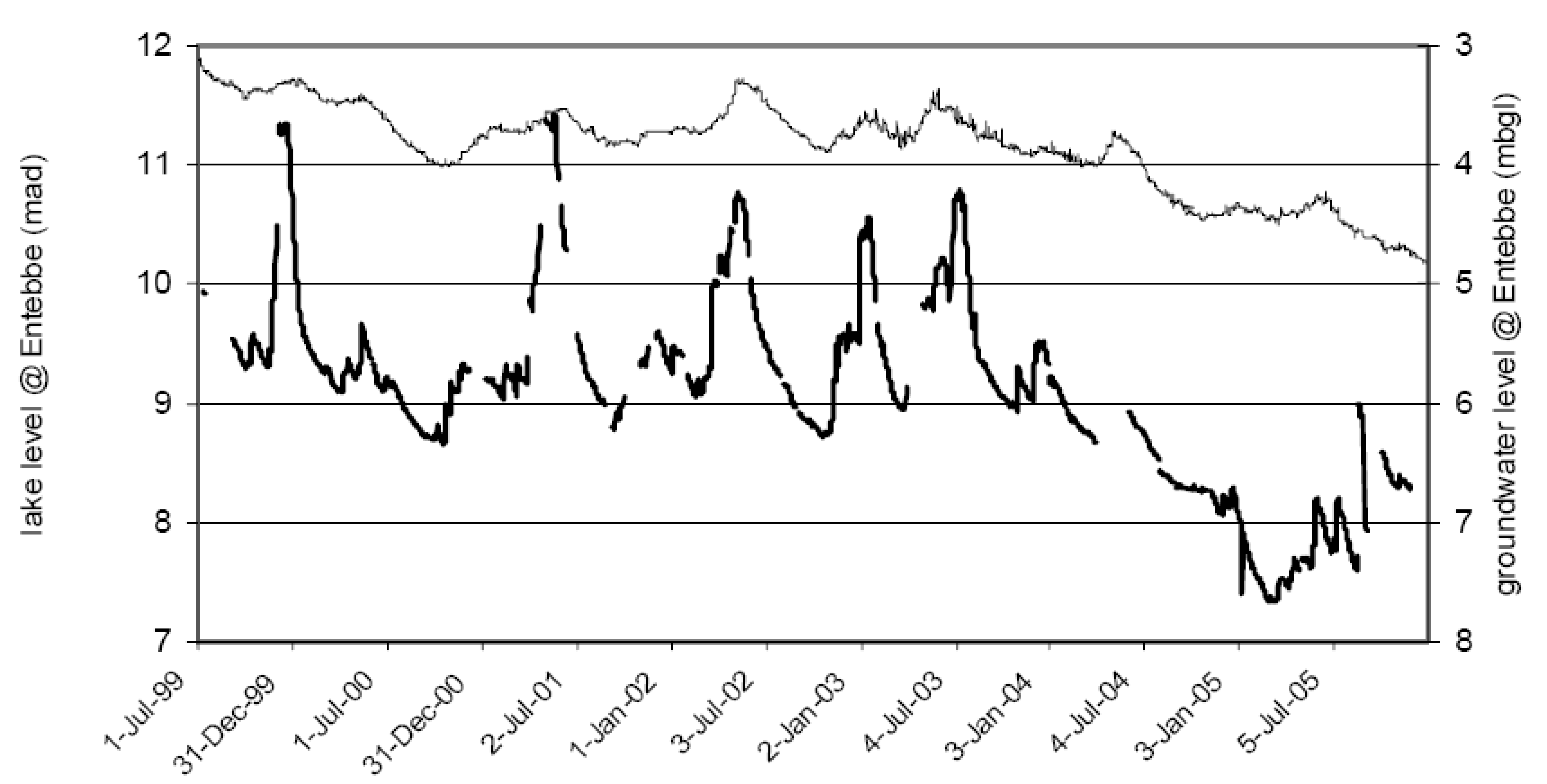
Groundwater contribution to streamflows in the U.S.



U.S. Geological Survey Circular 1139 (1998)

Lake Victoria and groundwater at Entebbe



Recent water level fluctuations in Lake Victoria (thin line) and in ground water at Entebbe (thick line) 32.5 32.50E, 0.2 E, 0.20N N (after Basalirwa et al. (2006))

Groundwater-surface water interactions: impacts of climate variability and human induced changes

- Declining streamflows have been observed in many parts of the tropics during the dry season (indication of reduced discharge, linked declining recharge and storage of groundwater).
- The relative importance of changes in land use and climate in controlling this phenomenon still needs to be unravelled. Soil degradation (affecting e.g. hillslope hydrological properties) and urbanisation following forest conversion have markedly changed recharge conditions in many areas, thereby complicating the identification of the key controls of declining baseflows.

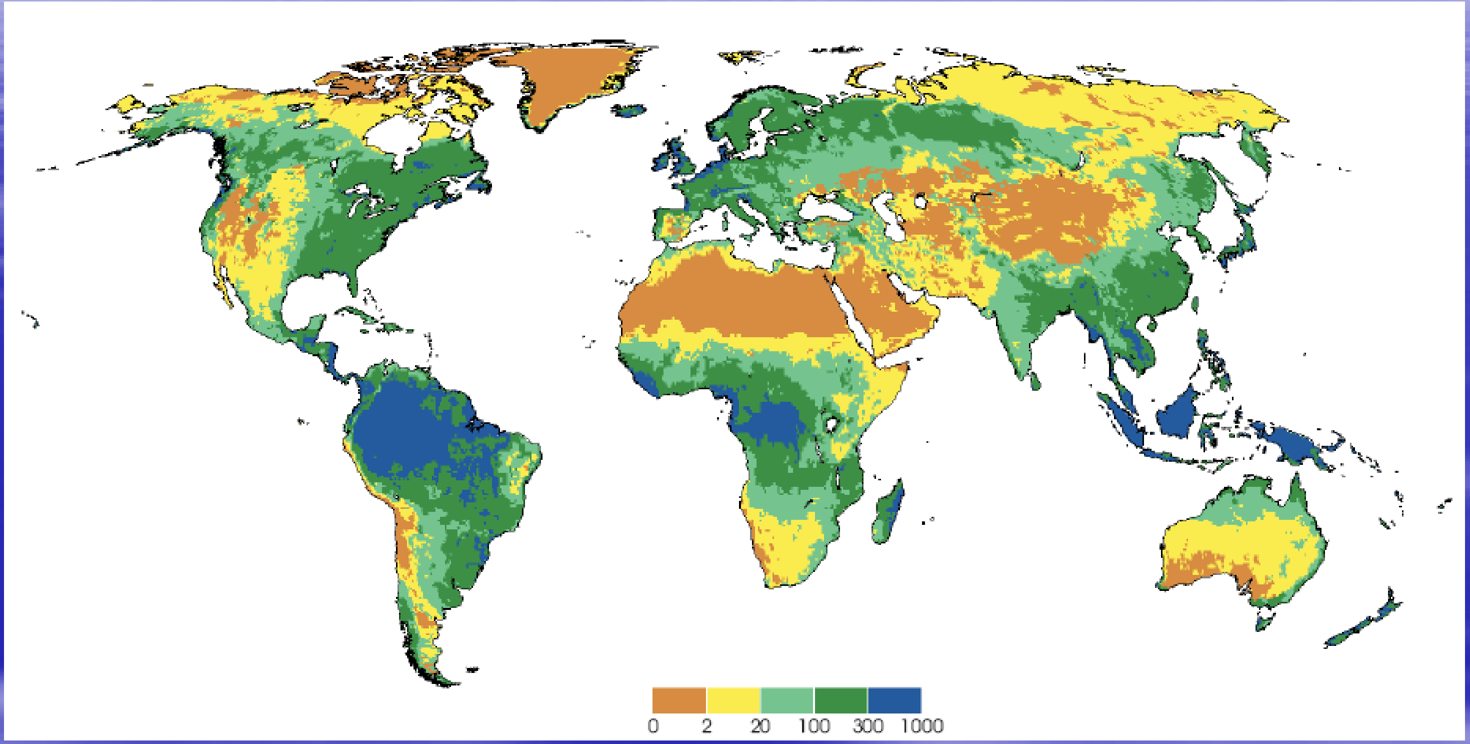
Climate variability and change impacting on recharge

- Changes in temperature (In aquifers with significant seasonal snow cover, groundwater recharge might decrease under conditions with less snow)
- Changes in sea level (shifting level of discharge, saltwater intrusion into coastal aquifers)
- Rainfall pattern changes
- Extreme weather events
- Changing vegetation which in turn influences recharge

IPCC 2007 report: groundwater quotations

- “In coastal areas, sea level rise will exacerbate water resource constraints due to increased salinisation of groundwater supplies.”
- “There may be regions, such as south-western Australia, where increased groundwater withdrawals have been caused not only by increased water demand but also because of a climate-related decrease in recharge from surface water supplies (Government of Western Australia, 2003). …Owing to a lack of data and the very slow reaction of groundwater systems to changing recharge conditions, climate-related changes in groundwater recharges have not been observed. [WGII 1.3.2, 3.2]”

Long-term average diffuse groundwater recharge



Long-term average diffuse groundwater recharge for the time period 1961–1990 in mm/yr; ensemble mean of groundwater recharge as computed by two WGHM model runs with either GPCC or CRU precipitation data as input

P. Döll and K. Fiedler 2008: Global-scale modeling of groundwater recharge

According to the results of a global hydrological model…, groundwater recharge, when averaged globally, increases less than total runoff (by 2% as compared with 9% until the 2050s for the ECHAM4 climate change response to the SRES A2 scenario: Döll & Flörke, 2005)

Potential of groundwater resources to help mitigate effects of climate change

- Where not only surface water availability but also groundwater recharge is reduced due to climate change, the opportunities to balance the effects of more variable surface water resources by groundwater use are restricted
- Shallow groundwater (unconsolidated deposits, fractured aquifers, coastal & small island aquifers) more vulnerable to changes in precipitation
- Increased drought frequency, or extended dry seasons will increase demand on rural groundwater supplies
- Concerns over food security are expected to lead to a much greater push for groundwater for irrigation
- Groundwater sources may fail, or not cope with demand

Projected climatic changes in groundwater recharge

Dramatical decreases in GW recharge projected in: NE Brazil, SW Africa and along the southern rim of the Mediterranean Sea. Percentage decrease of GW recharge is higher than that of total runoff (Assumption: in semi-arid areas groundwater recharge only occurs if daily precipitation exceeds a certain threshold).

Increases in GW recharge projected in: parts of the Sahel, the Near East, N China, Siberia, and W USA. (Possibly overestimated as increased occurrence of heavy rains, which leads to lower GW recharge due to infiltration limits, not considered. Attention: rising water tables may cause problems related to soil salinisation and wet soils in towns or agricultural areas).

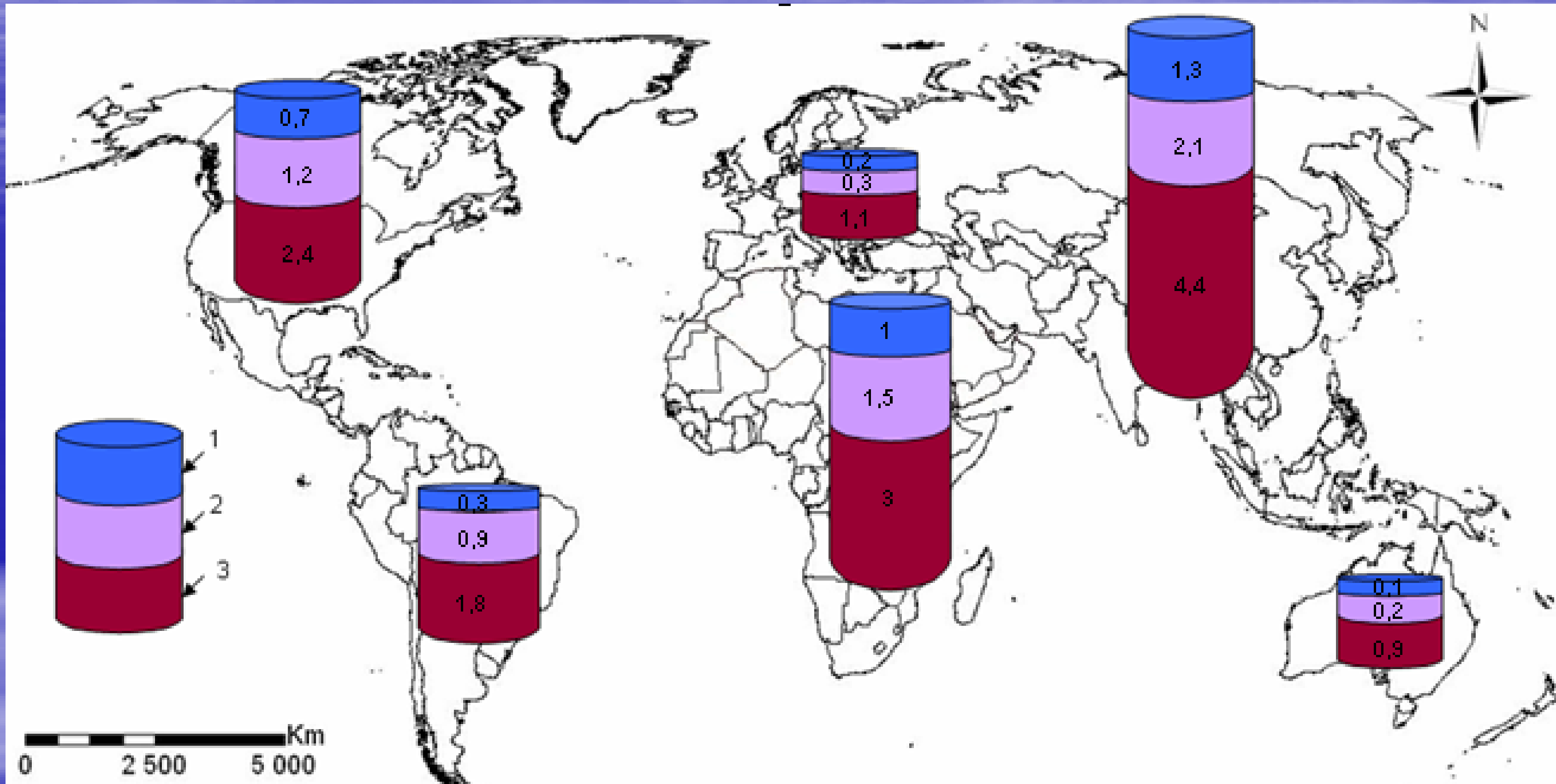
Hiscock *et al.* (2008) – projections for GW recharge in Europe: decreases in N Italy and S Spain / increases in N Denmark; S England; and N France

From Kundzewicz & Döll 2008

Orders of magnitude of groundwater storage by continent

(in 10^6 km^3 (10^{15} m^3)

J. Margat 2008



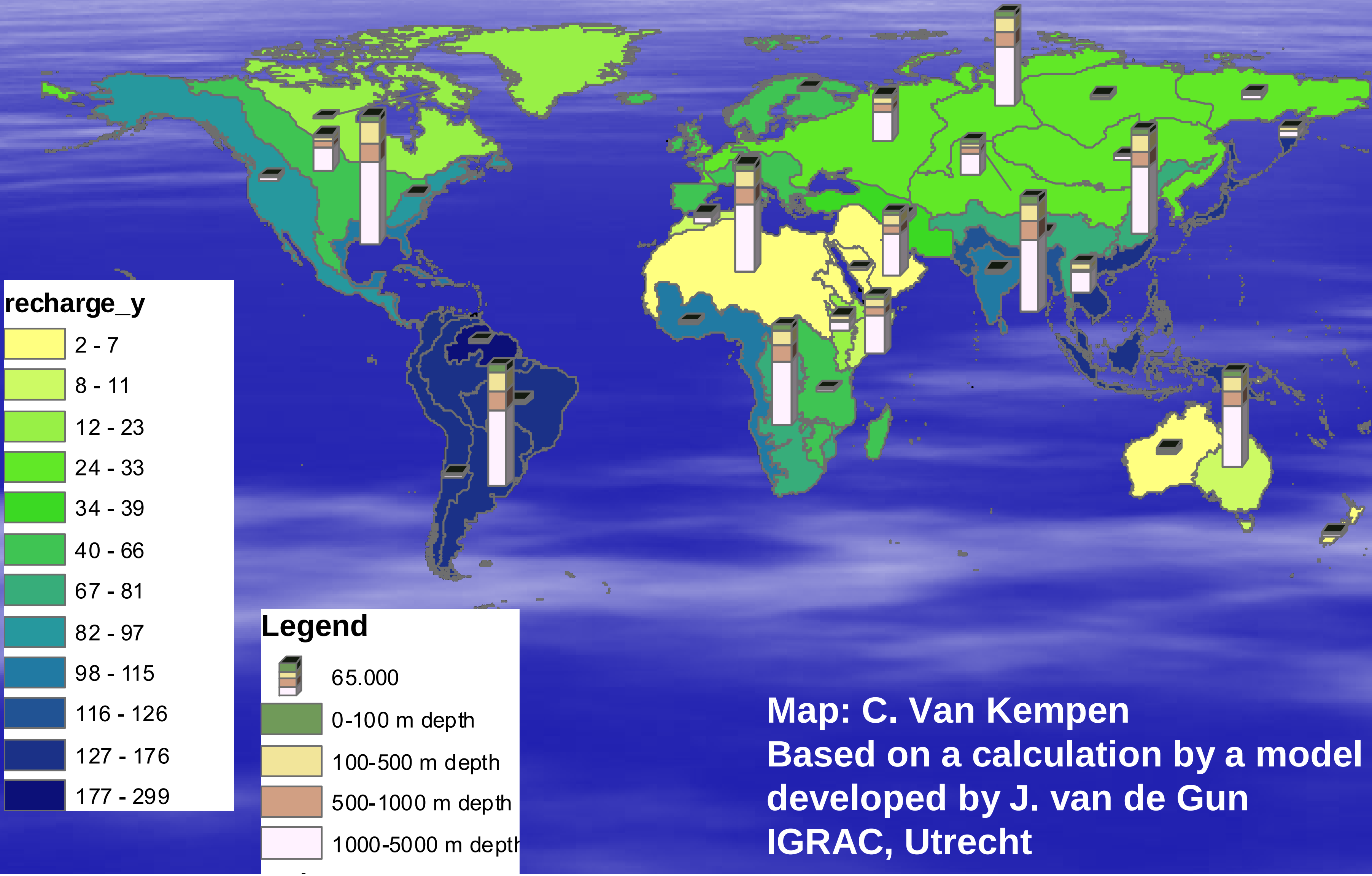
1 – zone of active exchange, water table aquifers or confined aquifers, above a depth of 100 m - freshwater (Total: 3,6)

2 – zone of rather active exchange, more commonly confined aquifers; 100-200 m depth – predominantly freshwater (total : 6,2).

3 – passive zone between the depths 0 and 2 000 m, predominantly salty water (total : 13,6).

Groundwater Storage and Recharge

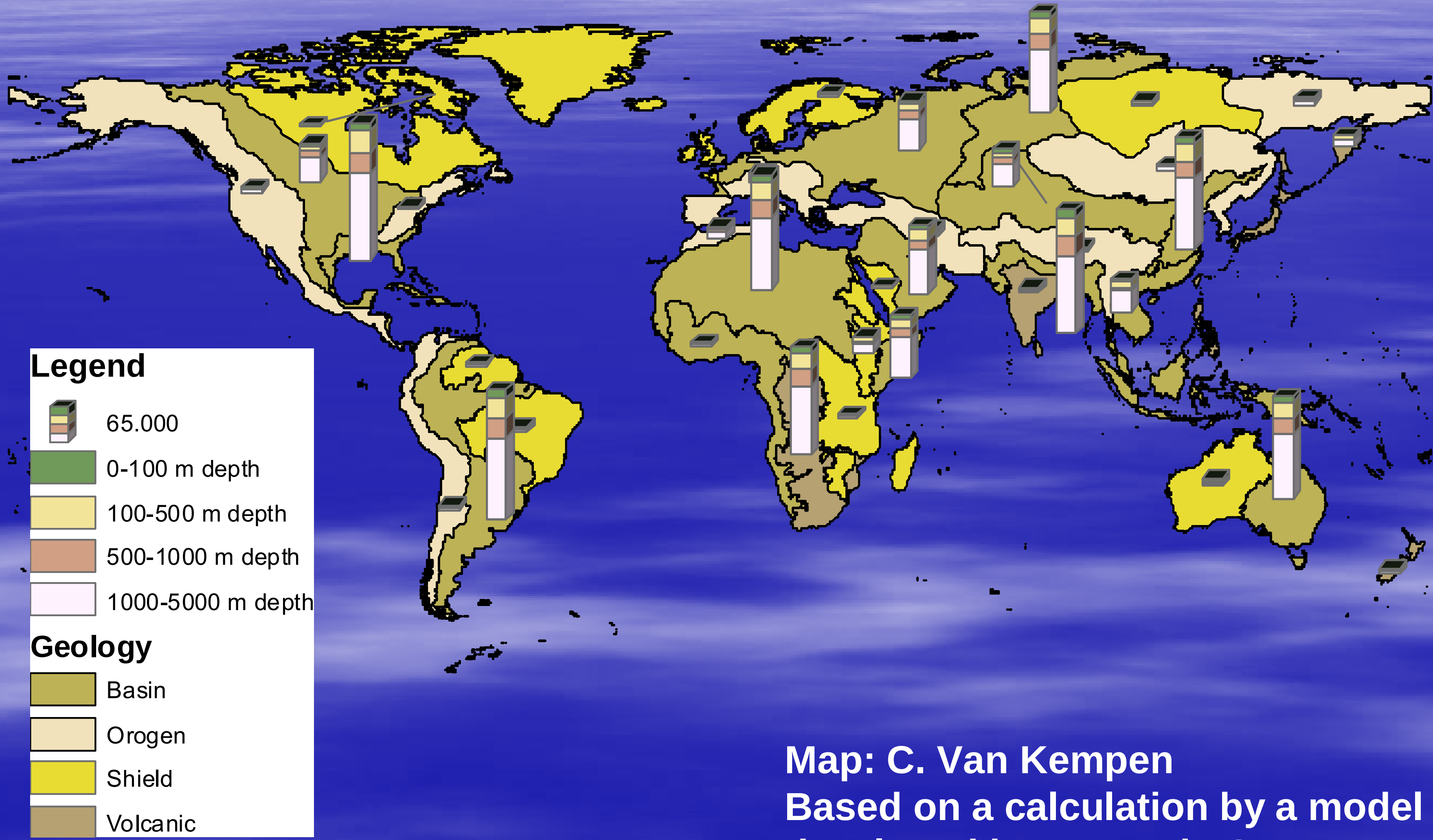
Groundwater Storage per Groundwater Region in million km^3



Map: C. Van Kempen
Based on a calculation by a model developed by J. van de Gun
IGRAC, Utrecht

Groundwater Storage

Groundwater Storage per Groundwater Region in million km^3



Map: C. Van Kempen
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IGRAC, Utrecht

Emerging for large-scale observation of storage changes: Gravity Recovery and Climate Experiment (GRACE) NASA, DLR

- High precision satellite gravimetry, first twin satellite gravimetry mission launched in 2002
- Generates time series of total terrestrial water variations → can be used to assess groundwater storage changes
- Monitoring of large scale water movement
- Disadvantages: low spatial and temporal resolutions and lack of information on the vertical distribution of observed water storage changes → not yet been fully embraced by the hydrological community
- Merging GRACE data with other datasets reveals much higher spatial and temporal resolution than GRACE alone → this technique may be the key to maximizing the value of GRACE data for groundwater resources studies

Water management challenges in arid and semi-arid areas

- Spatial and temporal variability – difficulty of quantifying the resource
- Commonly data scarcity
- Limited applicability of assessment tools such as models developed for more humid regions
- Vulnerability of drylands environment (vegetation etc.) to human-induced changes

Augmenting water resources in water-scarce areas: options

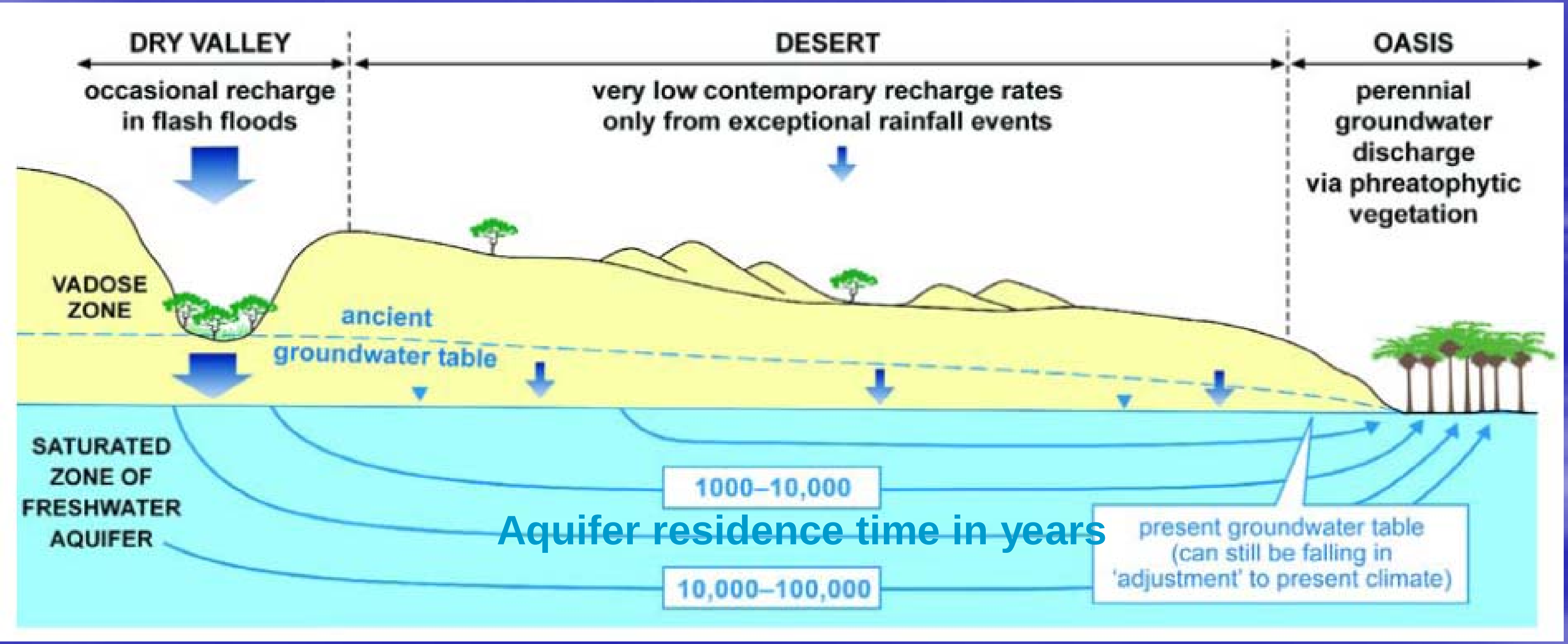
- Managed Aquifer Recharge
- Traditional groundwater collection systems (e.g. qanats)
- Non-renewable groundwater
- Water reuse
- Rainwater harvesting
- Fog collection
- Desalinization
- …and important to manage DEMAND also
- Consider all sources in an integrated way and assign to most appropriate uses taking into account quality and quantity requirements!

“Mining the storage”: non-renewable groundwater resources

- Aquifer recharge very limited but aquifer storage very large
- Rate of groundwater resource renewal: Average annual aquifer recharge rate/Total drainable aquifer storage reserves
- Renewal is comparative (not absolute) concept – relative to both aquifer storage and recharge AND thus subject to very wide variation due to geological factors (aquifer thickness and drainable porosity) and climatic parameters (especially rainfall regime)
- Development of these resources implies mining of the reserves
- Development can be considered “socially-sustainable” when certain criteria are met.

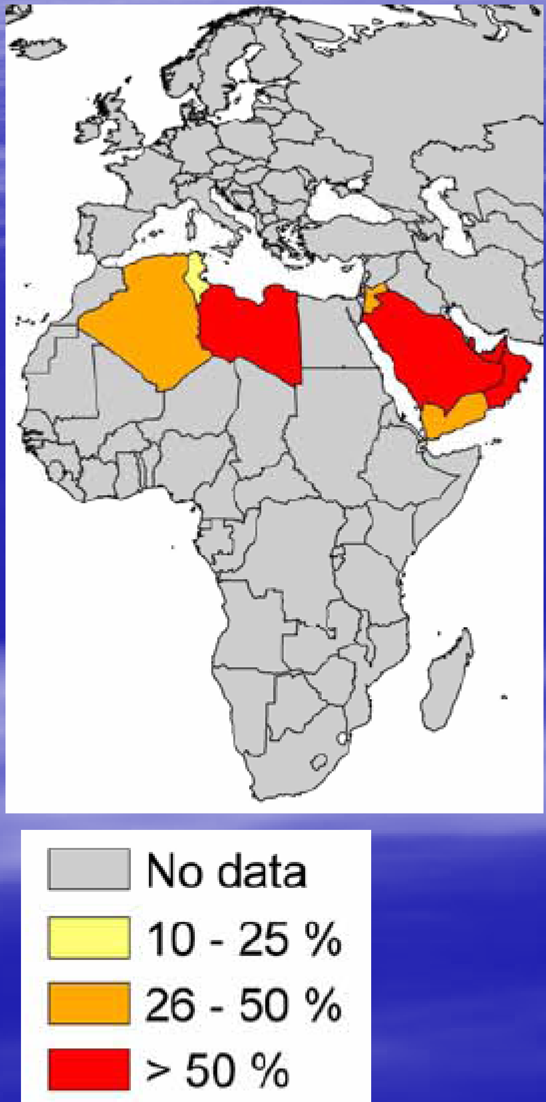
(UNESCO-IHP/World Bank monograph)

An example of a hydrogeological setting illustrating the occurrence of essentially non-renewable groundwater resources



Foster & Loucks 2006. UNESCO

Current utilisation of non-renewable resources



COUNTRY	YEAR(S) OF ESTIMATE	GROUNDWATER (Mm^3/a)		
		Share of demand *	Total use	Non-renewable
Algeria	(2000)	54%	2,600	1,680
Saudi Arabia	1999 (1996)	85%	21,000	17,800
Bahrain	1999 (1996)	63%	258	90
Egypt	1999 (2002)	7%	4,850	900
UAE	1999 (1996)	70%	900	1,570
Jordan	1999 (1994)	39%	486	170
Libya	1999	95%	4,280	3,014
Oman	1999 (1991)	89%	1,644	240
Qatar	1999 (1996)	53%	185	150
Tunisia	2000	59%	1,670	460
Yemen	1999 (1994)	62%	2,200	700

Note:
* Proportion of total actual water demand met from groundwater.
Source: Based on Margat (1995, 1998, 2004), UN-FAO (1997), UN-ECSWA (1999).

Foster & Loucks 2006. UNESCO

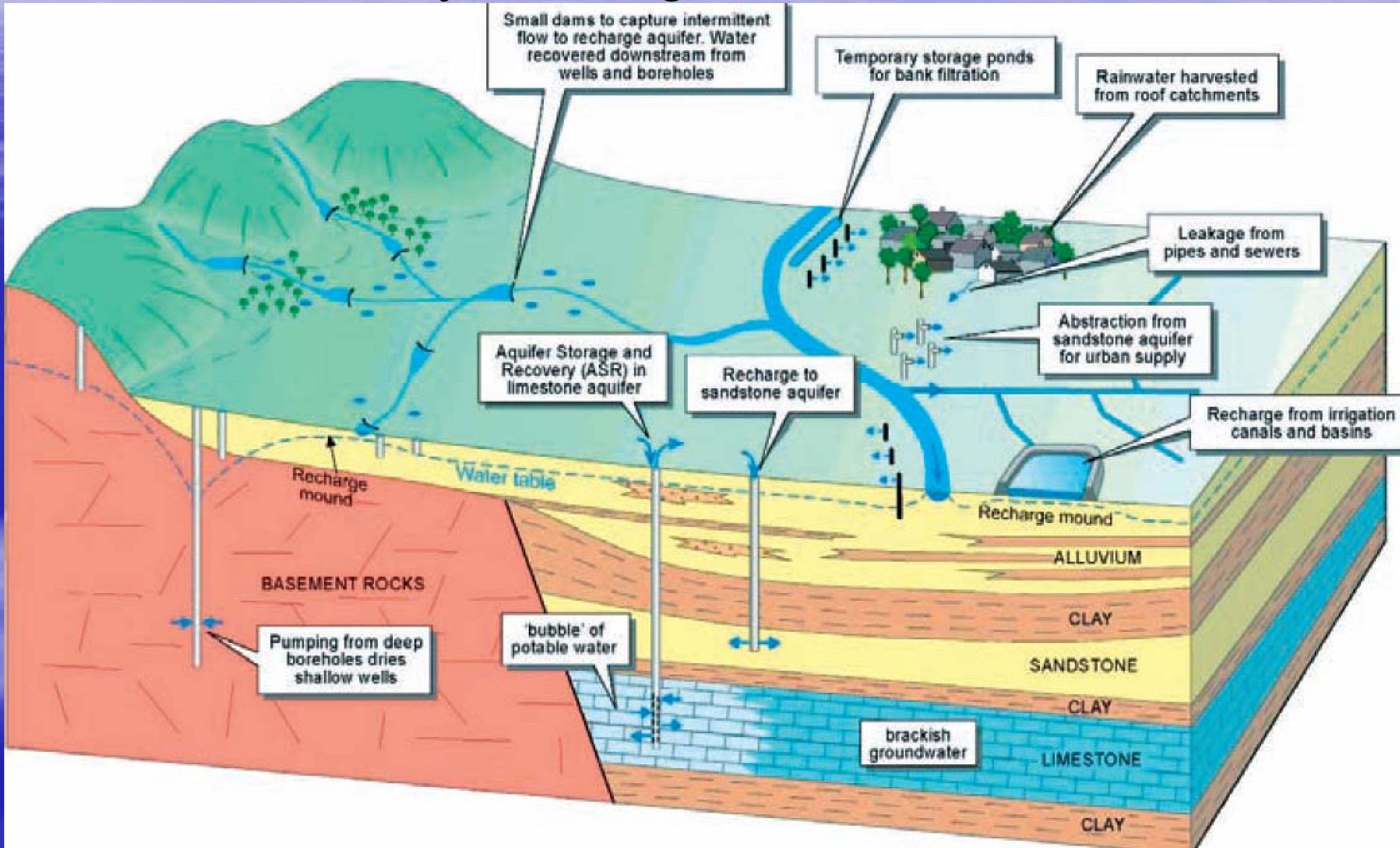
Action/management considerations

- Vulnerability of groundwater resources (GW) to climate variability: current recharge and residence times; recharge vs storage
- Base your recharge estimation on monitoring of sufficient duration with a view of the observed variability
- GW levels in relation to sea & surface water course levels
- Flood and drought history – max & min
- Watch out for exposure to increased evaporation from a shallow GW table in arid areas
- Prospects for enhancement of recharge

Coping with water scarcity – enhancing recharge

- Adaptation to declining low flows: construction of managed aquifer recharge (MAR) schemes to retain part of the stream flow during the wet season. Advantage of retention structures like sand dams over reservoirs: smaller evaporation losses.
- Especially bigger schemes require understanding the hydrogeology, estimating space in aquifer to store additional water and quantifying the components of the water balance
- Understanding the factors governing efficiency require more study
- Hydrological and environmental impacts downstream have to be considered

Various ways of recharge occurring –Managed Aquifer Recharge (MAR) can also serve reduction of vulnerability to drought and variable rainfall

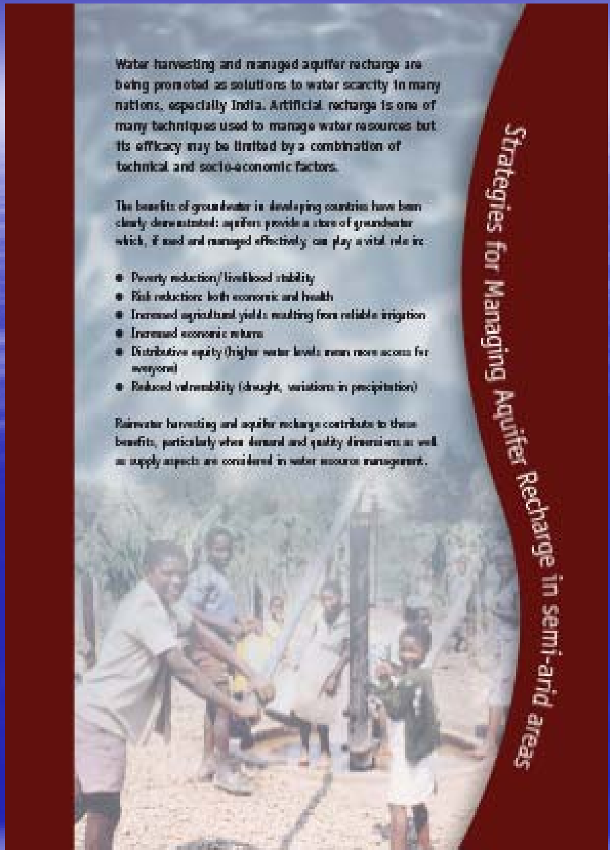


Gale 2005

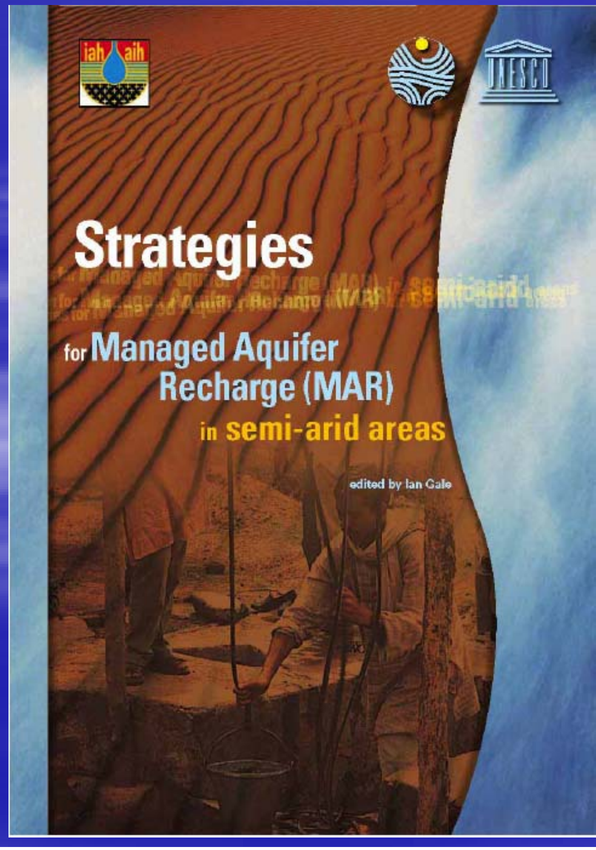
Sources of water for Managed Aquifer Recharge

- Perennial stream/river/canal
- Floods in intermittent streams and wadi's
- Storage dam
- Treated waste or reclaimed water
- Treated potable water
- Urban storm water
- Rooftop rainwater harvesting

Further guidance on using MAR: UNESCO booklet Strategies for Managed Aquifer Recharge in Semi-Arid Areas



- UNESCO-International Association of Hydrogeologists joint publication
- Authored by Ian Gale
- Available for free download at www.unesco.org ("Documentation")
- Free hardcopies available at the Secretariat of IHP in UNESCO



- Strategies for managing Aquifer recharge in semi-arid areas

Future & some adaptation considerations

- Variable rainfall; mean annual rainfall may be altered by global warming; intensity and frequency play a role in recharge
- Groundwater recharge responds to changes in e.g. rainfall non-linearly
- Recharge is very sensitive to temporal distribution of rainfall, soil properties and soil cover/vegetation – heterogeneity to be accounted for
- More work needed on assessing impacts of climate variability and change on groundwater
- Water quantity affects quality!
- In adaptation, preparedness along the same lines as for hydrological extremes makes sense (for helpful guidance thinking of water managers, see www.waterandclimate.org); all water sources to be considered, especially in semi-arid areas

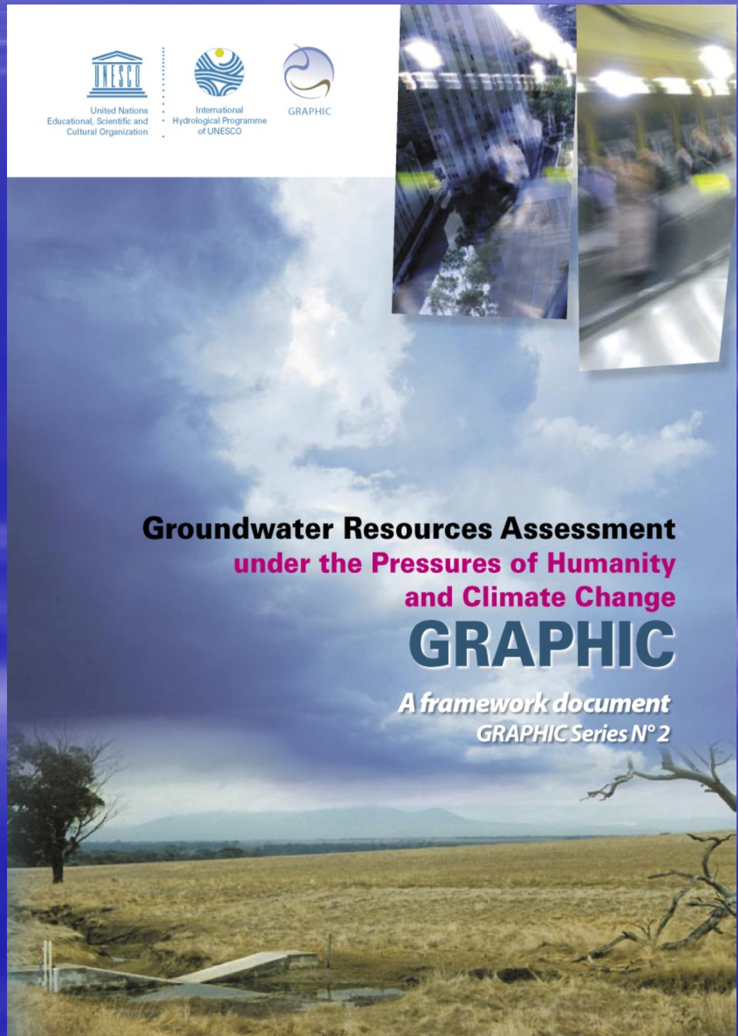
Objectives of UNESCO GRAPHIC project

- to improve our understanding of how groundwater interacts within the global water cycle, how it supports ecosystems and humankind and, in turn, responds to the impacts of climate change.
- to promote consideration of groundwater in the use of climate change information as a contribution to adaptation and advancing climate prediction;
- to initiate dialogue between groundwater and climate scientists at the global level; and
- to raise awareness within the climate community of climate-related groundwater research activities

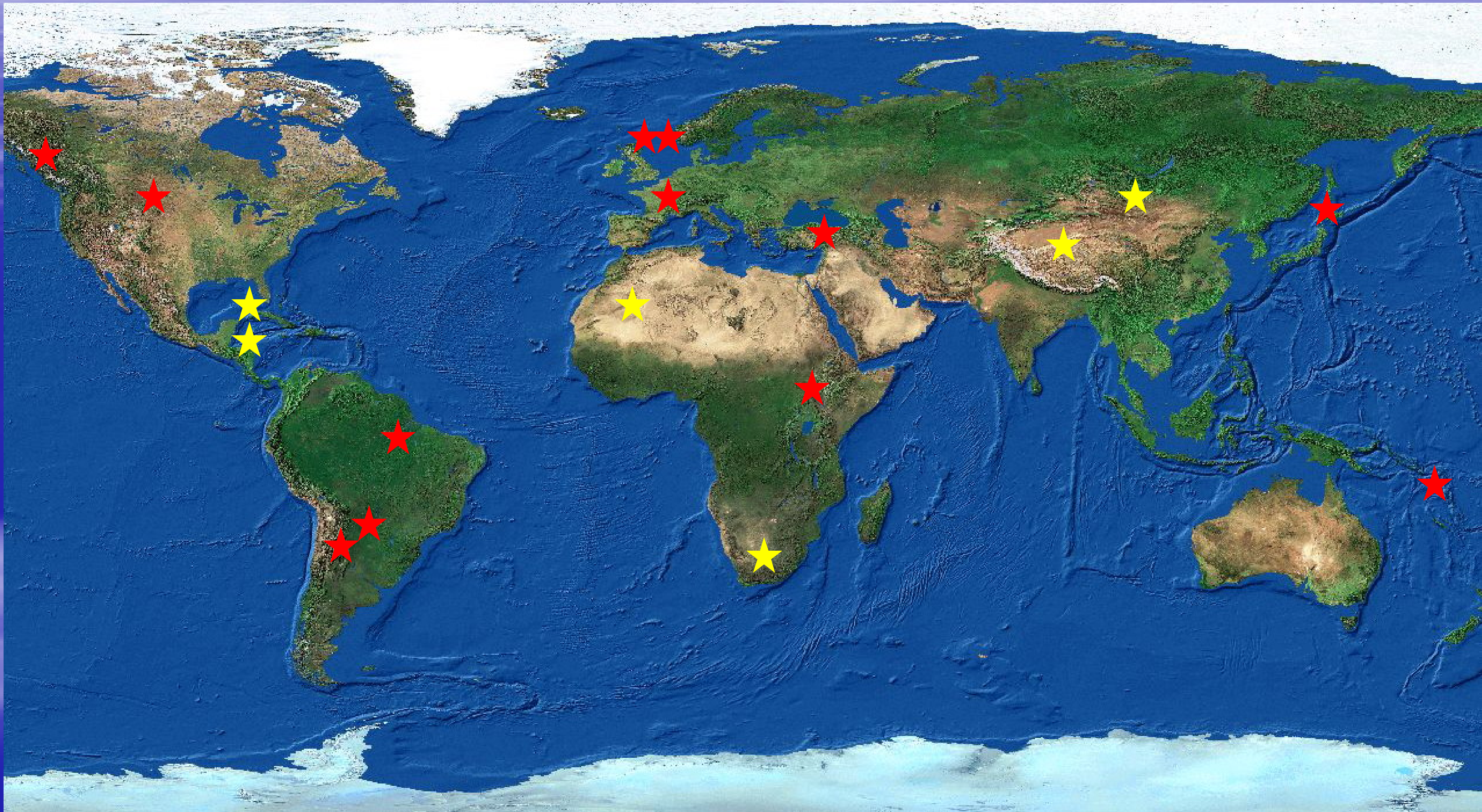
Groundwater Resources Assessment under the Pressures of Humanity and Climate Change

GRAPHIC Subjects and Methods

- Recently published: GRAPHIC Framework Document
- For download at http://www.unesco.org/water/ihp/graphic/
- Publications on GRAPHIC case studies foreseen for 2009



Structure of GRAPHIC: Case studies (existing and potential)



New call for case studies in 2009!

TIGER announcement of opportunity

Assessment of Water Resources in Africa under Global Climate Variability: *Turning Science into Operations*

- The TIGER partners invite African scientists, technical centres and water authorities to prepare and submit project proposals to participate in the Scientific Component of the second implementation period of the TIGER initiative (2009-2011). The deadline for submission of proposals is **May 22, 2009**
- Selected projects will be integrated into the TIGER Network and will benefit from the TIGER Capacity Building Facility. This includes: free access to EO data, scientific advice, free software, training, research stages, dedicated courses, installation of Data Dissemination Systems, support for the participation to TIGER-related workshops, E-learning and support for scientific publication
- For details, see: : http://eopi.esa.int/TIGER2