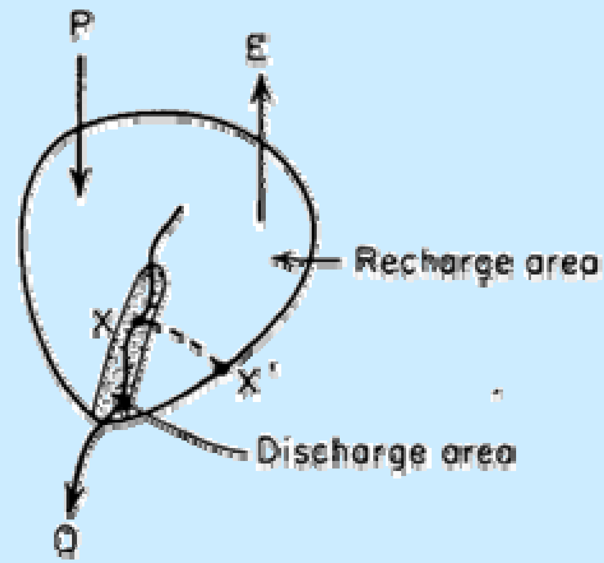
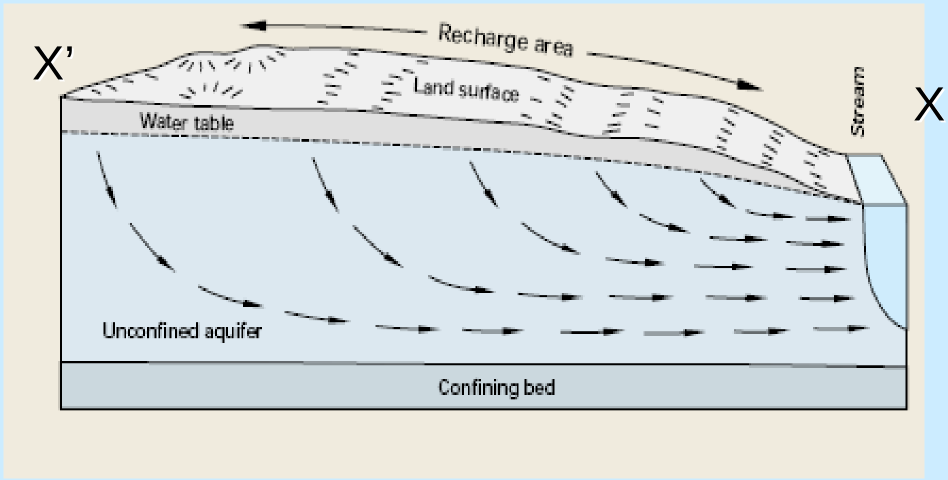
Multi-scale quantitative mapping of recharge/discharge to ground water systems in Minnesota

John L. Nieber and Roman Kanivetsky,
Dept. of Bioproducts and Biosystems
Engineering, University of Minnesota

and

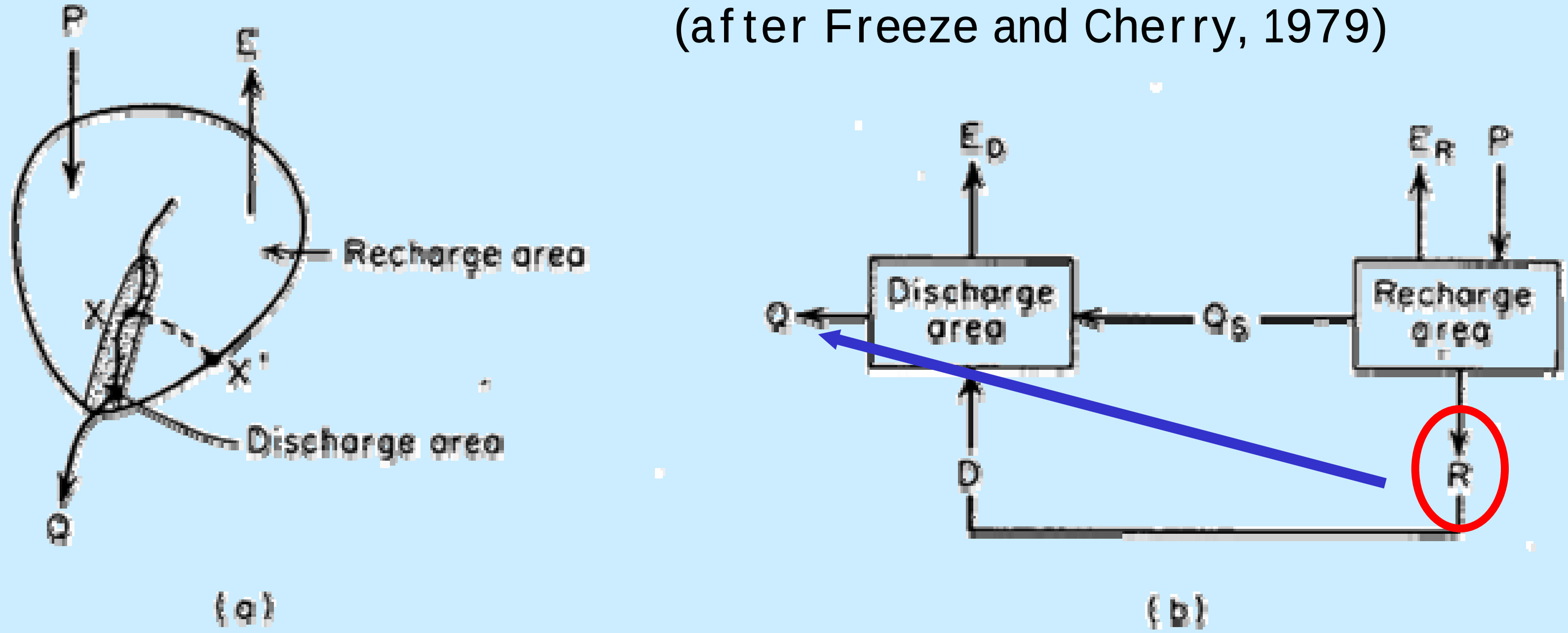
Boris Shmagin, Water Resources Center
South Dakota State University


P
E
Recharge area
X
X'
Discharge area
Q

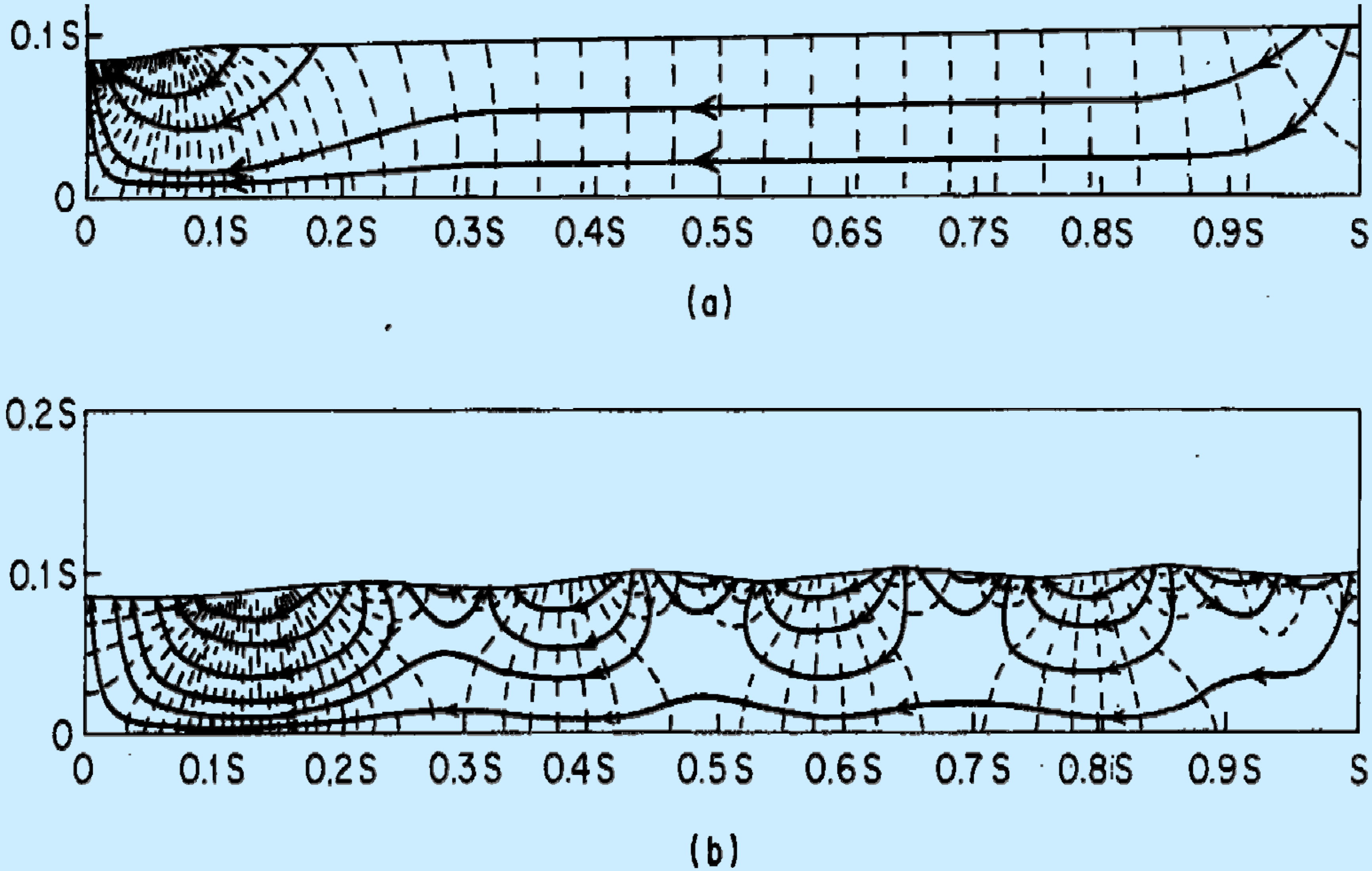

X'
Recharge area
Land surface
Stream
X
Water table
Unconfined aquifer
Confining bed

Watershed water balance

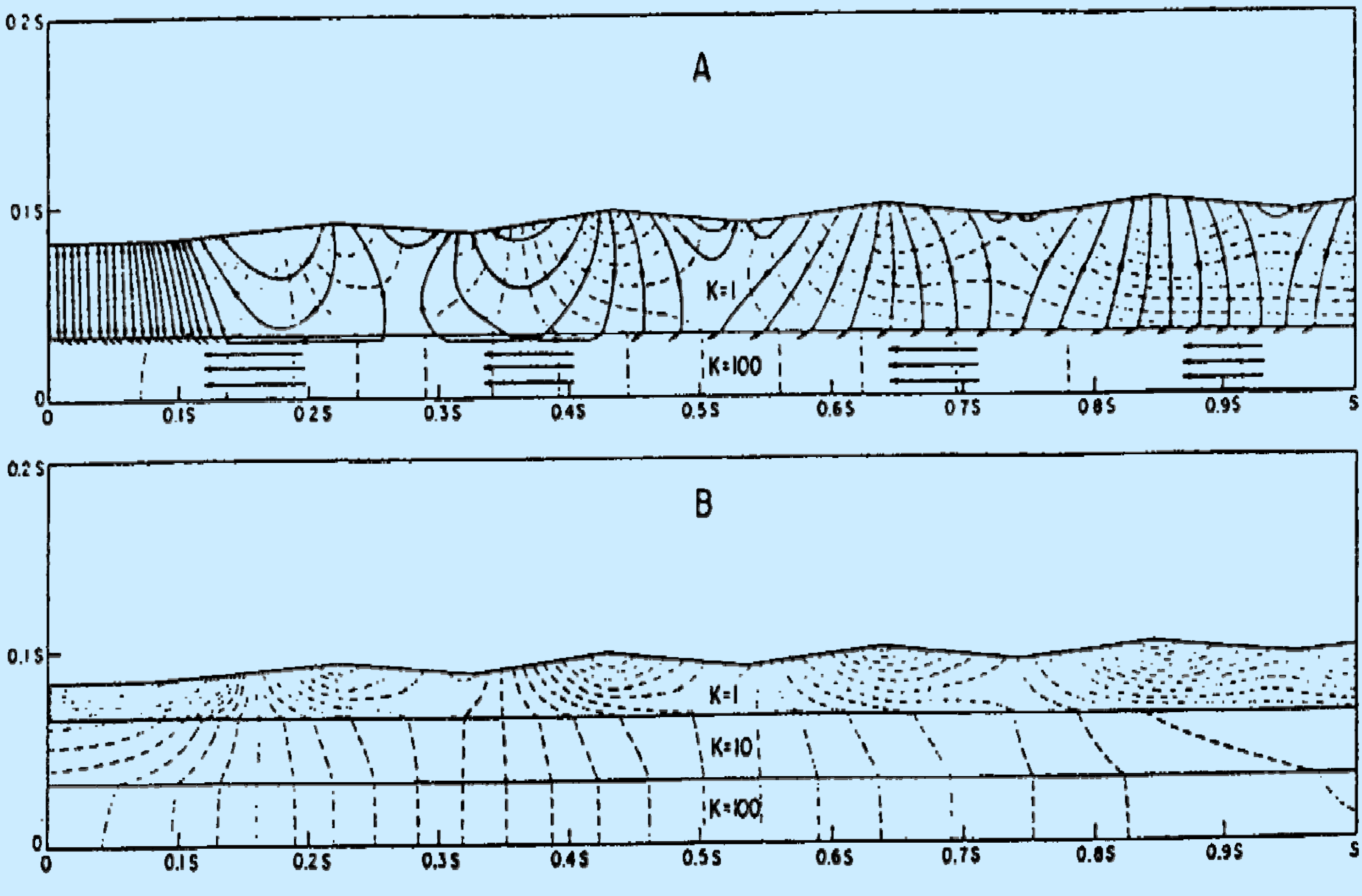
(after Freeze and Cherry, 1979)



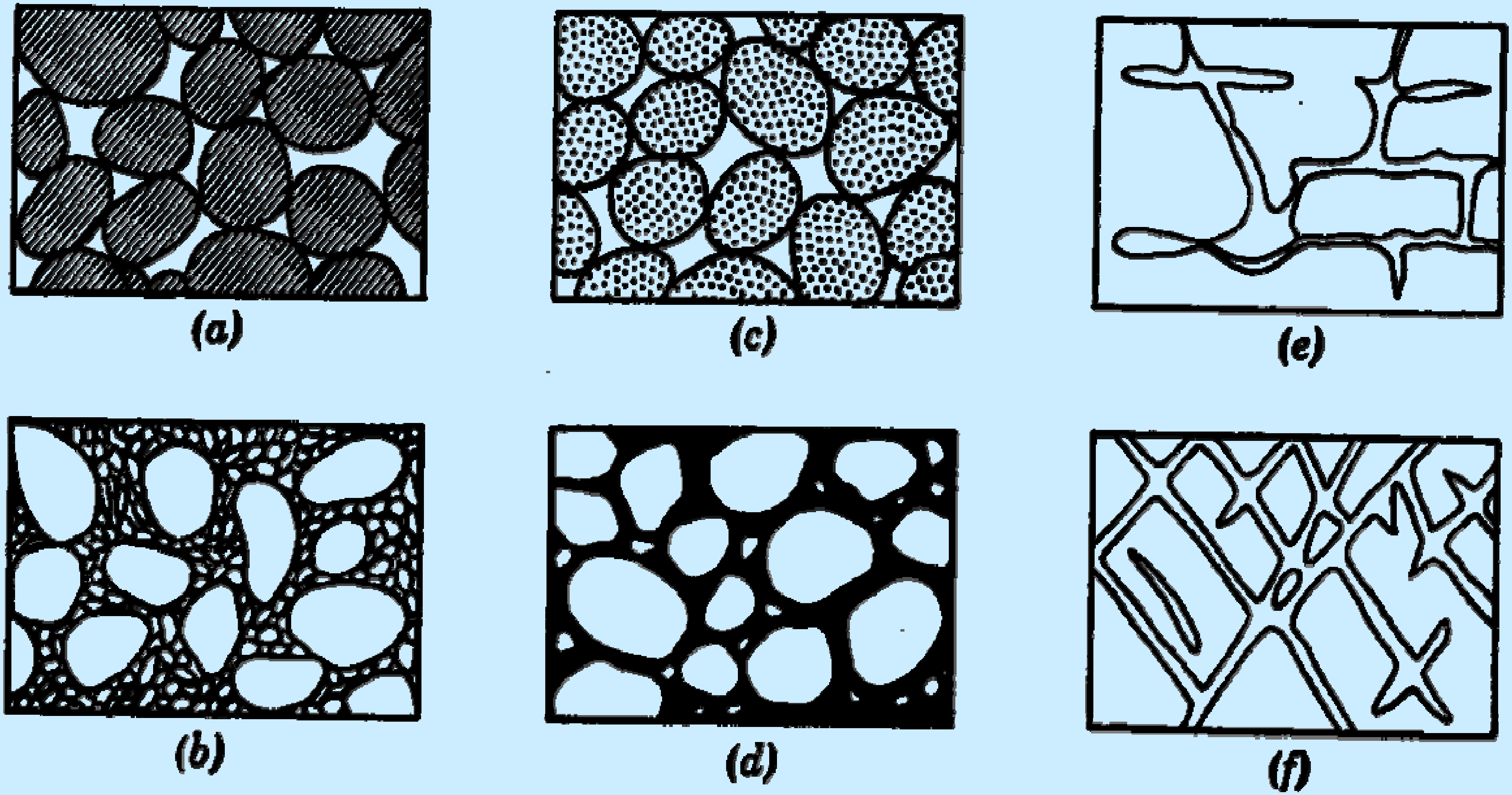
Elements of watershed water balance: P- precipitation, E- evapotranspiration, Q- runoff, Qs- the surface water component of average annual runoff, E_R- the average annual evapotranspiration from recharge area, E_D- the average annual evapotranspiration from discharge area, R- the average annual ground water recharge, D- the average annual ground water discharge; X--X'- cross-section shown in (b) - quantitative flow net and recharge-discharge profile in a two-dimensional section across the heterogeneous groundwater basin.



Drainage basins; Effect of topography on regional ground-water flow patterns (after Freeze and Witherspoon, 1967)

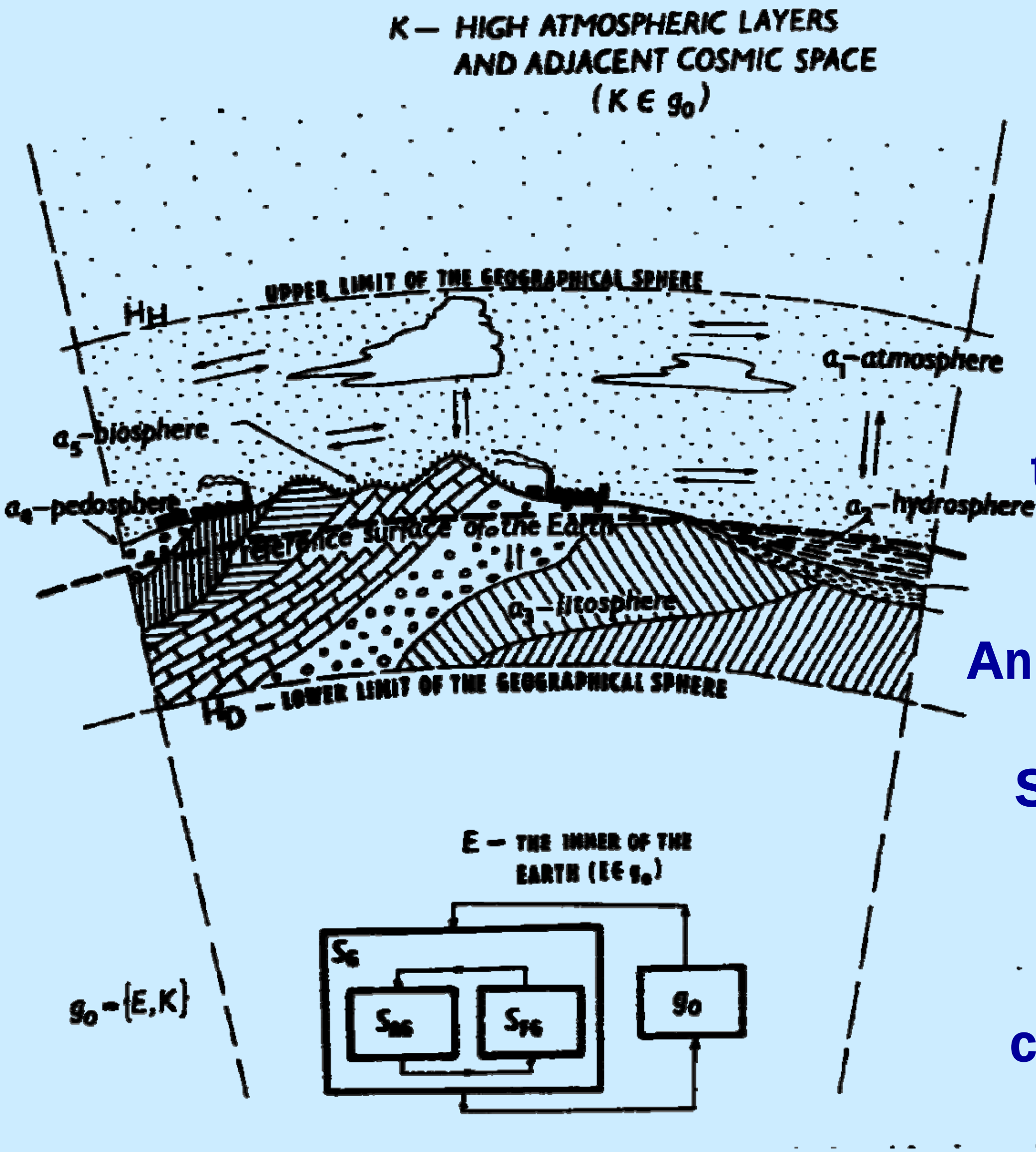


Drainage basins; Effect of geology on regional ground-water flow patterns (after Freeze and Witherspoon, 1967)



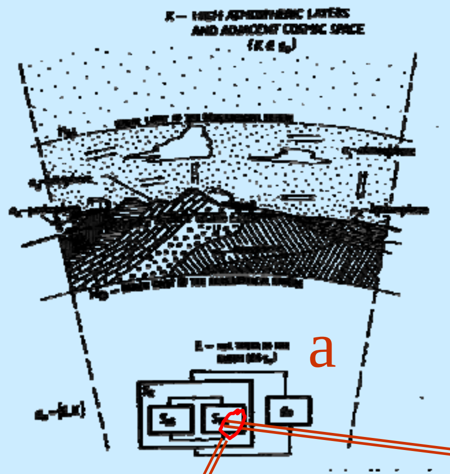
Porous media (after De Wiest, 1967)

The System Model of Geospheres

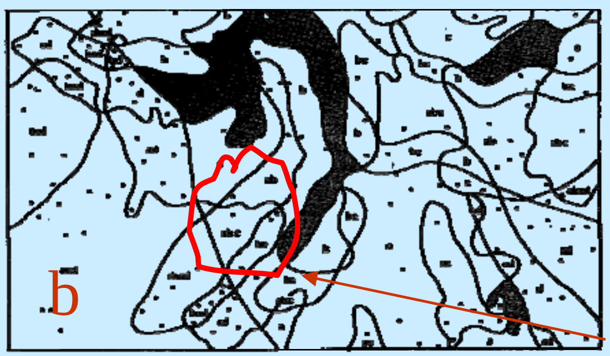


Vertical slice of the Geographical Sphere with two independent elements: System of Anthropological Geography (S_{AG}) and System of Physical Geography (S_{FG}). Arrows indicate vertical and horizontal components of matter, energy and information circulating (after Krcho, 1978)

System Model (a) for Watershed and Landscape, as Map of Conditions (b) and as Multilayer Map (c)

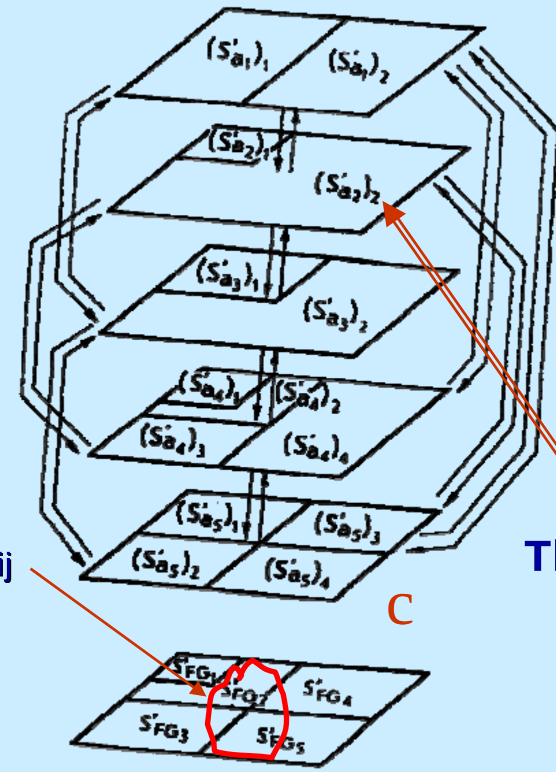


a



b

g_{ij}



c

System of Physical Geography Sphere (S_{FG}) with five independent elements:

a_1 - atmosphere,
a_2 - hydrosphere,
a_3 - lithosphere,
a_4 - pedosphere,
a_5 - biosphere.

Any watershed g_{ij} for a region may be considered as a part of the stream runoff system Sg_2.

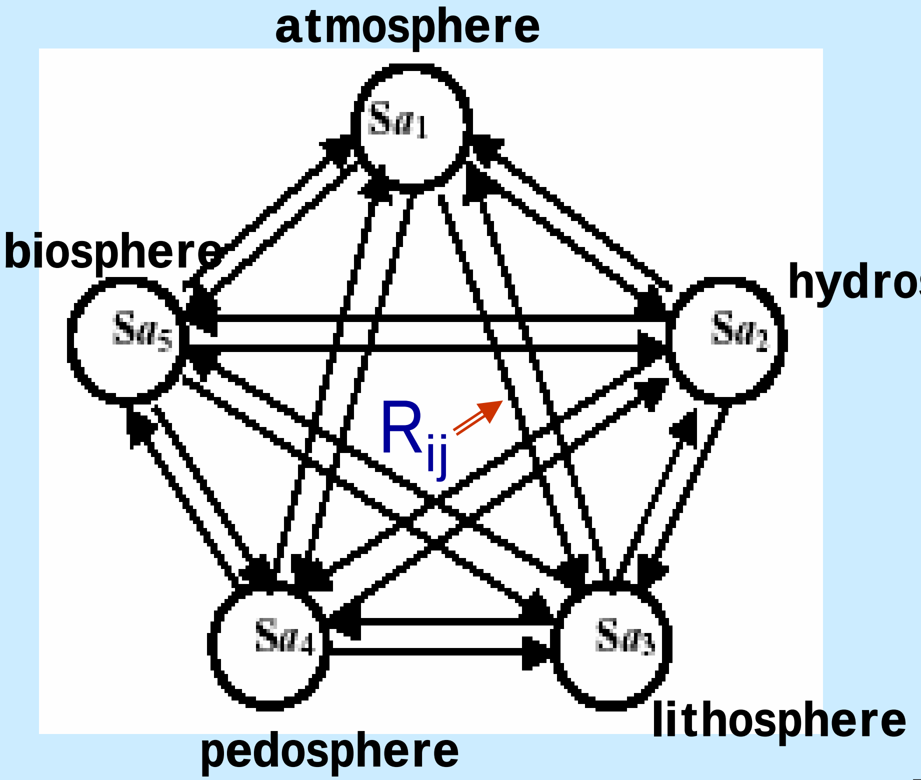
The Sg_2 - stream runoff system as a part of a_2 - hydrosphere may be presented as:

$$Sg_2 = \{ g_{ij}, R_{ij} \}$$

Each of these components may be characterized by a matrix of input [W], a matrix of output {Q}, and a matrix of states {H}.

$$[W]\{H\}=\{Q\}$$

Regime of stream runoff as multidimensional structure



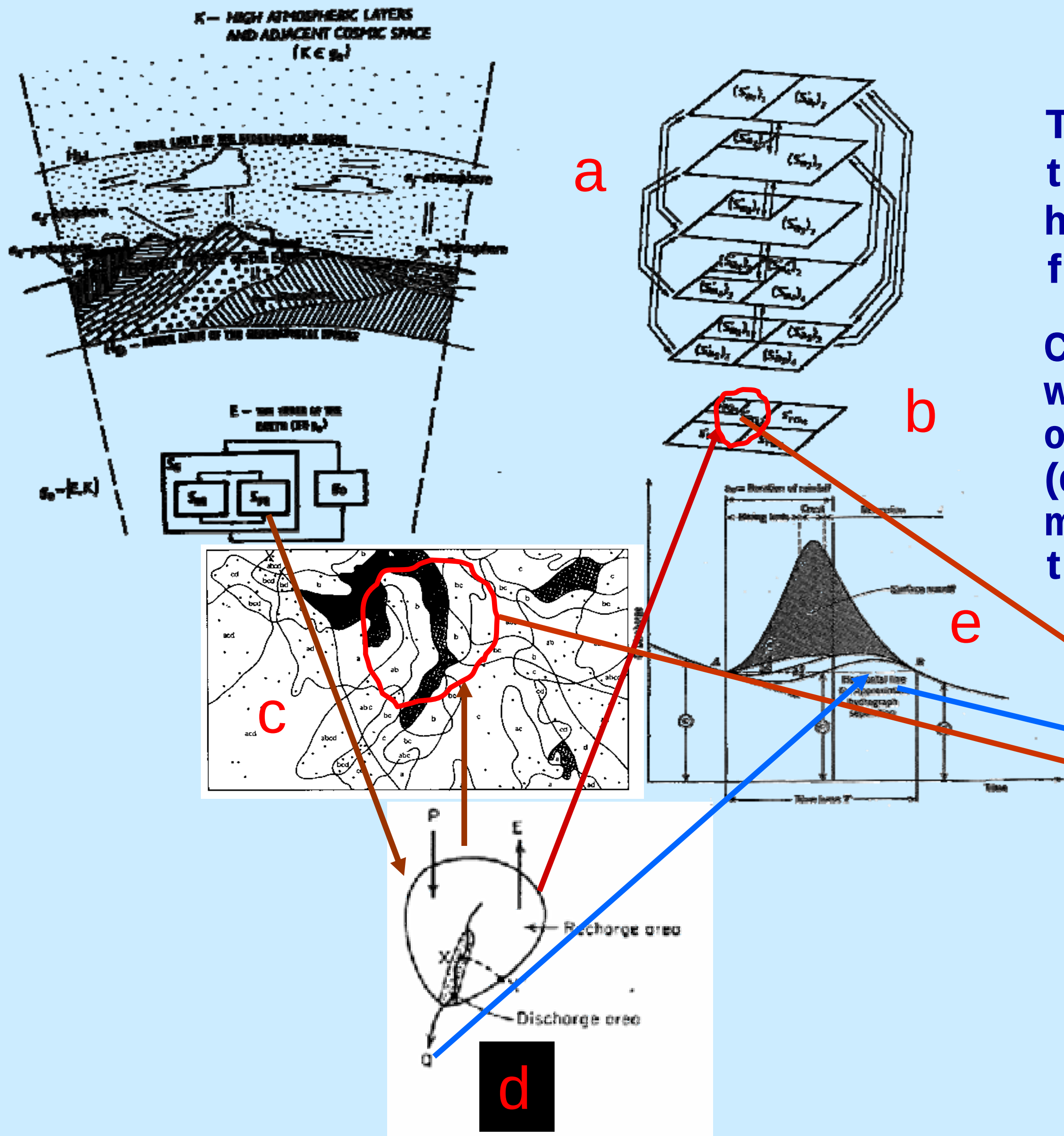
The number of characteristics for elements of a landscape and watershed is unlimited but for a fixed landscape a set of watersheds with data allows us to obtain a statistical description of the connections.

$\{R_{ij}\}$ is a matrix of relations between parts of a landscape. Entering the codes and numbers for initial matrix $\{X_{n*p}\}$ we open the way to recover (or discover) the connections that exist in the landscape

Example of characteristic combinations:

- Humid climate
- Hardwood (oak, maple, etc) forest
- Silt loam soil
- Drift
- Limestone
- Shale
- Sandstone
- …..

How the System Model works



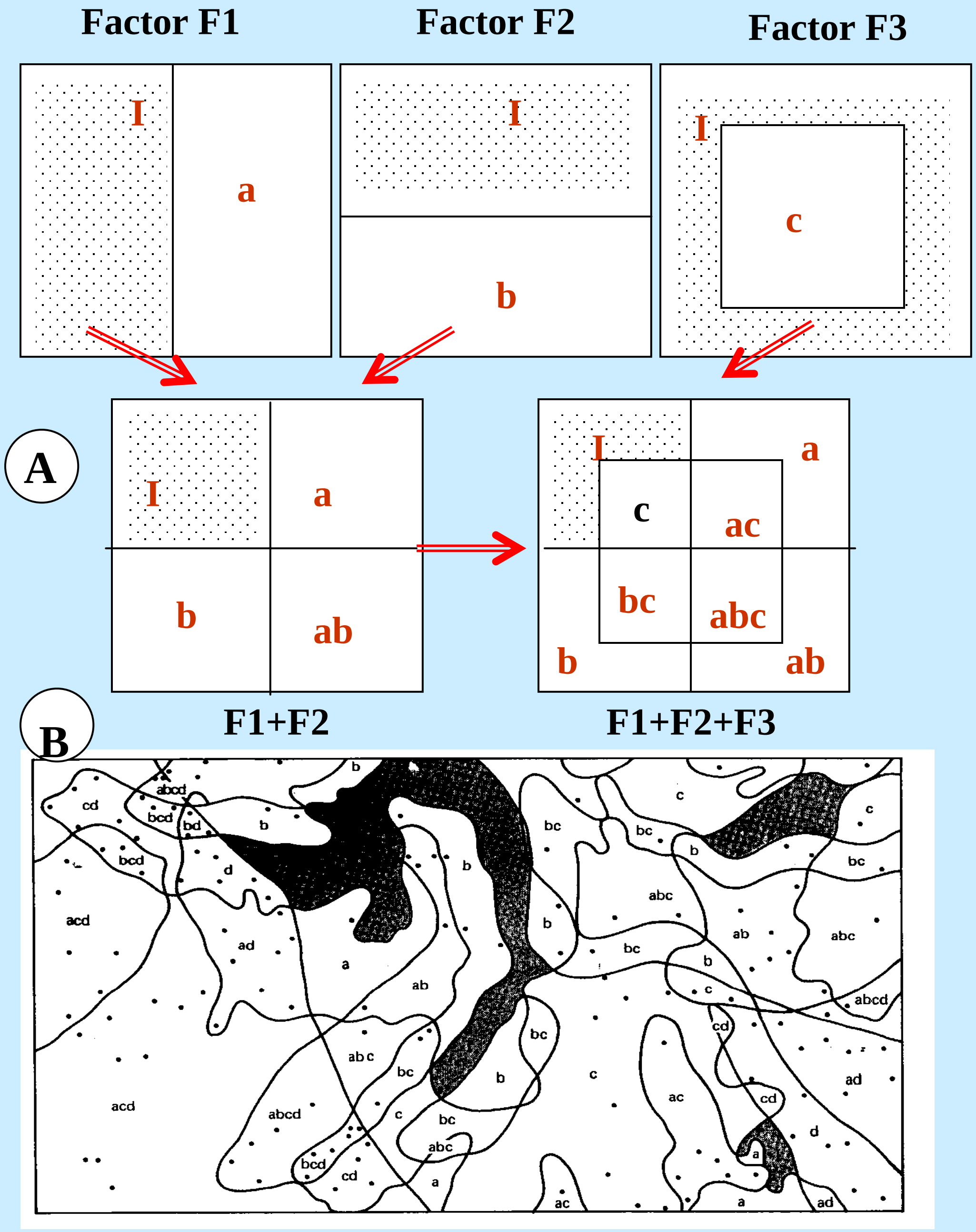
The research task is to discover the connections (R_{ij}) between the hydrosphere layer and the other four geosphere layers.

Coding the conditions for watershed (a, b & c) and obtaining runoff characteristics (d & e) lets us create the initial matrix (X_{n*j}) and then to apply the statistical analysis.

conditions

runoff

$$X_{(n*j)} = \left\{ \begin{array}{l} S_{m-1\,(i,j)},\ q_{m-1}\ \ldots \\ S_{m(2,1)},\ q_m\ \ldots \\ \ldots \\ S_{m(3,1)},\ q_m\ \ldots \\ S_{m(2,2)},\ q_m\ \ldots \\ S_{m\,(3,2)},\ q_m\ \ldots \\ S_{m+1(i,j)},\ q_{m+1}\ \ldots \end{array} \right\}$$



Characteristics for watershed

obtained from different landscape components may be presented as "condition-combination sampling".

A - Subdivision of a hypothetical region using combination of three conditions, *a, b,* and c, measured on a presence-absence scale. Areas where conditions are absent are denoted by I. Condition *b* and *c* are successively superimposed on *a.*

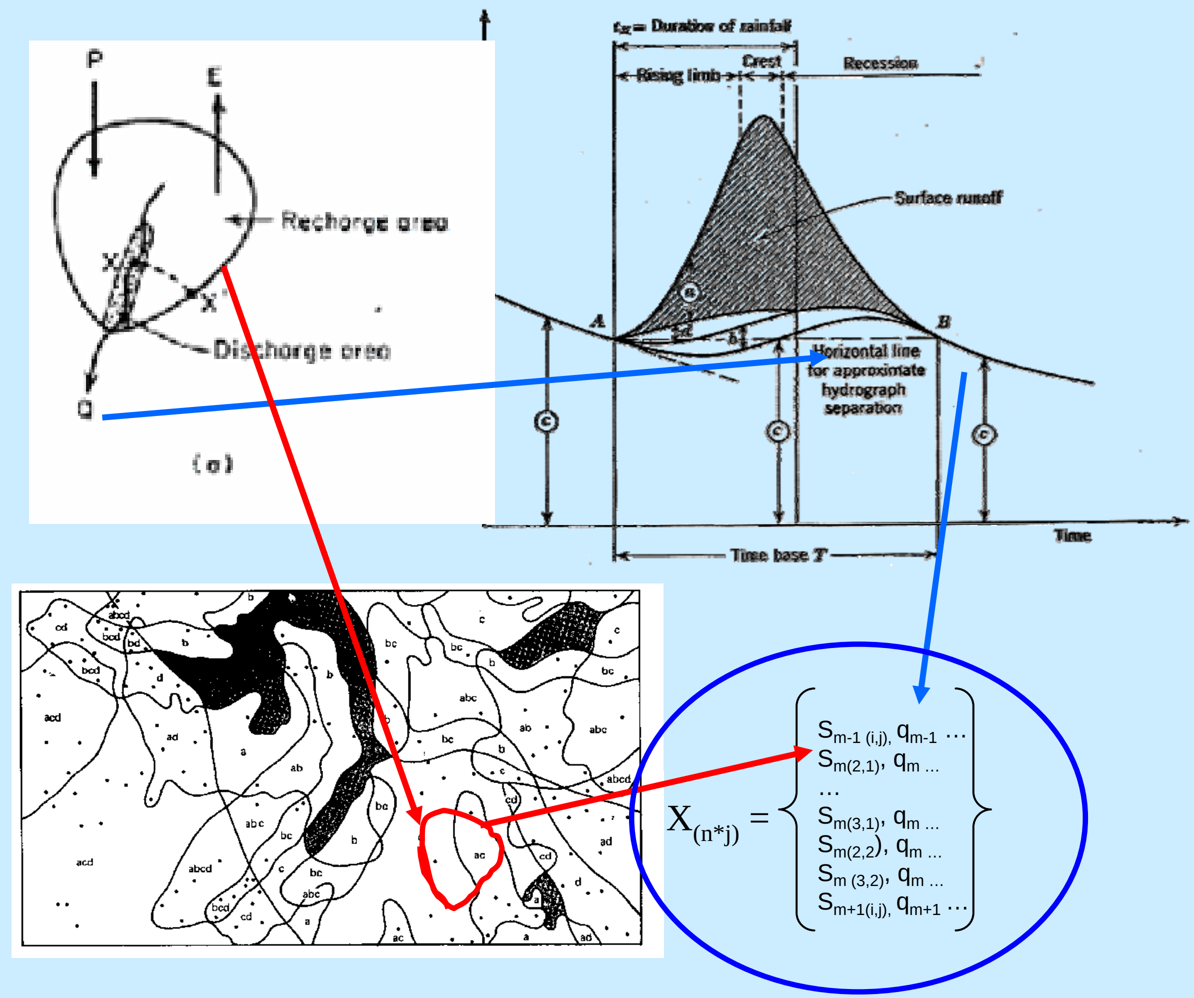
B – Example result: Location of sampling points within condition-combination regions in the Fortaleza Basin, Taubate county, Brazil (after Haggett, 1964).

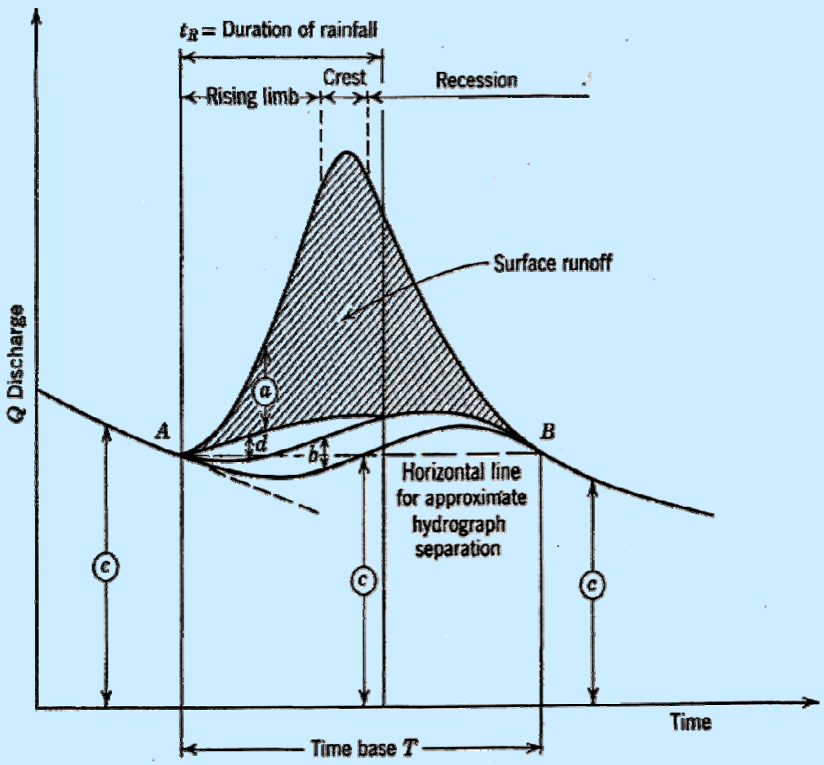
The initial matrix for a watershed

Our objective is to discover the link between the main components of the landscape to the components of the water balance.

To do this we create a matrix of values for the landscape components and the selected water balance components.

This matrix is then subjected to statistical analysis to find the link.





The specific hydrologic characteristics

used in analysis are:

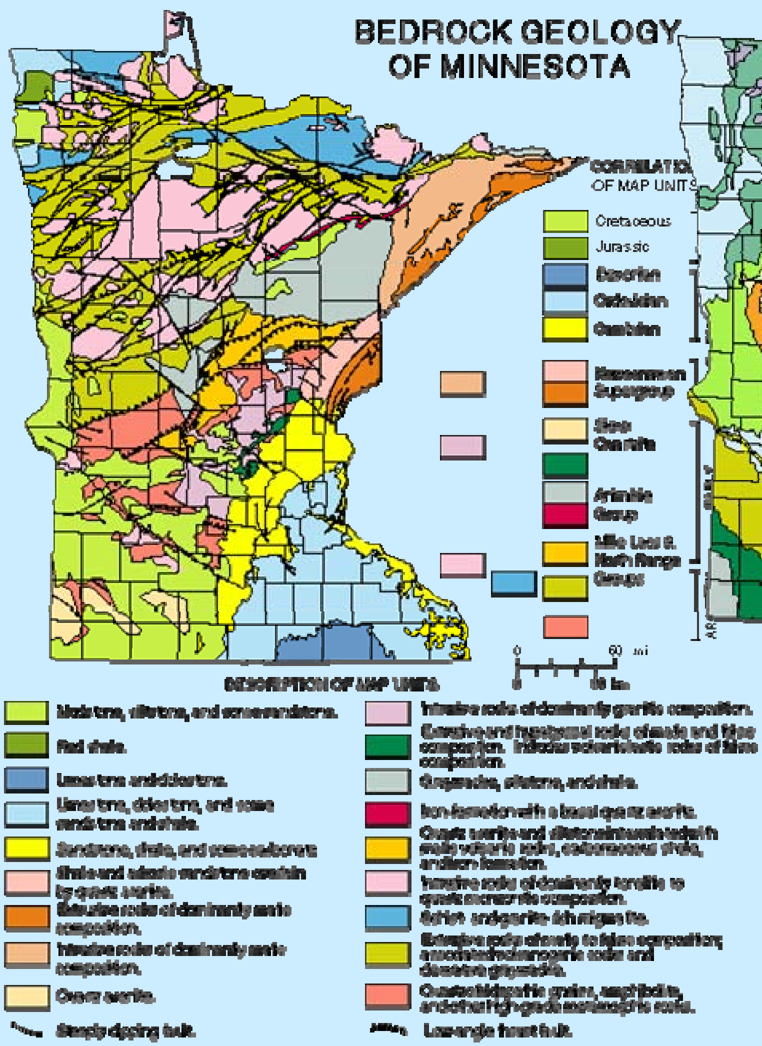
*** average annual stream runoff rate (modulus) [l/s/sq km or mm/year]**

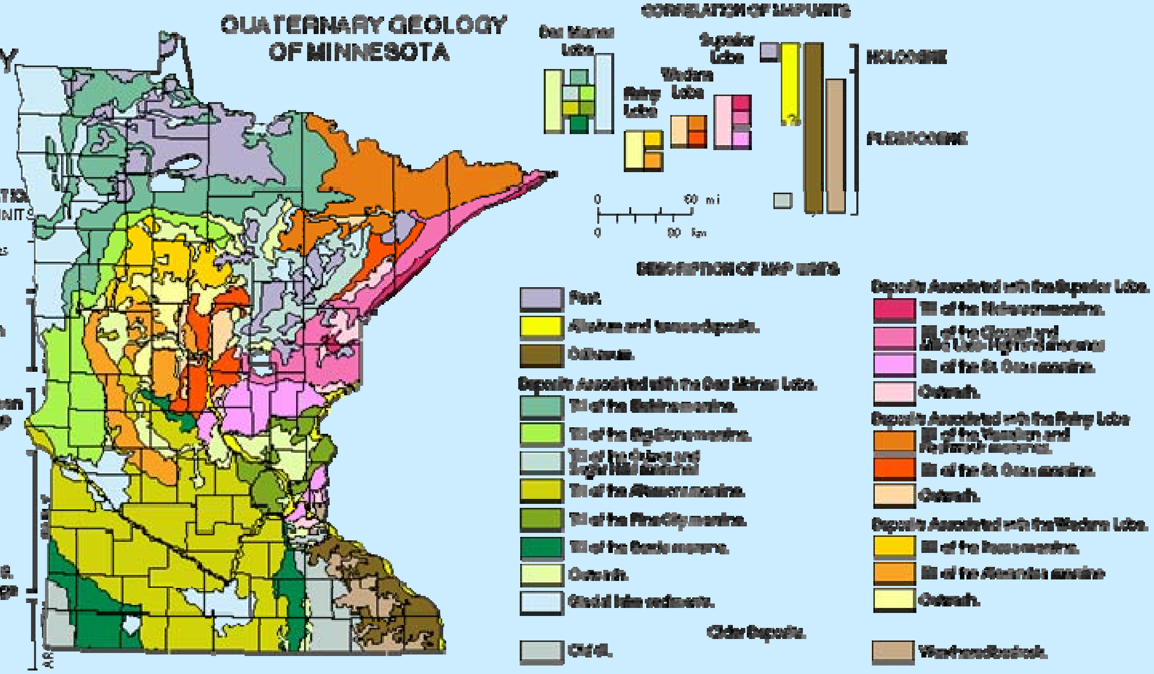
*** average rate (modulus) of minimal monthly stream runoff [l/s/sq km or mm/year]**

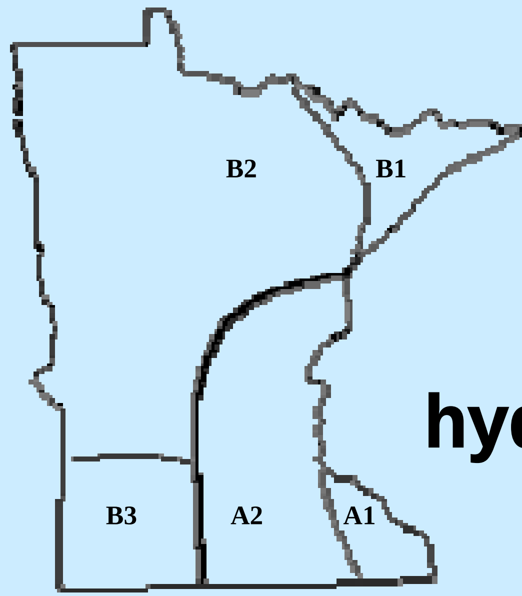
*** coefficient (ratio) of minimal ground-water contribution to stream runoff [% or as a parts of 1.0]**

Example application of ground water recharge on statewide basis in Minnesota streams

Examined data for 35 streams located throughout the state. The minimum flow in February was used as a surrogate for ground water recharge.



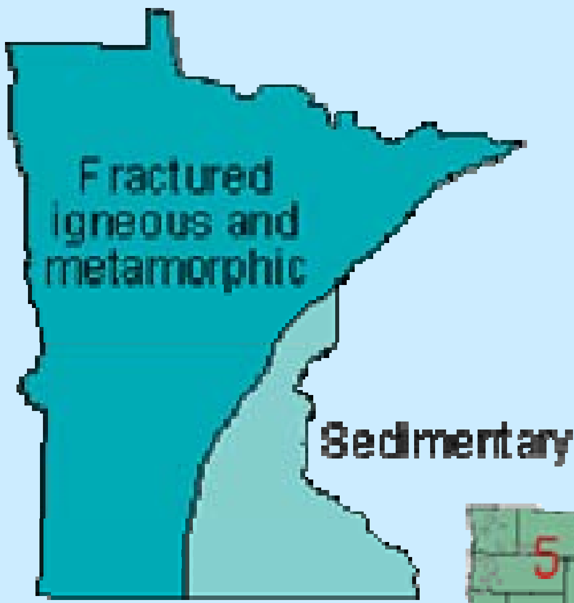




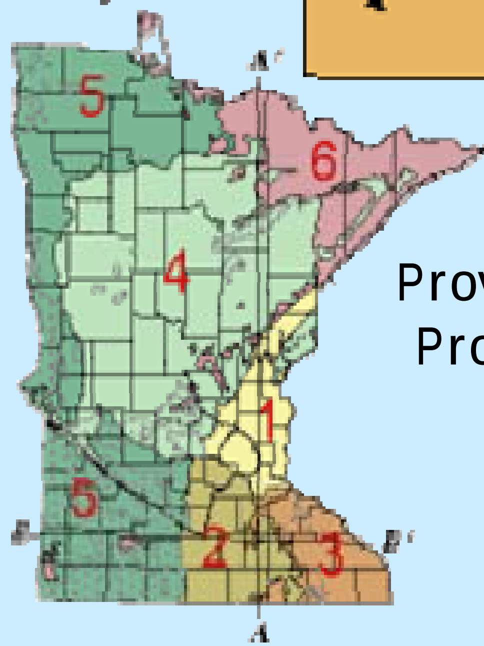
Geologic maps and hierarchical hydrogeological subdivision

Summary version of the previous maps

Bedrock features

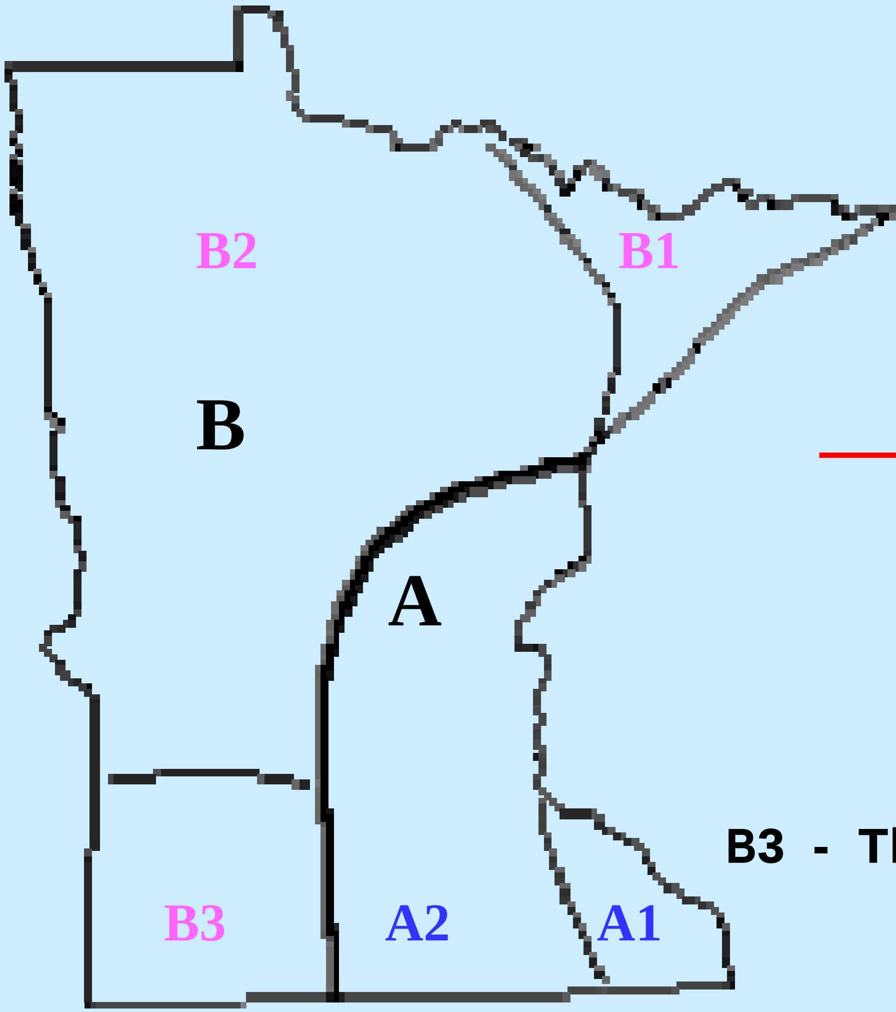


Quarternary geology features



Ground-Water Provinces in Minnesota (after MN DNR website)

Provinces 1: **Metro**
Provinces 2: **South-central**
Provinces 3: **Southeastern**
Provinces 4: **Central**
Provinces 5: **Western**
Provinces 6: **Arrowhead**

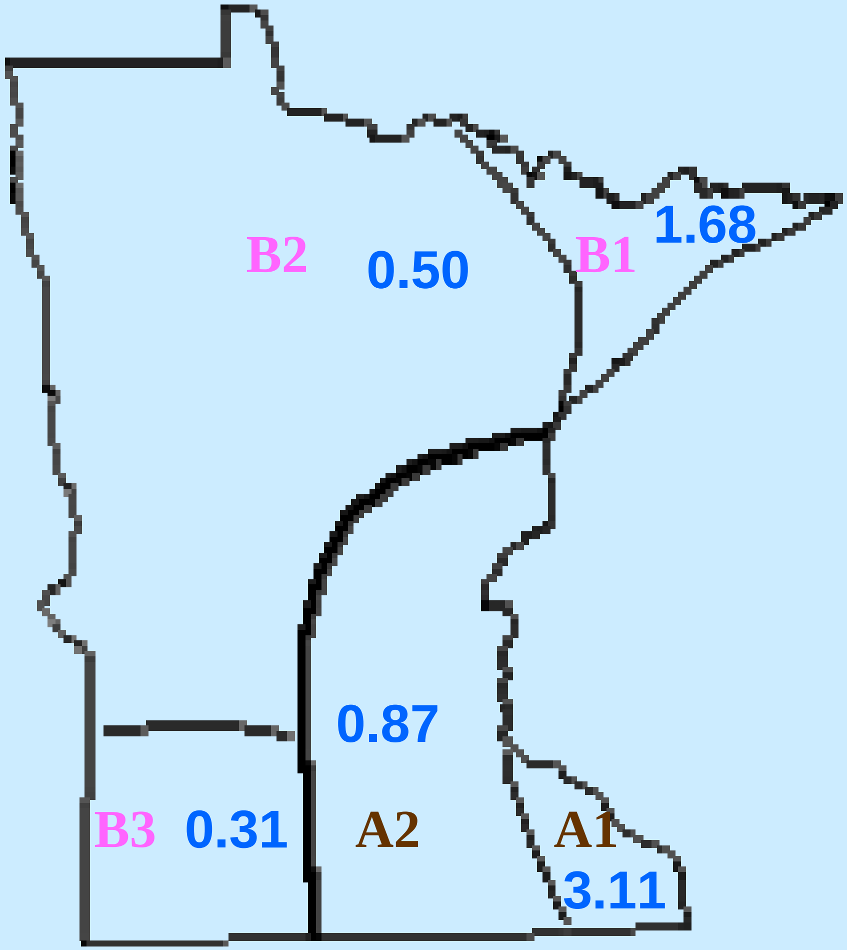


A - Paleozoic Artesian Basin
A1 - One ground-water flow field layer: Paleozoic artesian aquifers
A2 - Two ground-water flow field layers: Quaternary sediments and Paleozoic artesian aquifers

B - Precambrian Basement
B1 - One ground-water flow field layer: Precambrian Basement
B2 - Two ground-water flow field layers: Quaternary sediments and Precambrian Basement
B3 - Three ground-water flow field layers: Quaternary sediments, Cretaceous deposits and Precambrian Basement

Hierarchical hydrogeological subdivision in Minnesota based on overlaying previous two maps

Results of statewide analysis



Minimal monthly stream runoff in Minnesota

A= 2.09

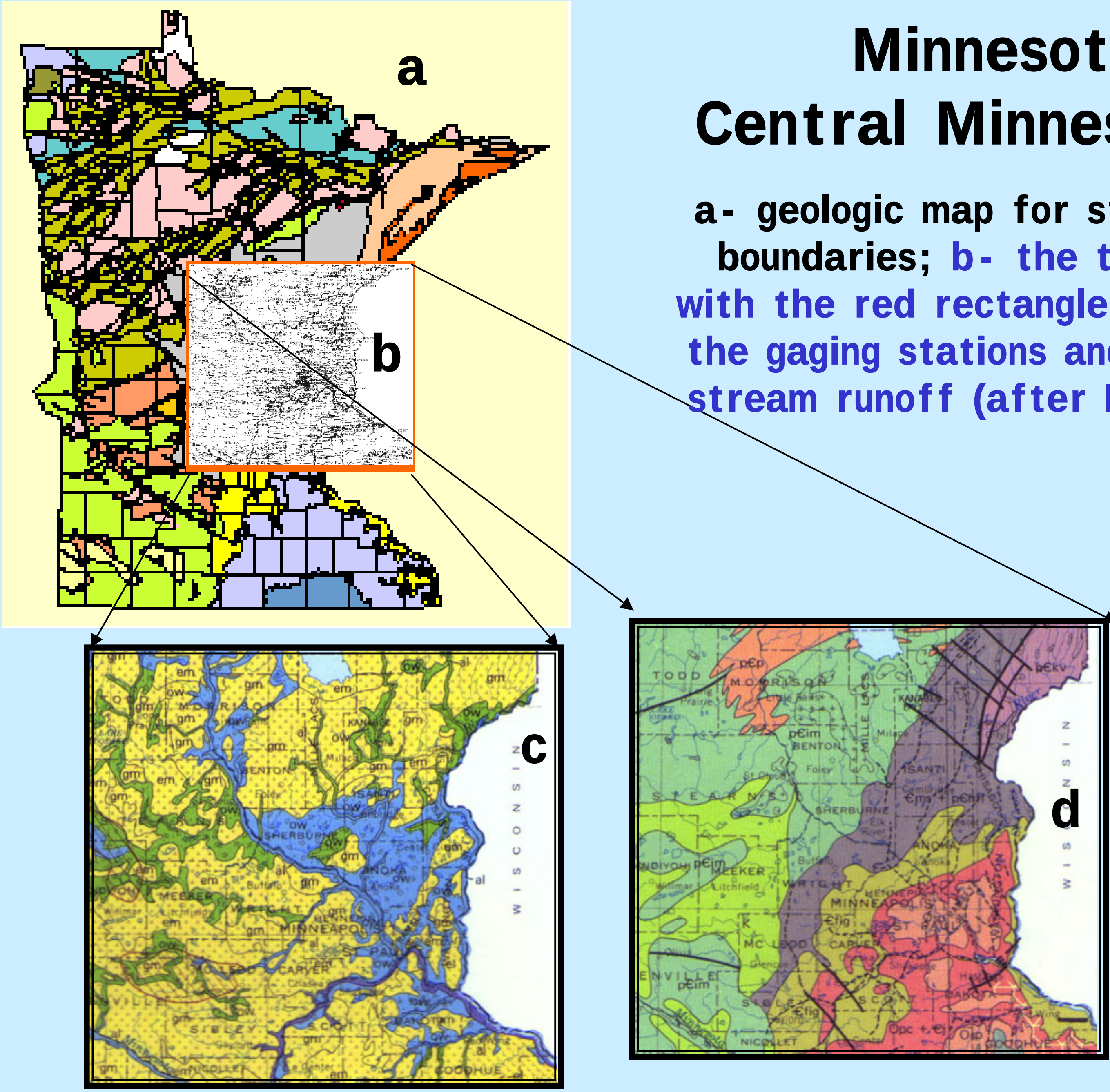
B= 0.83

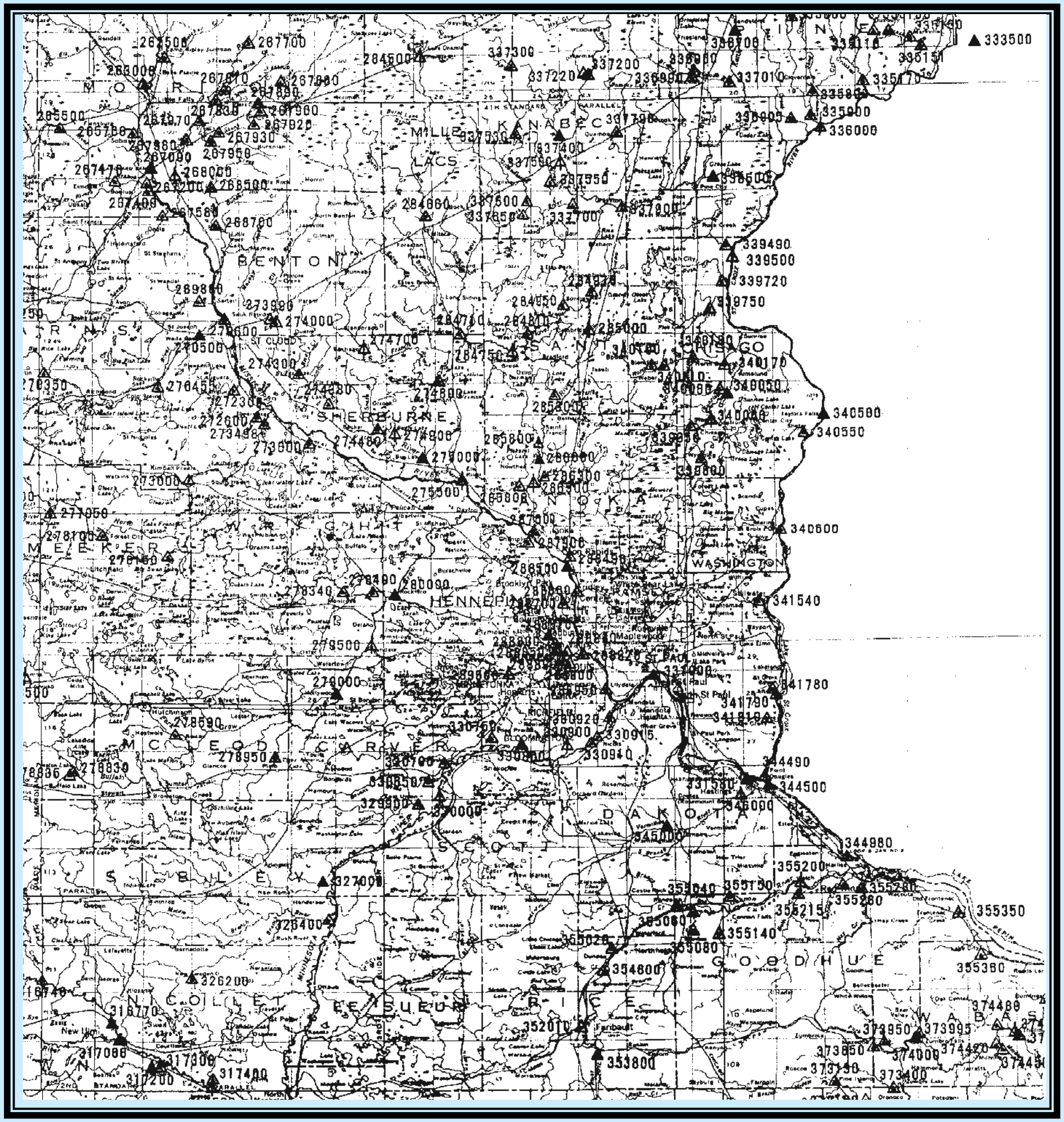
Values are February Stream Runoff in [l/s/sq km]

These figures are the estimated ground water recharge derived from the statistical analysis

Minnesota and East Central Minnesota (ECM)

a- geologic map for state with county boundaries; b- the territory of ECM with the red rectangle is the map with the gaging stations and records of low stream runoff (after Lindskov, 1977), c- Quaternary and d- bedrock maps (after Kanivetsky, 1978, 1979)

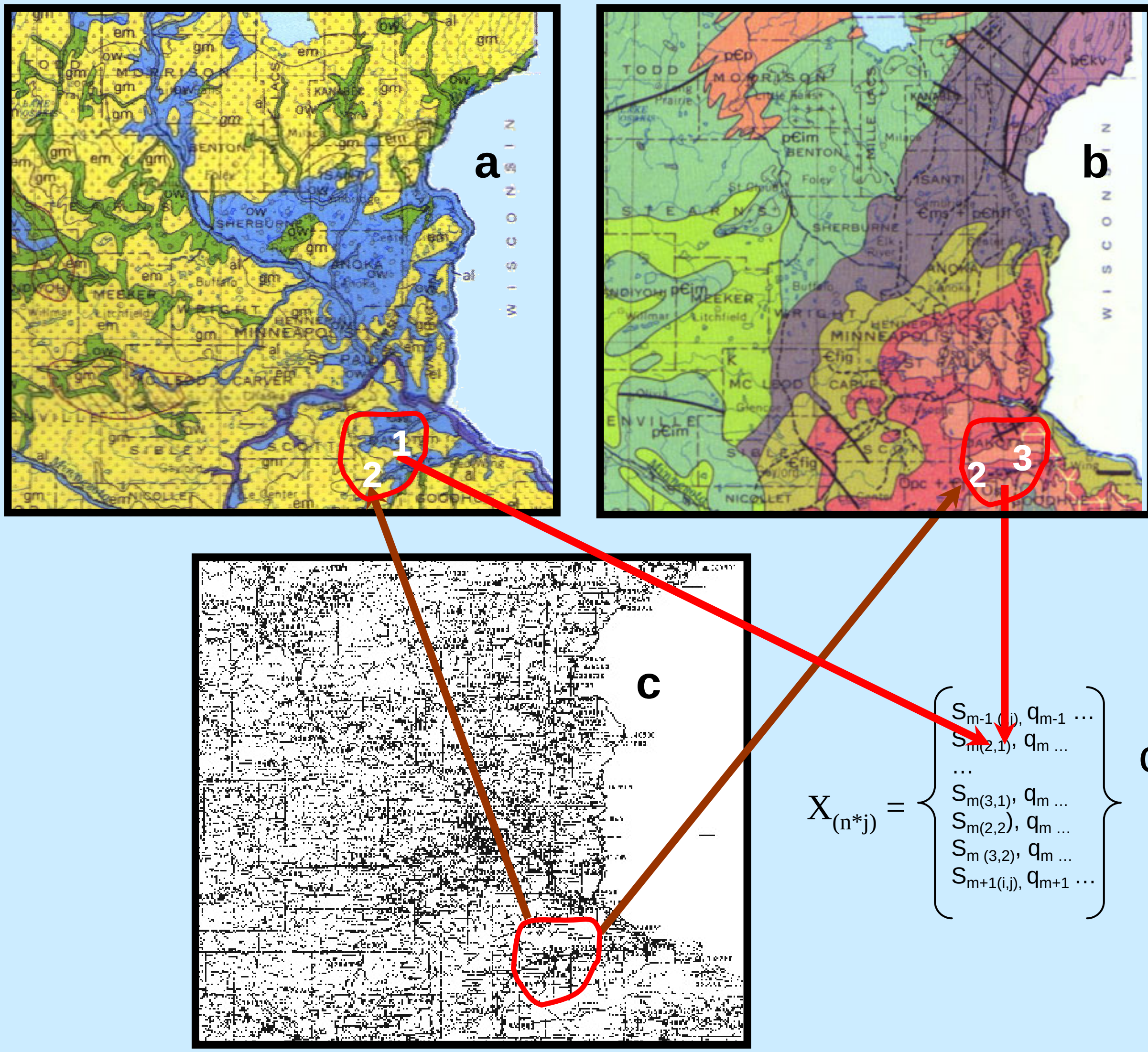




Location of (101) random gaging stations in ECM

(after Lindskov, 1977)

Procedure to acquire an initial matrix, $X_{(n*j)}$



$$X_{(n*j)} = \left\{ \begin{array}{l} S_{m-1\,(i,j)},\ q_{m-1} \cdots \\ S_{m(2,1)},\ q_m \ldots \\ \ldots \\ S_{m(3,1)},\ q_m \ldots \\ S_{m(2,2)}),\ q_m \ldots \\ S_{m\,(3,2)},\ q_m \ldots \\ S_{m+1(i,j)},\ q_{m+1} \cdots \end{array} \right\}$$

In the matrix: $S_{(m)}$ – watershed with specific landscape characteristic (m= 1, 2, 3… n+) and q_m minimal monthly discharge (m= 1, 2, 3… n); "n+"- means that we sometimes have to consider and code the same watershed with different landscape codes as $S_{m(2,1)}$, $S_{m(3,1)}$, and $S_{m(2,2)}$ but with the same discharge- q_m

Table of average modulus of
minimal ground-water discharge/recharge for ECM

Symbol and Hydrogeologic Region (Number of watersheds used)	**Recharge Mean (Ranges: Low & Upper Quartile) [l/s/sq. km]**	**Symbol and Hydrogeologic Subregion (Number of watersheds used)**	**Recharge Mean (Ranges: Low & Upper Quartile) [l/s/sq. km]**	**Symbol and Hydrogeologic District (Number of watersheds used)**	**Recharge Mean (Ranges: Low & Upper Quartile) [l/s/sq. km]**	**Symbol and Hydrogeolic Subdistrict (Number of watersheds used)**	**Recharge Mean (Ranges: Low & Upper Quartile) [l/s/sq. km]**
PB- Precambrian Basement (49)	0.59 (0.24-0.69)	**B/Q-** Two ground-water flow field layers: Quaternary sediments and Precambrian Basement (43)	0.63 (0.28-0.78)			**B/Q1**- overlain by sand and gravel (18)	0.90 (0.45-1.22)
						B/Q2- overlain by clayey till(15)	0.31 (0.11-0.51)
						B/Q3- overlain by sandy till (11)	0.59 (0.33-0.82)
		B/K/Q- Three ground-water flow field layers: Quaternary sediments, Cretaceous confining unit and Precambrian Basement (5)	0.26 (0.1-0.5)			**B/K/Q2-** overlain by clayey till (4)	0.20 (0.06-0.34)
PAB- Paleozoic Artesian Basin (88)	1.67 (0.52-2.37)	**A**- One ground-water flow field layer: Paleozoic artesian aquifers (exposed or shallow bedrock) (27)	3.11 (2.06-4.23	**A2**- Franconia- Ironton- Galesville aquiter (mixed shale, sandstone, some shaly carbonates)		**A2/Q-** Overlain by sediments in valley of Mississippi River (7)	2.90 (0.78-4.72)
				A3&4- Prairie du Chien Jordan aquifer (sandstone, limestone) (16)	3.56 (2.51-4.48)		
				A5- St. Peter aquifer (sandstone) (4)	1.71 (1.41-2.01)		
		A/Q- Two ground-water flow field layers: Quaternary sediments and Paleozoic artesian aquifers (58)	1.06 (0.41-1.24)	**A1/Q-** Quaternary sediments and Mt. Simon-Hinckley- Fond du Lac aquifer (sandstone) (23)	1.01 (0.51-1.10)	**A1/Q1-** overlain by sand and gravel (10)	1.43 (0.51-2.12)
						A1/Q2- overlain by clayey till (7)	0.70 (0.51-0.96)
						A1/Q3- overlain by sandy till (8)	0.75 (0.54-0.96)
				A2/Q- Quaternary sediments and Franconia- Ironton- Galesville aquiter (mixed shale, sandstone, some shaly carbonates) (3*)	0.58 (-)*	**A2/Q1**- overlain by sand and gravel (1)*	1.24 (-)*
						A2/Q2- overlain by clayey till (2)* */- not sufficient set for statistical analysis	0.26 (-)*
				A3&4/Q- Quaternary sediments and Prairie du Chien Jordan aquifer (sandstone, limestone) (12)	0.98 (0.34-1.18)	**A3&4/Q1**- overlain by sand and gravel (4)	1.56 (0.36-2.76)
						A3&4/Q2- overlain by clayey till (8)	0.70 (0.29-1.07)
				A5/Q- Quaternary sediments and St. Peter aquifer (sandstone) (20)	1.23 (0.54-1.81)	**A5/Q1**- overlain by sand and gravel (5)	1.74 (1.44-2.16)
						A5/Q2- overlain by clayey till (15)	1.06 (0.38-1.44)

Decreasing scale

Table of average modules of minimal ground-water discharge-recharge for 22 HHS units for ECM to choose the interval for a color legend on the map

Modules [l/s/km2]	Modules [in/year]	Difference [in/year]	**Boundaries for legend [in/year]**
			<0.1
0.2	**0.25**		**0.1-0.5**
0.26	**0.32**	0.07	
0.31	**0.38**	0.06	
0.58	**0.72**	0.34	**0.5-1.5**
0.59	**0.73**	0.01	
0.63	**0.78**	0.05	
0.7	**0.87**	0.09	
0.75	**0.93**	0.06	
0.9	**1.12**	0.19	
0.98	**1.22**	0.1	
1.01	**1.25**	0.03	
1.06	**1.31**	0.06	
1.23	**1.53**	0.22	**1.5-2.5**
1.24	**1.54**	0.01	
1.43	**1.77**	0.23	
1.56	**1.93**	0.16	
1.67	**2.07**	0.14	
1.71	**2.12**	0.05	
1.74	**2.16**	0.04	
			> 2.5

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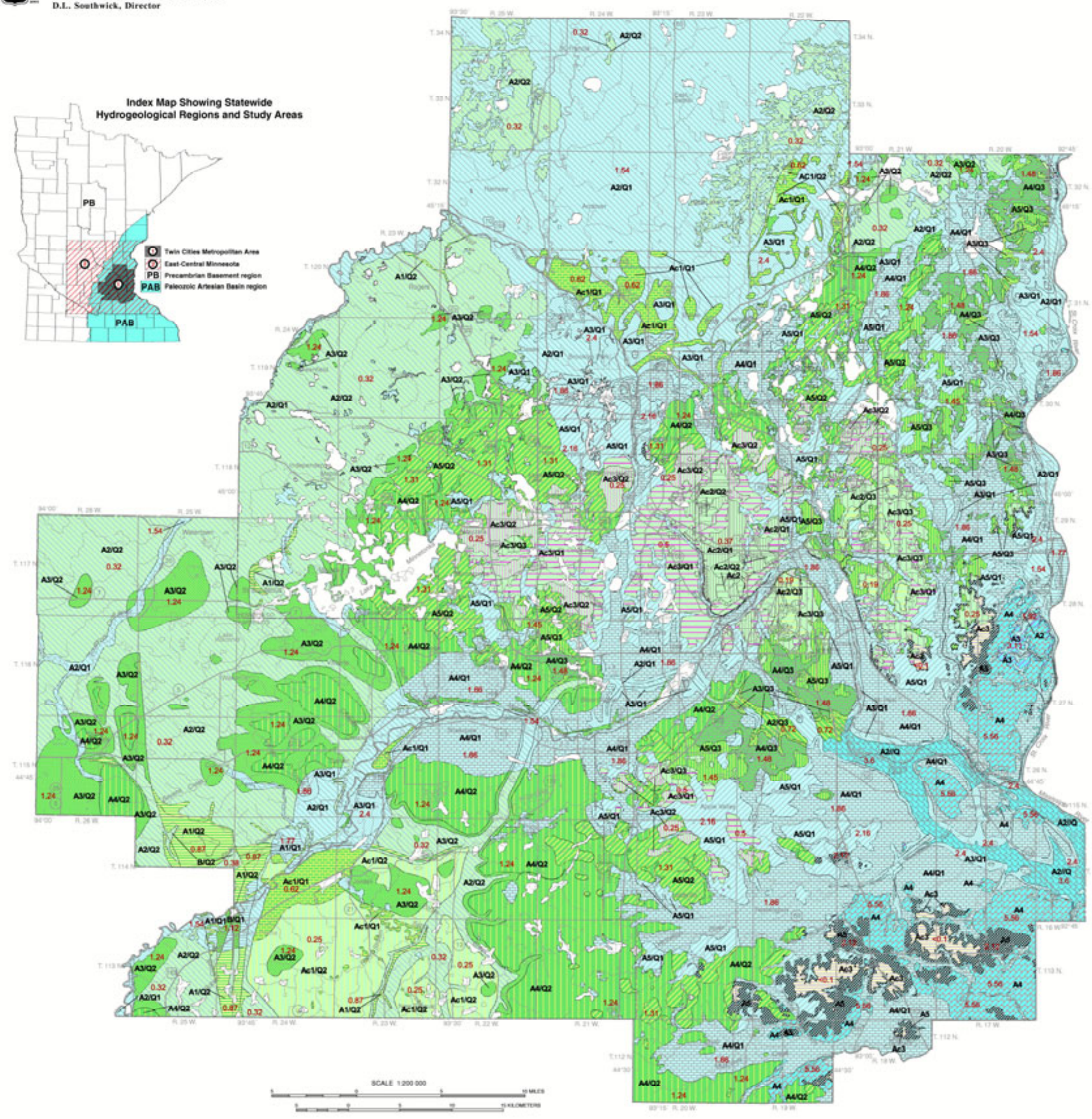


Minimal Annual Ground-Water Recharge Based on February Monthly Discharge Mean Measurements Period 1935-1981

Symbol and Hydrogeologic Region and Subregion		Symbol and Hydrogeologic District (Number of watersheds used)	District Recharge Mean (Only units with color appear on map) (*Low & Upper Quartile) [inches per year]	Symbol and Hydrogeologic Subdistrict (Number of watersheds used)	Subdistrict Recharge Mean (*Lower & Upper Quartile) [inches per year]
PB- Precambrian Basement	B/Q- Two ground-water flow field layers	B/Q- Two ground-water flow field layers: Quaternary sediments and Precambrian Basement (intrusive and extrusive rocks)		B/Q1- overlain by sand and gravel (18)	1.12 (0.56-1.51)
				B/Q2- overlain by clayey till (15)	0.38 (0.14-0.63)
PAB- Paleozoic Artesian Basin	A- One ground-water flow field layer: Paleozoic artesian aquifers (exposed or shallow bedrock)	A2- Franconia- Ironton- Galesville aquifer (mixed shale, sandstone, some shaly carbonates)	1.92	A2/Q- overlain by sediments in valley of Mississippi River (7)	3.60 (0.97-5.85)
		A3- Jordan aquifer (sandstone)	3.11		
		A4- Prairie du Chien aquifer (limestone)	5.56		
		Ac2- Decorah confining unit (most tight and homogeneous shale)	<0.1		
		Ac3- Platteville Glenwood confining unit (dolomitic limestone and shale)	<0.1		
		A5- St. Peter aquifer (sandstone) (4)	2.12 (1.75-2.42)		
	A/Q- Two ground-water flow field layers: Quaternary sediments and Paleozoic artesian aquifers	A1/Q- Quaternary sediments and Mt. Simon- Hinckley- Fond du Lac aquifer (sandstone) (23)	1.25 (0.63-1.36)	A1/Q1- overlain by sand and gravel (10)	1.77 (0.63-2.64)
				A1/Q2- overlain by clayey till (7)	0.87 (0.63-1.19)
		Ac1/Q- St. Lawrence confining unit (shale with some limestone)		Ac1/Q1- overlain by sand and gravel	0.62
				Ac1/Q2- overlain by clayey till	0.25
		A2/Q- Quaternary sediments and Franconia- Ironton- Galesville aquifer (mixed shale, sandstone, some shaly carbonates) (3)	0.72†	A2/Q1- overlain by sand and gravel (1)	1.54†
				A2/Q2- overlain by clayey till (2)	0.32†
				A2/Q3- overlain by sandy till	0.72
		A3/Q- Quaternary sediments and Jordan aquifer (sandstone)		A3/Q1- overlain by sand and gravel	2.4
				A3/Q2- overlain by clayey till	1.24
				A3/Q3- overlain by sandy till	1.48
		A4/Q- Quaternary sediments and Prairie du Chien aquifer (limestone)		A4/Q1- overlain by sand and gravel	1.86
				A4/Q2- overlain by clayey till	1.24
				A4/Q3- overlain by sandy till	1.48
		Ac2/Q- Decorah confining unit (most tight and homogeneous shale)		Ac2/Q1- overlain by sand and gravel	0.37
				Ac2/Q2- overlain by clayey till	0.12
				Ac2/Q3- overlain by sandy till	0.19
		Ac3/Q- Platteville Glenwood confining unit (dolomitic limestone)		Ac3/Q1- overlain by sand and gravel	0.5
				Ac3/Q2- overlain by clayey till	0.25
				Ac3/Q3- Overlain by sandy till	0.25
		A5/Q- Quaternary sediments and St. Peter aquifer (sandstone) (20)	1.53 (0.67-2.24)	A5/Q1- overlain by sand and gravel (5)	2.16 (1.79-2.68)
				A5/Q2- overlain by clayey till (15)	1.31 (0.47-1.79)
				A5/Q3- overlain by sandy till	1.45

* Ranges are shown where data were available

† Insufficient set for statistical analysis

Minimal Annual Ground-Water Recharge Ranges (inches per year)

- > 2.5 — >2.5 in/yr
- 1.5 - 2.5 — 1.5 - 2.5 in/yr
- 0.5 - 1.5 — 0.5 - 1.5 in/yr
- 0.1 - 0.5 — 0.1 - 0.5 in/yr
- < 0.1 — <0.1 in/yr

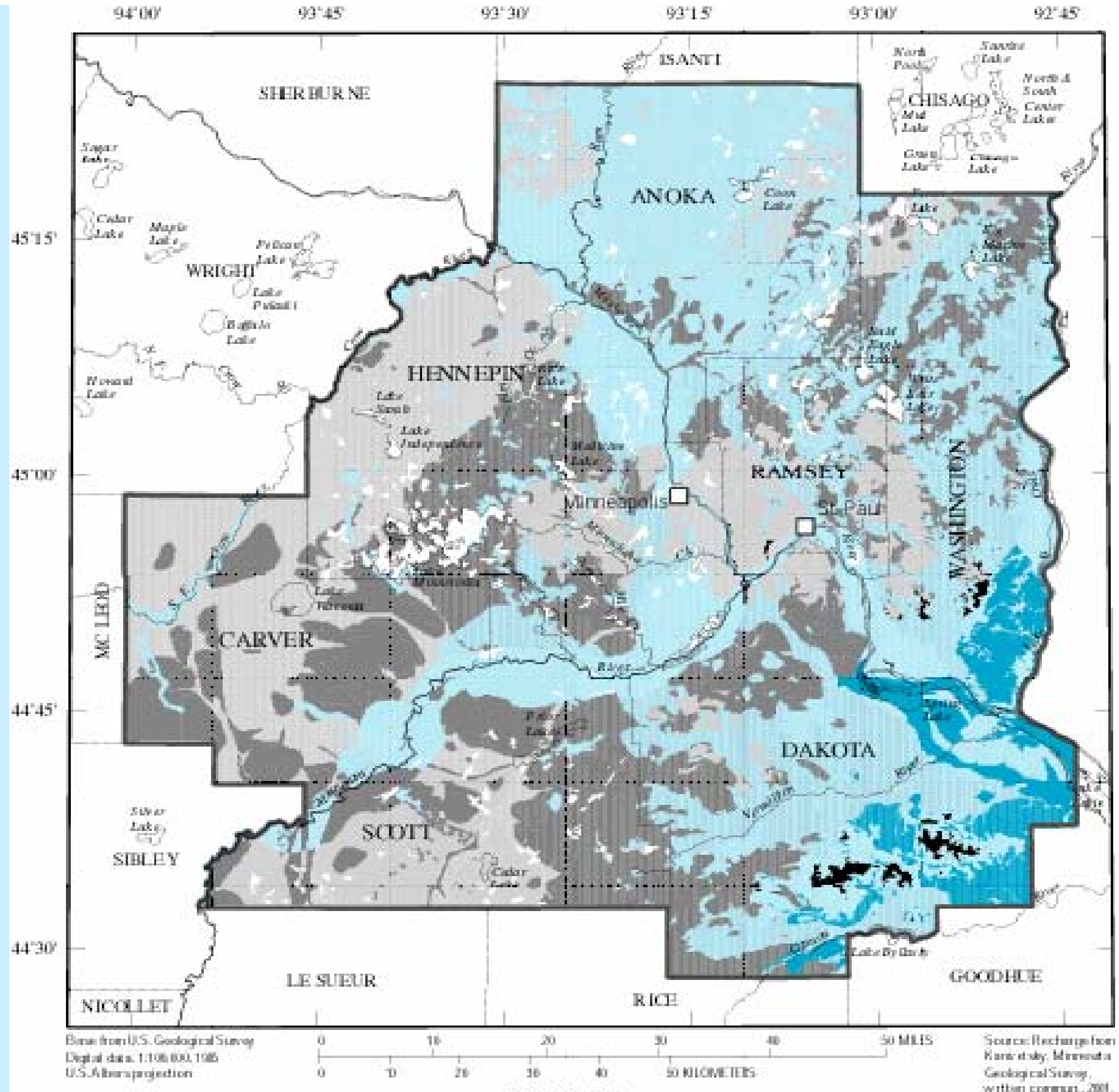
Minimal Annual Ground-Water Recharge in the Twin Cities Seven-County Metropolitan Area

Roman Kanivetsky and Boris Shmagin
2001

Modules		Difference	Boundaries for legend
[l/s/km2]	[in/year]	[in/year]	[in/year]
			<0.1
0.2	**0.25**		**0.1-0.5**
0.26	**0.32**	0.07	
0.31	**0.38**	0.06	
0.58	**0.72**	0.34	**0.5-1.5**
0.59	**0.73**	0.01	
0.63	**0.78**	0.05	
0.7	**0.87**	0.09	
0.75	**0.93**	0.06	
0.9	**1.12**	0.19	
0.98	**1.22**	0.1	
1.01	**1.25**	0.03	
1.06	**1.31**	0.06	
1.23	**1.53**	0.22	**1.5-2.5**
1.24	**1.54**	0.01	
1.43	**1.77**	0.23	
1.56	**1.93**	0.16	
1.67	**2.07**	0.14	
1.71	**2.12**	0.05	
1.74	**2.16**	0.04	
			> 2.5

Table of average modules of minimal ground-water discharge-recharge for 22 HHS units for ECM to choose the interval for a color legend on the map

Minimal ground-water recharge in TCMA (after Ruhl, Kanivetsky, and Shmagin, 2002. WRIR 02-4092 USGS)



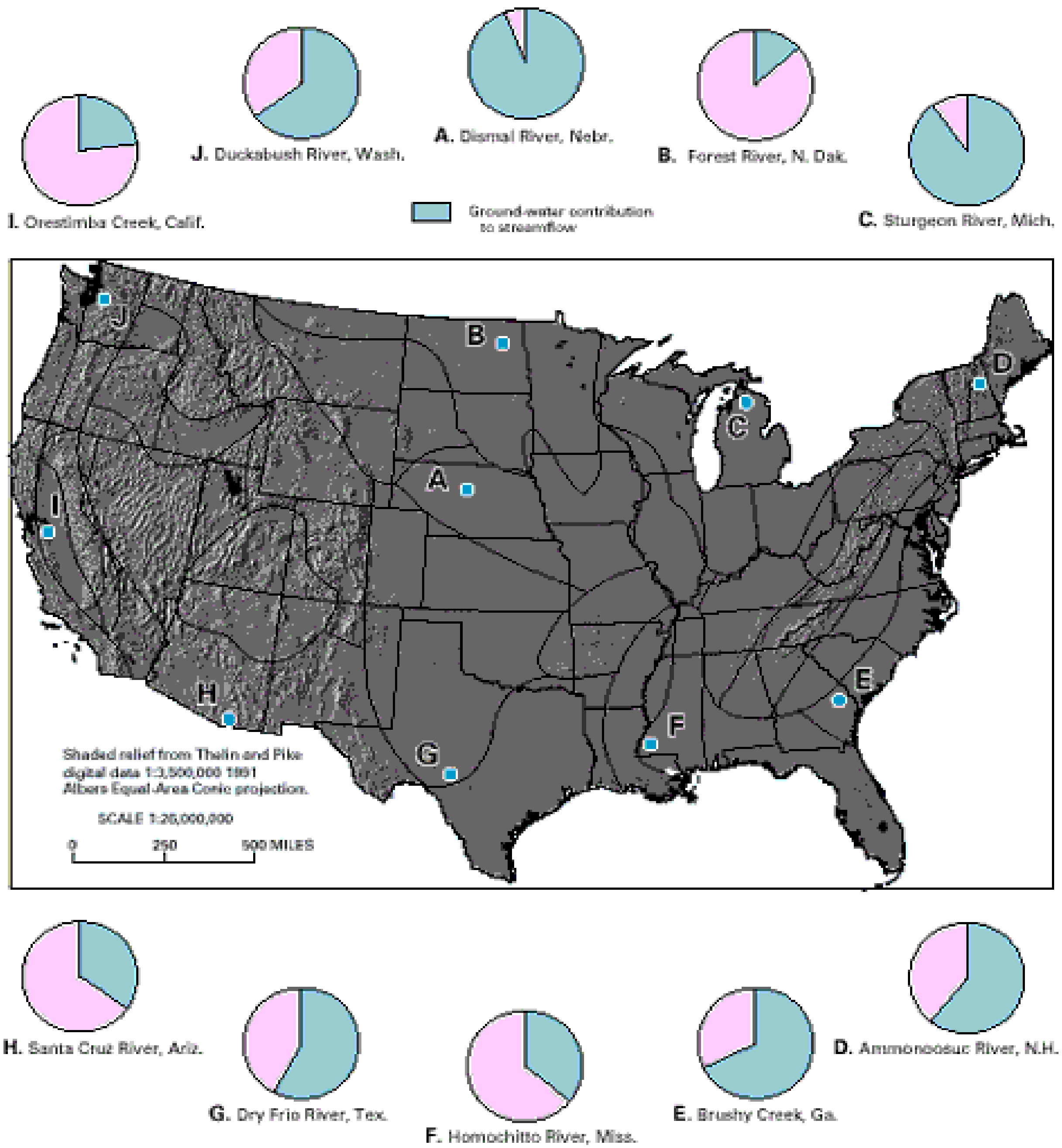
EXPLANATION

Minimal recharge range, in/yr

>2.5	Greater than or equal to 2.5
1.5 – 2.5	1.5 to less than 2.5
0.5 – 1.5	0.5 to less than 1.5
0.1 – 0.5	0.1 to less than 0.5
<0.1	less than 0.1

Study area boundary

County boundary



Regional patterns of surface - ground water interactions

based on streamflow hydrograph separation (after Winter at al., 1998)

will be quantified by our methodology and presented as a map

Where do we want to go from here?

- Take account for other geophere attributes including climate, soil type, vadose zone characteristics, biological characteristics, and landuse activities.
- Recharge and water budget mapping
- Trend analysis of water quantity and quality in intensive use areas
- Input and validation of local and regional flow models
- Promote a new paradigm for freshwater sustainability
- Building information systems for water resources management

Quantitative Information System (QIS)

WATER SUSTAINABILITY CONCEPT

IS

BALANCING WATER FOR HUMANS <u>AND</u> NATURE

Need for New Paradigm

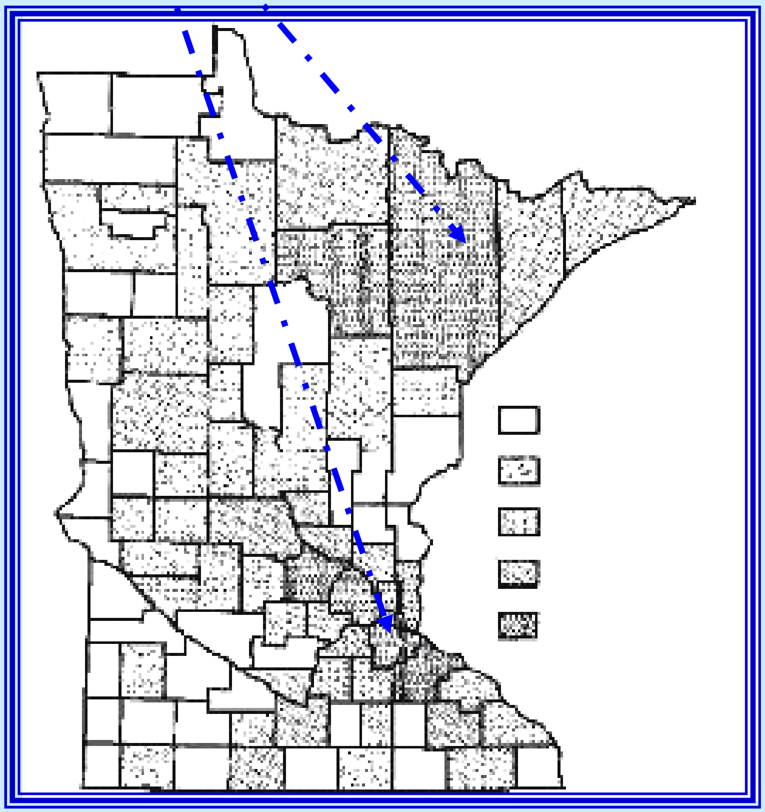
- **Need to view precipitation as the gross freshwater resource to sustain human and natural systems**
- **Ground water resources should be quantified using multiscale recharge/discharge mapping**
- **Renewable freshwater resources should be based on the recharge/discharge constants defined at multiple scales**

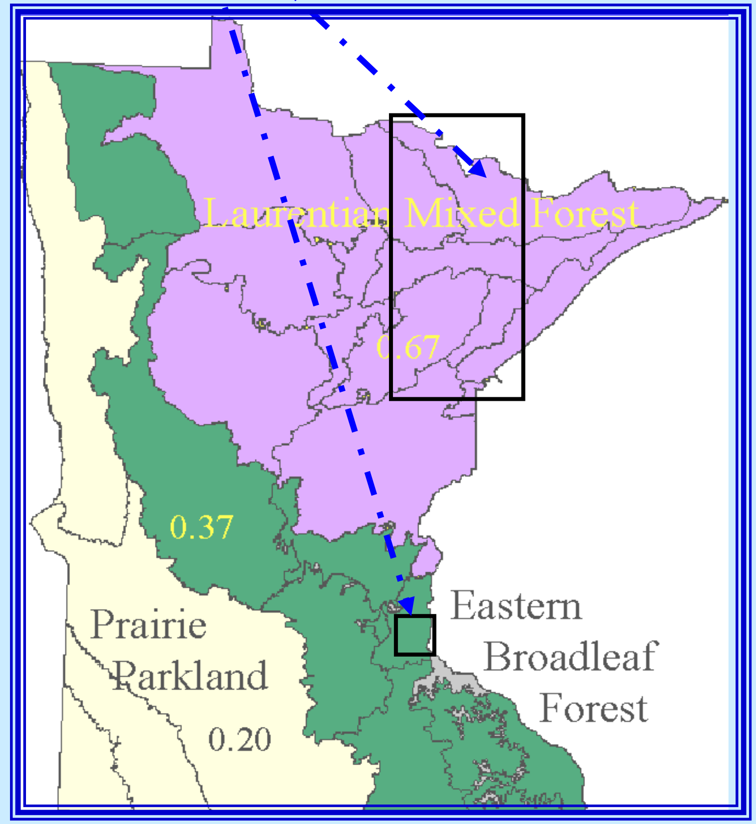
Quantitative information system for ground water sustainability planning

- Develop GIS recharge/discharge maps at multiple scales
- Overlay GIS water use coding to the area units defined on recharge/discharge maps
- Develop an expert information and decision support system for sustainable water use planning

County	Land Area [sq mi]	Water Use: Surface	Ground	Total
St. Louis	6321	0.06	0.001	0.061
Ramsey	158.2	0.93	0.46	1.39

County	Water: Use	/ Resources	= %
St. Louis	0.061	0.67	8.1
Ramsey	1.39	0.37	366.0





Water resources versus water use in Minnesota

left: Water use [cfs/sq. mi] (Water Year, 1995 &1996, DNR data); right: Water resources [cfs/sq. mi] (after Shmagin and Kanivetsky, 2002)

Conclusion

"…There is a need for improved regional-scale estimates of recharge…and other components of the water cycle…..However, it has been difficult to synthesize local analyses into regional and national pictures"- USGS Report to Congress, Circular 1223 (2002)

- **The watershed characteristics approach can address these challenges.**
- **There is a need for development of a Quantitative Information System to achieve freshwater sustainability**