

Atlases of Minnesota Water Sustainability: Creation from Models, Analytical Methods, & Database of Watershed Characteristics



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& FRANCISCO LAHOUD**

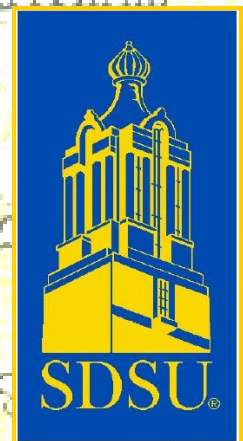
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Topics

- Introduction
- Model of 3D watershed & watershed characteristics
- Data (hydrologic, numeric & classification) & philosophy of analysis
- Analysis stream runoff in MN for period 1955-79
- Maps for Eastern Central MN & TC area
- Maps & Regime – units & boundaries
- Questions

Introduction

Water Resources Development,
Vol. 24, No. 2, 201-215, June 2008

Routledge
Taylor & Francis Group

CLIMATE CHANGE AND WATER

July 2008

IPCC Technical Paper VI

Wake Up to Realities of River Basin Closure

JOHAN FALKENMARK* & DAVID MOLDEN**

*Stockholm International Water Institute (SIWI), Stockholm, Sweden; **International Water Management Institute (IWMI), Colombo, Sri Lanka

Do we know the time spatial variability of water resources?

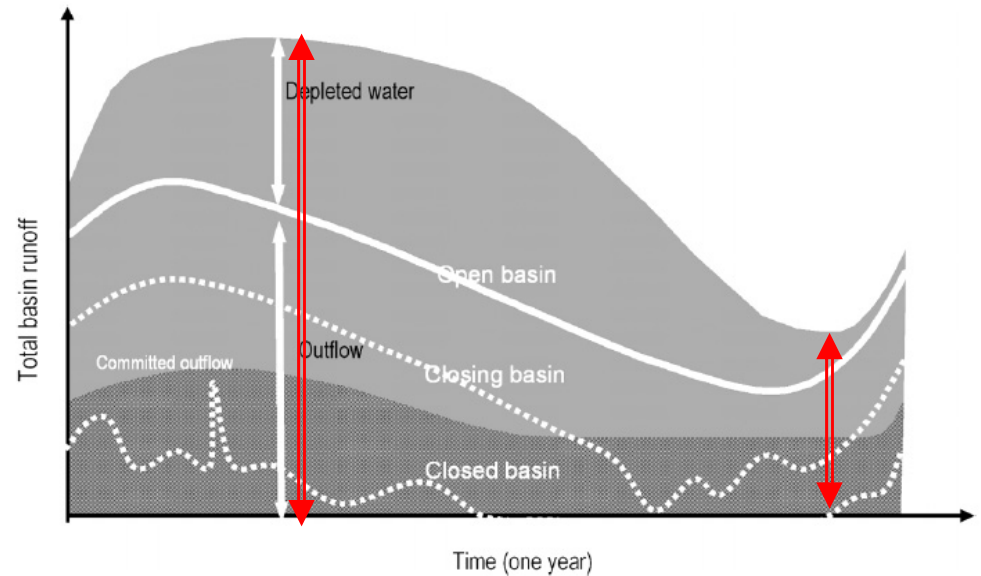


Figure 1. The process of closure over time. In open basins more water can be allocated and diverted, while in a closed basin, flows are over-allocated and diversions of water have impacts on the levels committed for environmental flows and downstream users. Source: From Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture (<http://www.earthscan.co.uk>)

Nature Precedings : doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008



Intergovernmental Panel on Climate Change



Sustainability of ground water resources on a map (units & boundaries)

Nature Precedings : doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008



The goal of research is to describe spatial temporal variability of water recourses & put its on a map

The goal for my presentation is to tell a story about our work

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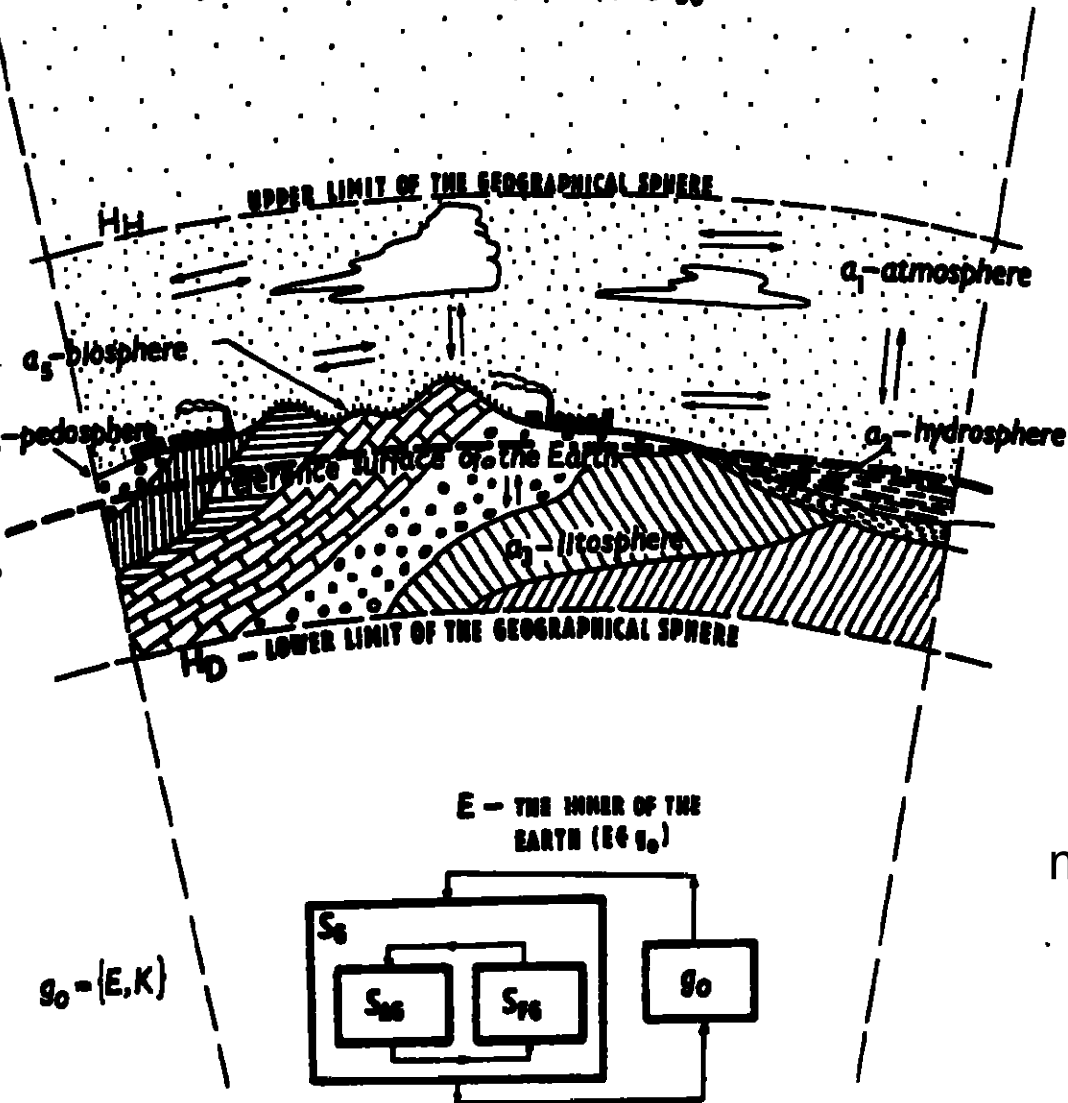
COME IN. KEEP GOING.

| START | 1: | IL RIDGE | 0.0 mi |
|----------------|---|----------|----------|
| → | 2: Turn RIGHT onto TRAIL RIDGE RD W. | | 0.3 mi |
| → | 3: Turn RIGHT onto MUSTANG PASS. | | 0.2 mi |
| → | 4: Turn RIGHT onto MAINWAY S. | | 2.3 mi |
| ↙ | 5: Turn SLIGHT LEFT onto CR-7. | | 0.2 mi |
| ↙ | 6: Turn SLIGHT LEFT onto 216TH ST/CR-12. | | 0.2 mi |
| → | 7: Stay STRAIGHT to go onto CR-7. | | 0.2 mi |
| ↙ | 8: CR-77 becomes I-90 E. | | 0.8 mi |
| ↙ | 9: Turn LEFT onto 217TH ST/CR-24. | | 1.4 mi |
| → | 10: Merge onto I-29 S. | | 43.8 mi |
| EXIT 90 SOUTH | 11: Merge onto I-90 E via EXIT 84A toward ALBERT LEA (Crossing into MINNESOTA). | | 175.4 mi |
| EXIT 35 SOUTH | 12: Merge onto I-35 S via EXIT 159A toward DES MOINES (Crossing into IOWA). | | 41.0 mi |
| EXIT 190 SOUTH | 13: Take the US-18 E exit, EXIT 190, toward MASON CITY/CHARLES CITY. | | 1.6 mi |
| EXIT 27 SOUTH | 14: Merge onto IA-27 S. | | 79.6 mi |
| EXIT 218 SOUTH | 15: Keep LEFT at the fork to go on US-218 S/IA-27 S. | | 0.5 mi |
| RAMP EAST | 16: Take the US-218 S ramp toward WATERLOO. | | 0.3 mi |
| EXIT 57 EAST | 17: Merge onto IA-57 E. | | 0.0 mi |

Model of 3D watershed - hydrologic structure

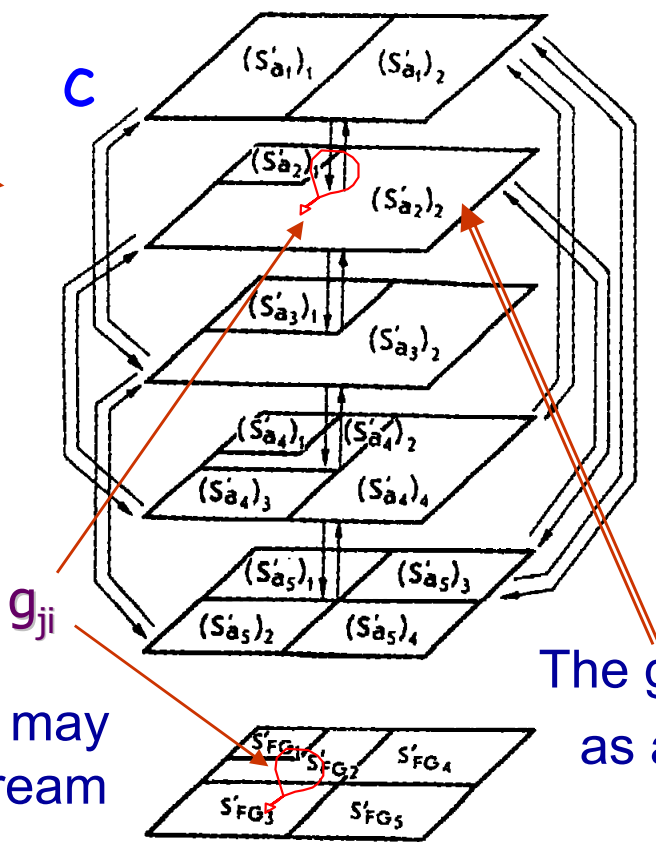
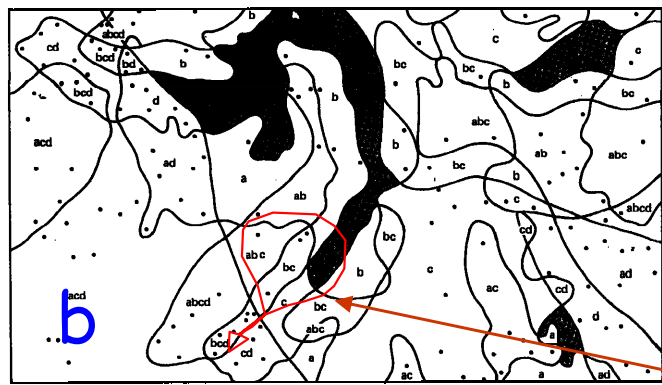
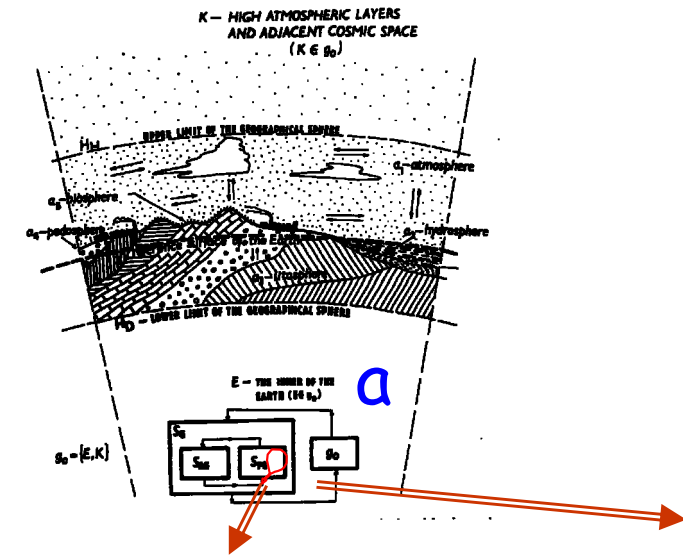
Nature Precedings : doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008

K - HIGH ATMOSPHERIC LAYERS
AND ADJACENT COSMIC SPACE
($K \in g_0$)



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

System Model (a) for Watershed in Landscape, with Map of Conditions (b) & Multilayer Map (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.

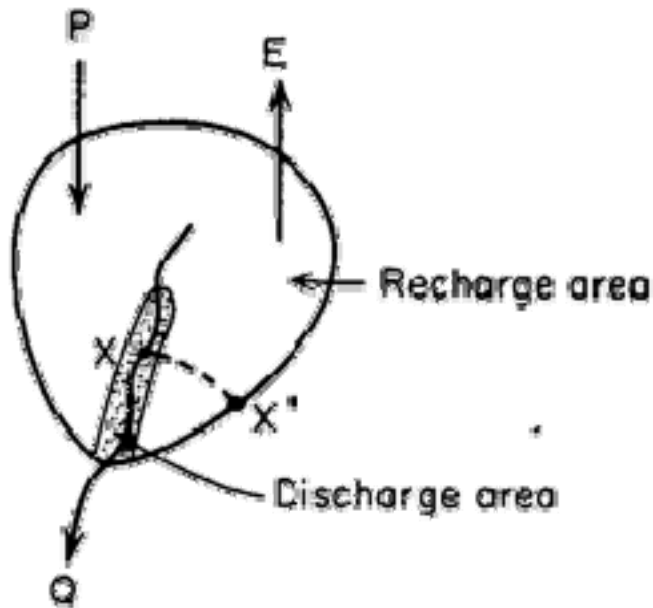
The g_2 - stream runoff system as a part of a_2 - hydrosphere may be presented as:

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

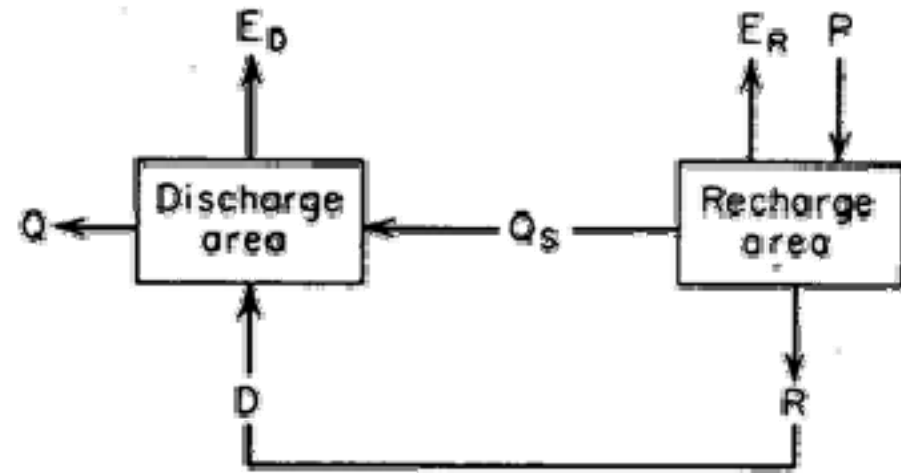
where g_{ji} - watershed.

Any watershed g_{ji} for territory may be considered as a part of stream runoff system Sg_2 . Each of these components may be characterized by matrix of input $\{Wi\}$, matrix of output $\{Qi\}$, & matrix of states $\{Hi\}$.

Watershed water balance



(a)



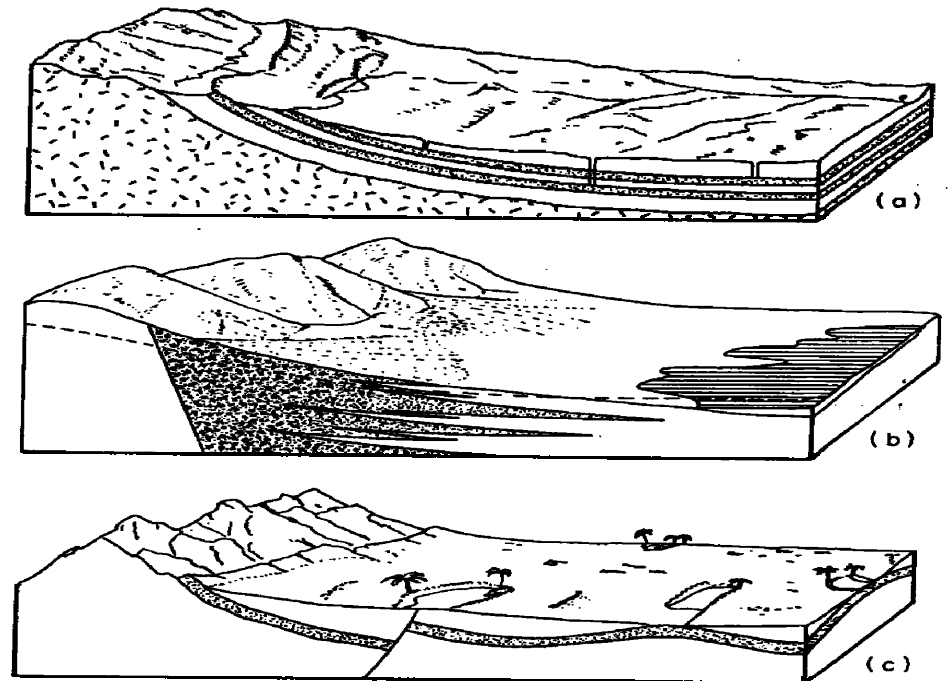
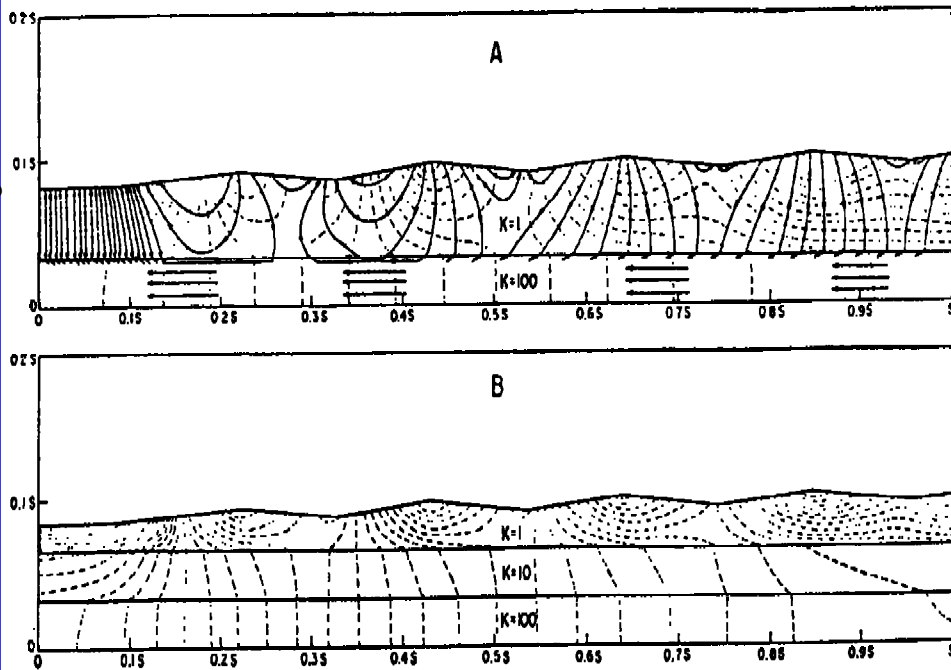
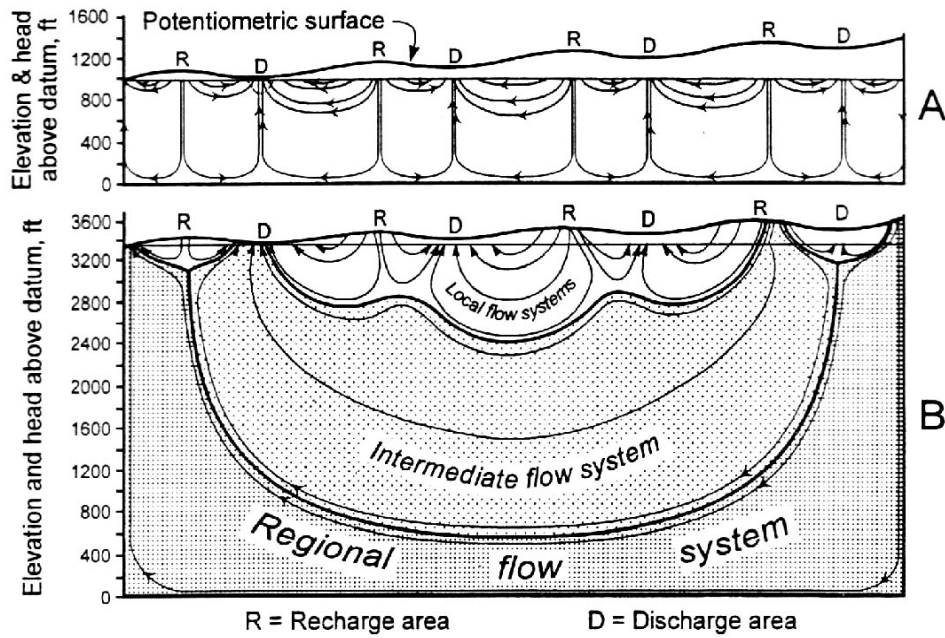
(b)

Elements of watershed water balance:

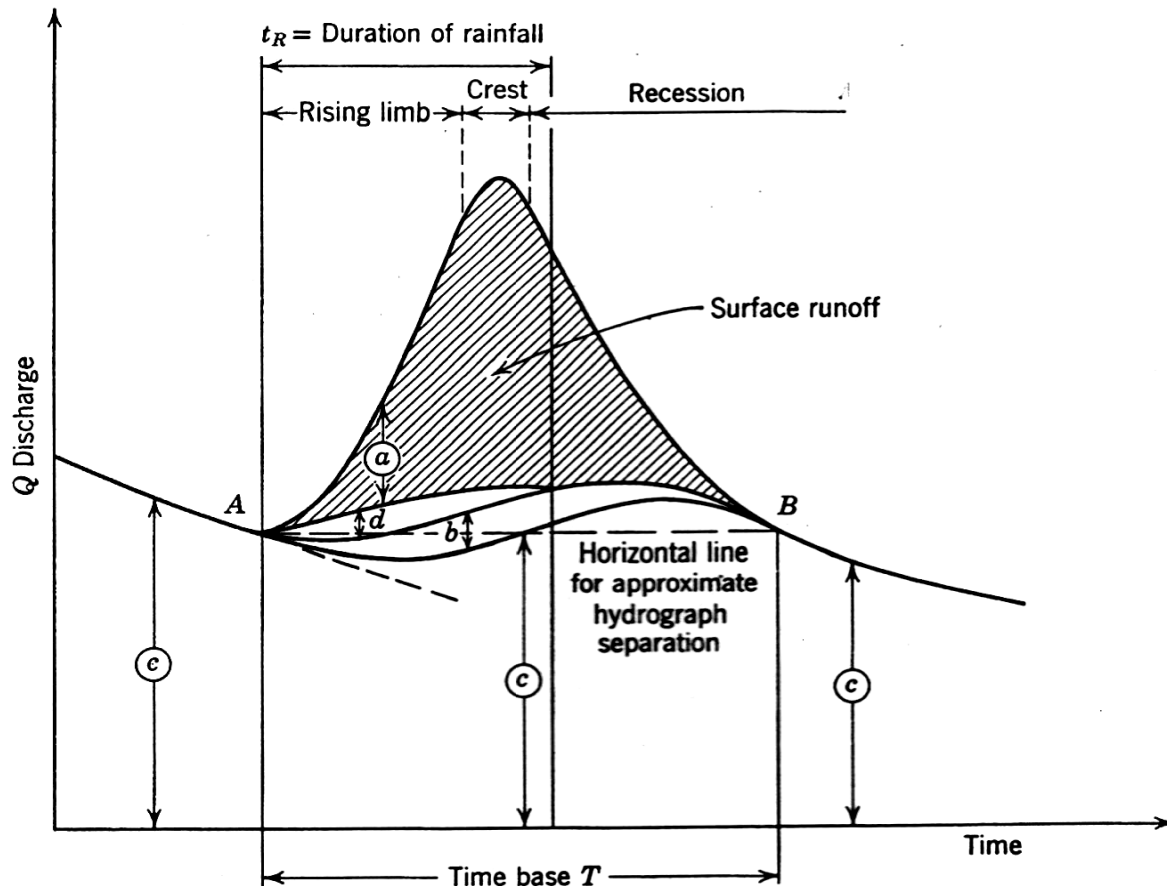
P - precipitation, E - evapotranspiration, Q - runoff, Q_s - the surface water component of average annual runoff, E_R - the average annual evapotranspiration from recharge area, E_D - the average annual evapotranspiration from discharge area, R - the average annual ground water recharge, D - the average annual ground water discharge;
 $X-X'$ - cross-section from shown in (b) - quantitative flow net & recharge-discharge profile in a two-dimensional section across the heterogeneous groundwater basin (after Freeze and Cherry, 1979)

Watershed in a landscape

Cross-sections for different hydrogeological settings, showing the influence of stratigraphy & structure on regional aquifer occurrence (after Freeze and Cherry, 1979).



The components of a hydrograph & watershed characteristics



The specific hydrologic characteristics used in analysis are:

- average annual stream runoff rate or yield [l/s/sq km or mm/year]
- average rate or yield of minimal monthly stream runoff [l/s/sq km or mm/year]
- monthly proportion of annual stream runoff [% or as a parts of 1.0]

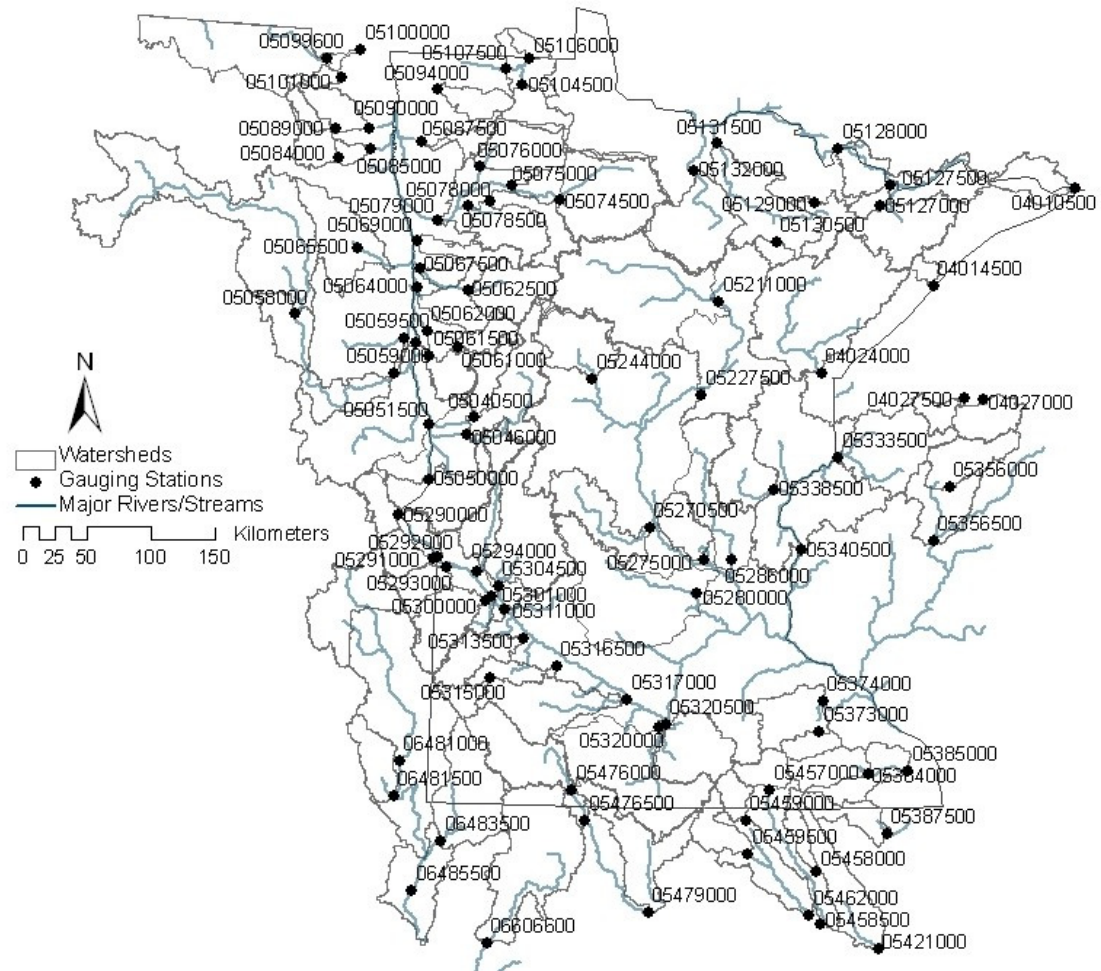
Components of hydrograph (De Wiest, 1967)

Analysis stream runoff in MN for period 1955-1979

Initial matrix:

$Q_{(n \times p)}$ or $Q_{(93 \times 14)}$

there are:
 $n=93$ – number of rows or watersheds,
 $p=14$ – number of variables or 12 monthly proportions, February & annual yield



Data

Initial matrix:

$Q_{(n \times p)}$ or $Q_{(93 \times 14)}$

there are:

$n=93$ –

number of

rows or

watersheds,

$p=14$ –

number of

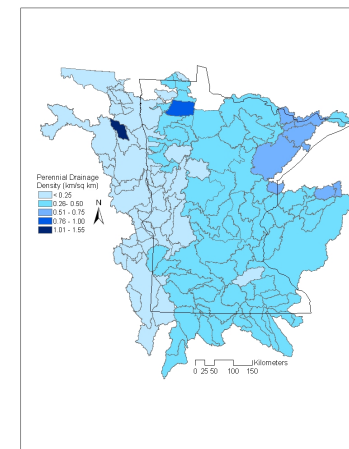
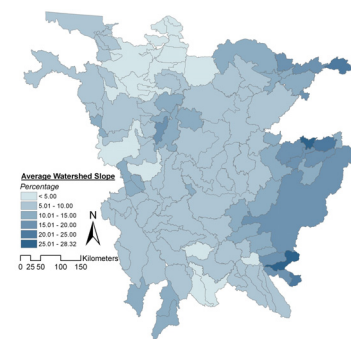
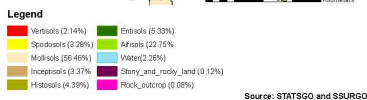
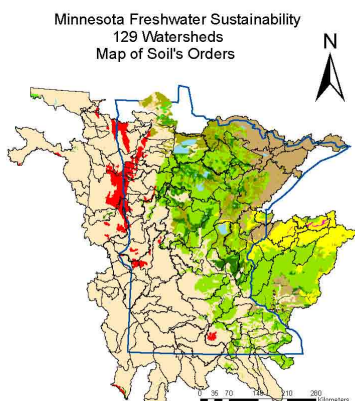
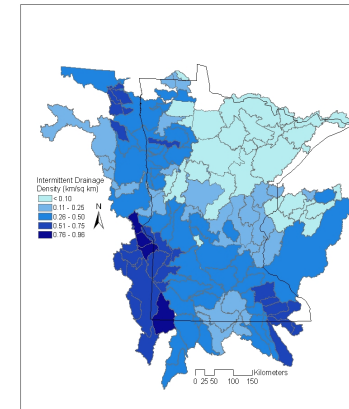
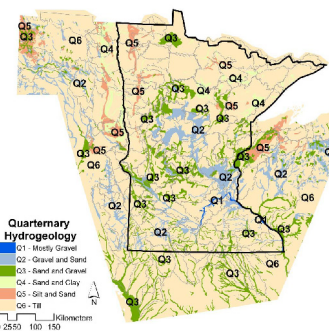
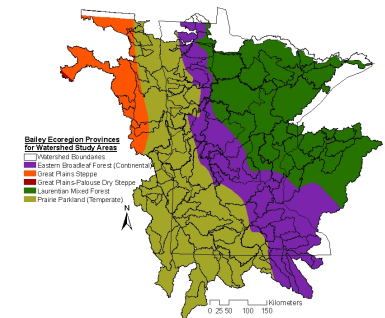
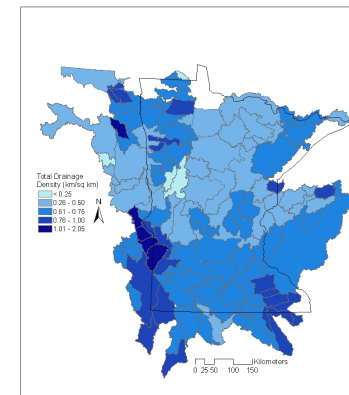
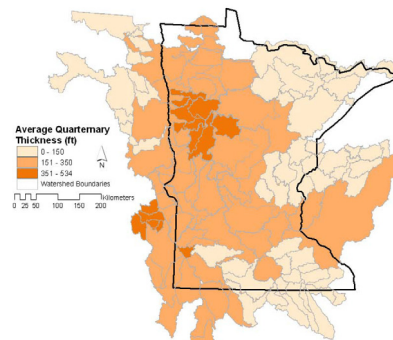
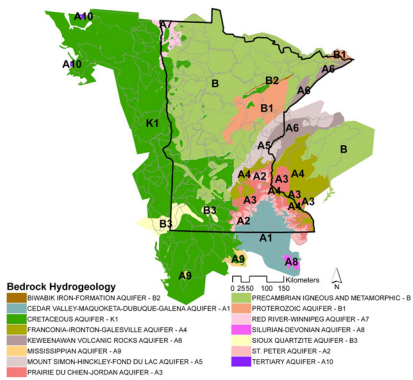
variables or 12

monthly

proportions,

February &

annual yield



Data & philosophy of analysis

A **factor** is a portion of a quantity, usually an integer or polynomial that, when multiplied by other factors, gives the entire quantity.

The determination of factors is called factorization (or sometimes "factoring"). It is usually desired to break factors down into the smallest possible pieces so that no factor is itself factorable.

Factor analysis allows the determination of common axes influencing sets of independent measured sets. It is "the granddaddy of multivariate techniques (Gould 1996, pp. 42-43) and was invented by Spearman.

Multivariate analysis is the simultaneous statistical consideration of relationships among many measured properties of a given system (Gould 1996, p. 42;).

The main applications of factor analytic techniques are:

- (1) to *reduce* the number of variables and
- (2) to *detect structure* in the relationships between variables, that is to *classify variables*.

(From: Wolfram *MathWorld*)

3D Sequential Graph of Monthly Proportions

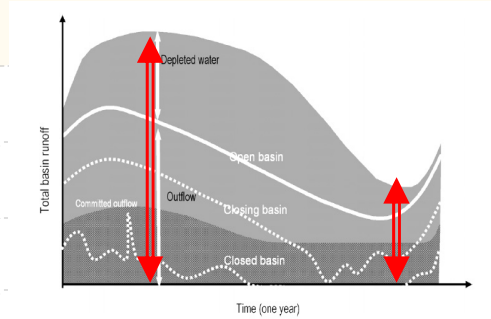
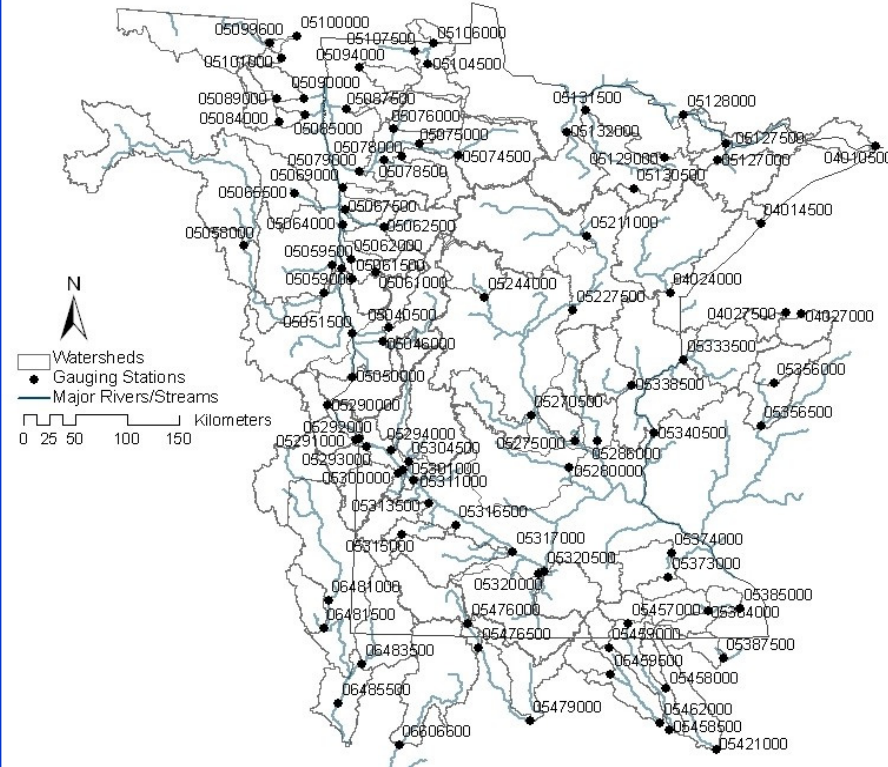
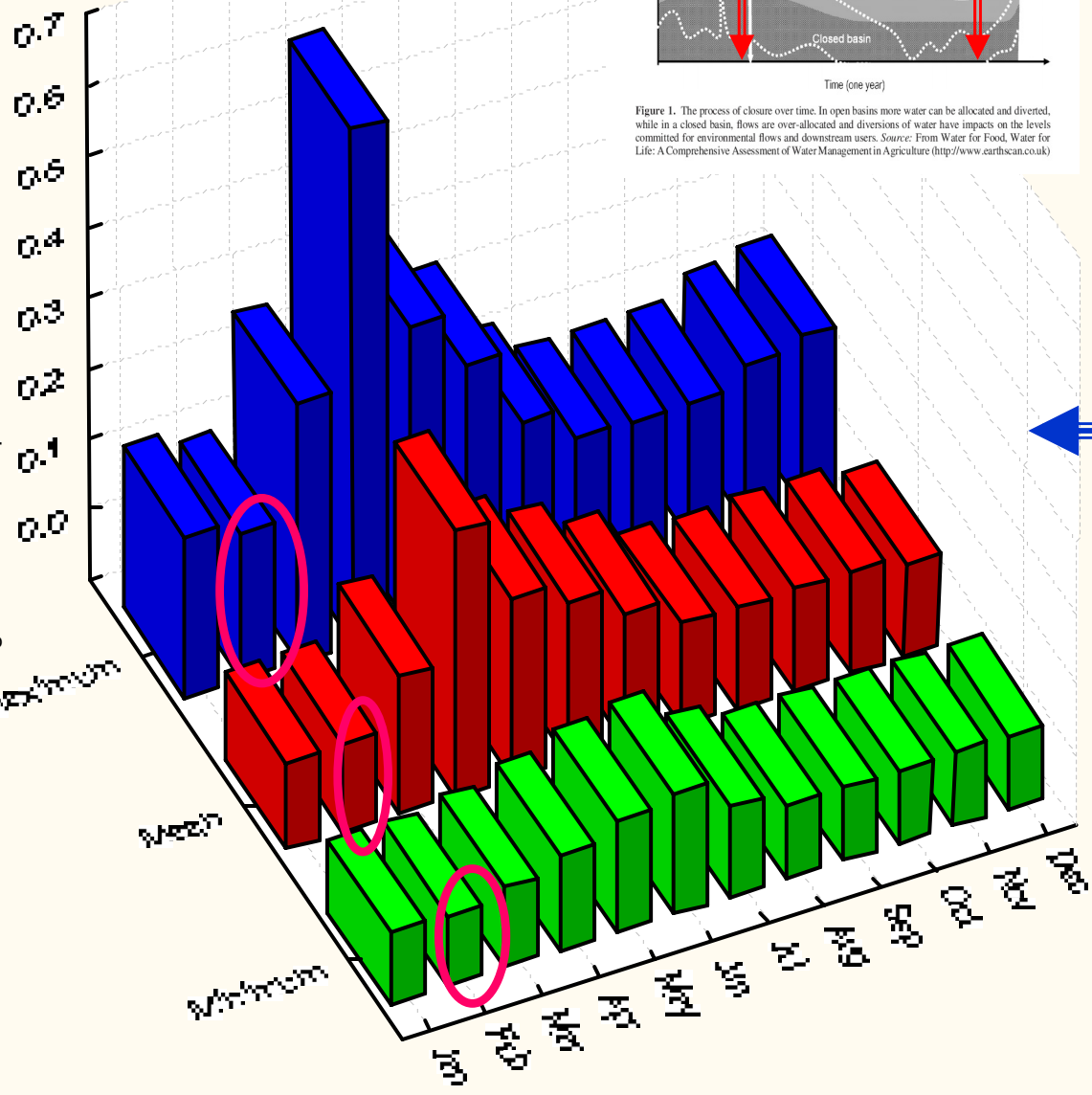


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The "hydrograph" of streamflow in MN

Nature Precedings : doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008



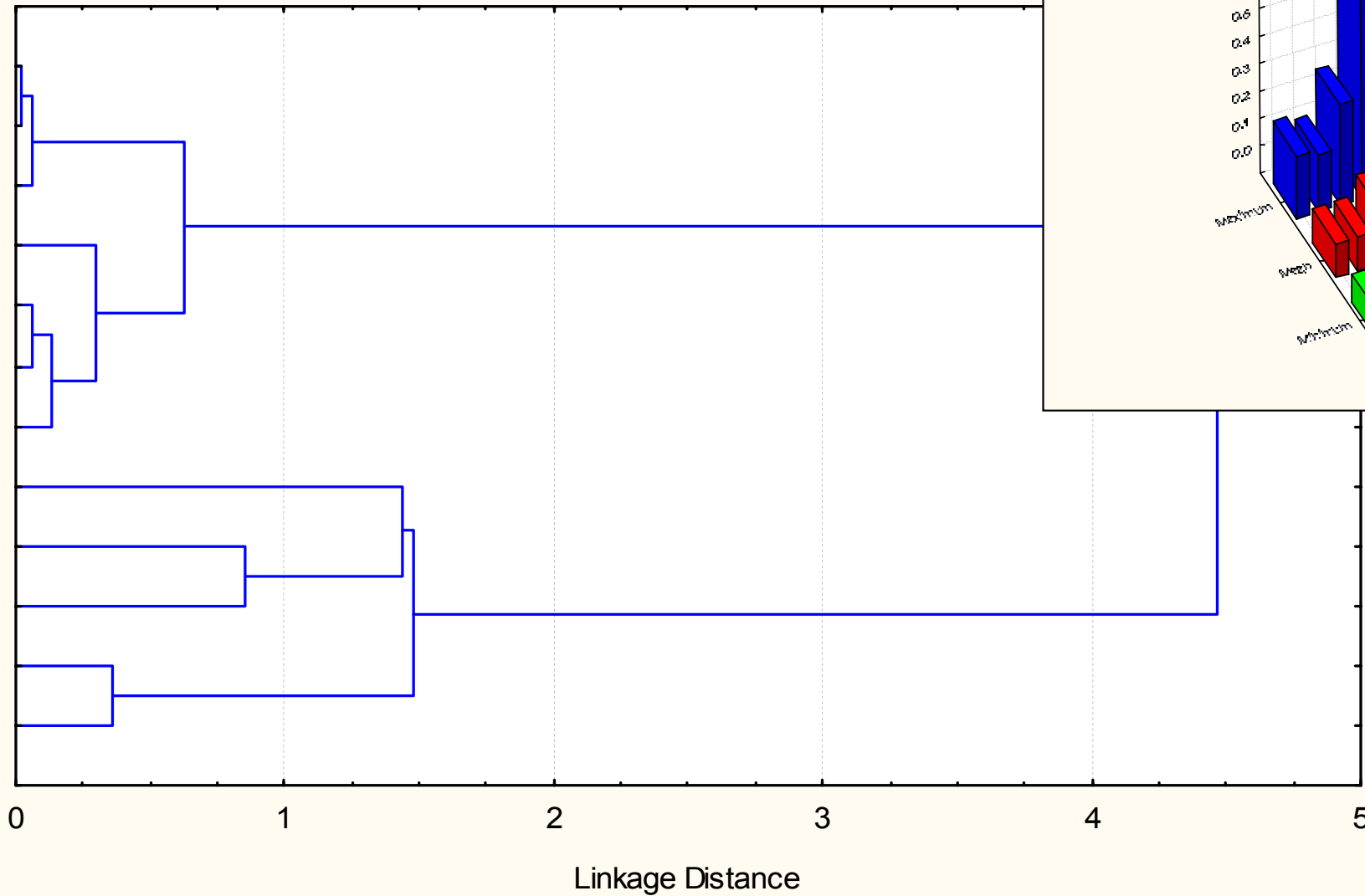
The monthly streamflow in MN as a cluster tree

Tree Diagram for 12 Variables

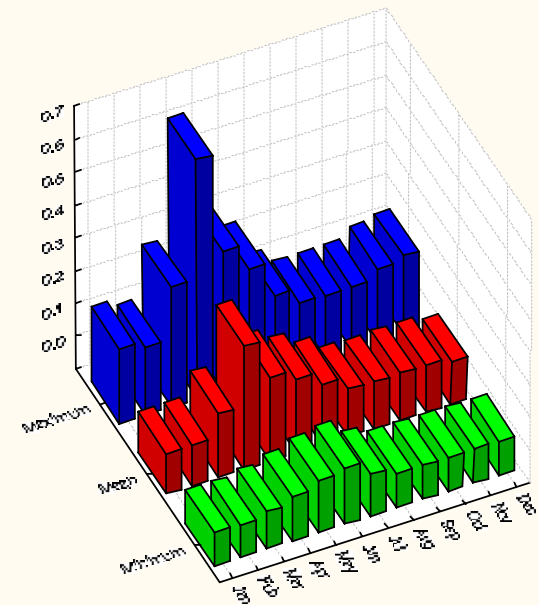
Ward's method

1-Pears on r

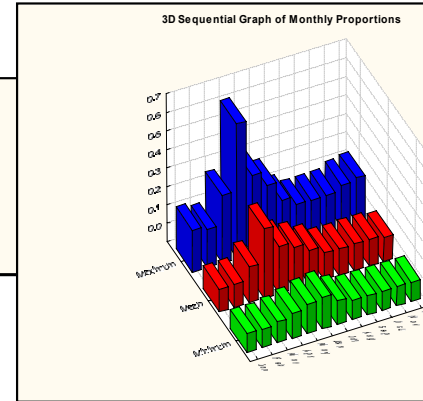
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Dec



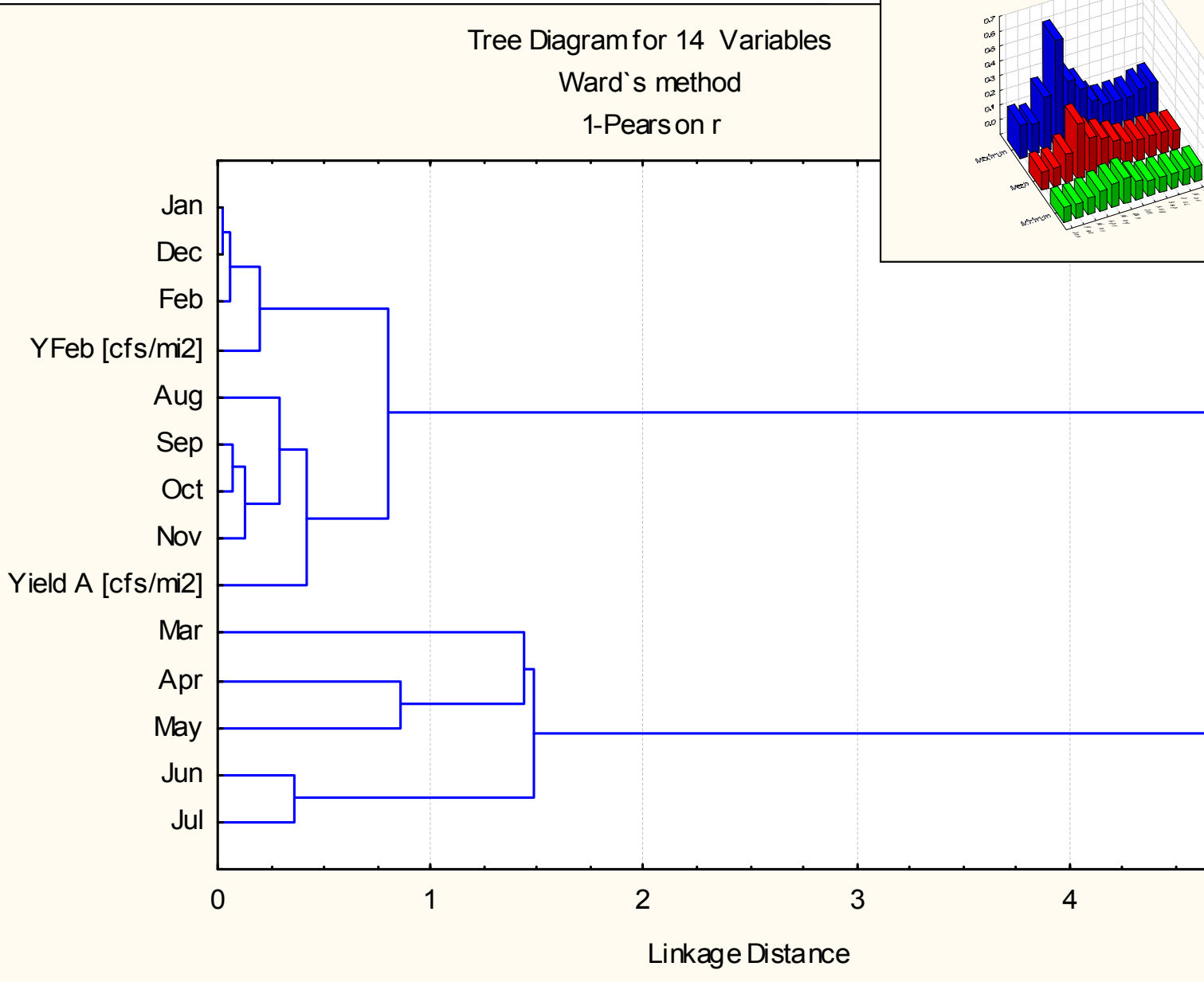
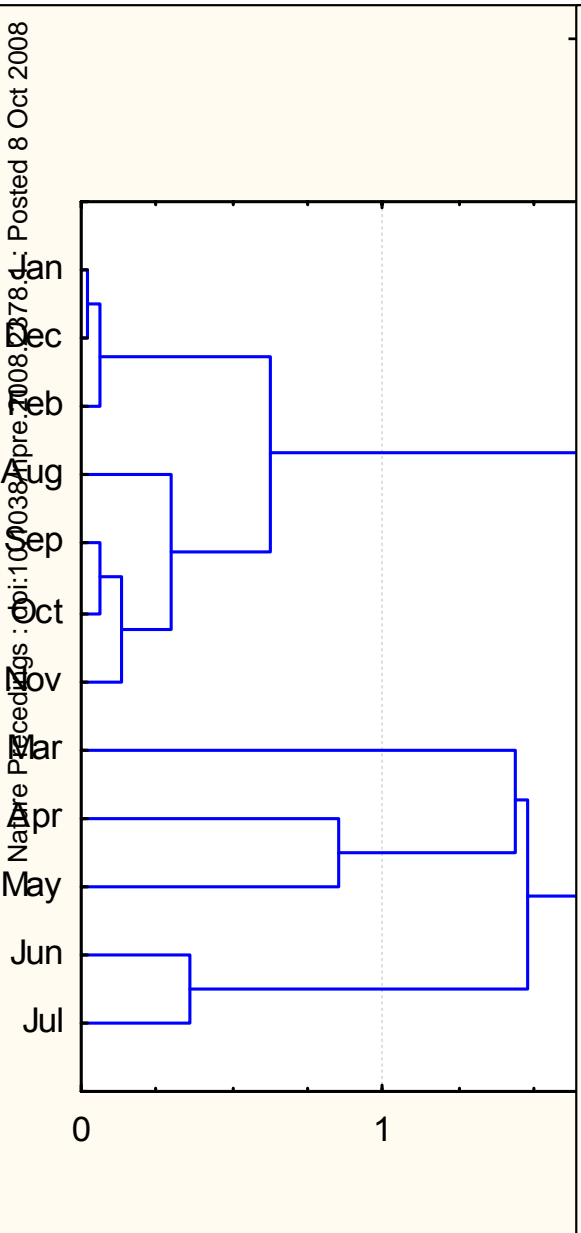
3D Sequential Graph of Monthly Proportions



Cluster trees for annual & February runoff



Tree Diagram for 14 Variables
Ward's method
1-Pearson r

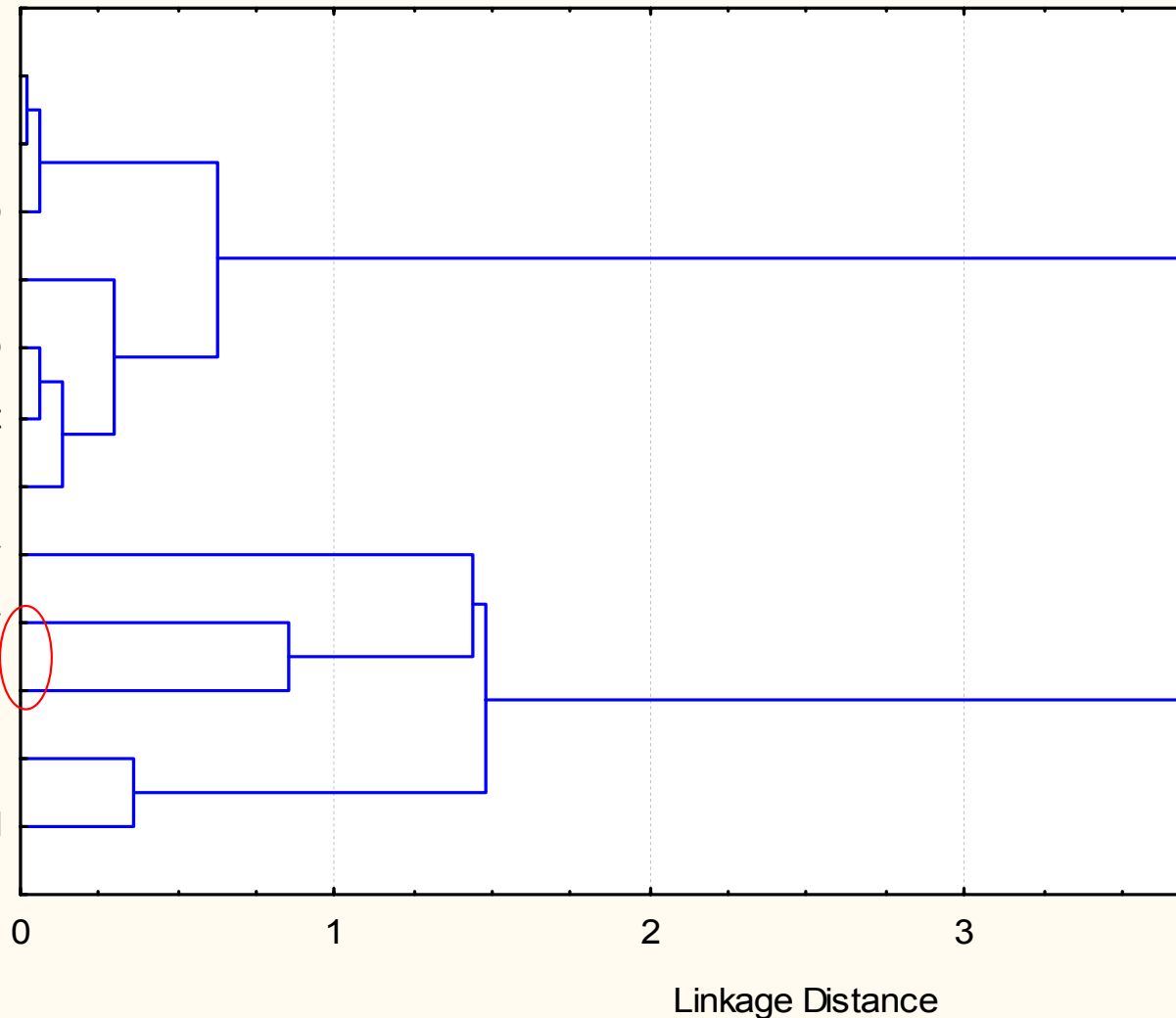


The monthly runoff in MN as a cluster tree & Factor Loading

Tree Diagram for 12 Variables
Ward's method
1-Pears on r

Table of Factor Loading
of monthly proportion for
1955-79

Nature Precedings : doi:10.1038/npre.2008.278.1
 Posted 8 Oct 2008



| | Factor 1 | Factor 2 | Factor 3 |
|----------|--------------|-------------|--------------|
| Nov | 0.96 | | |
| Dec | 0.95 | | |
| Sep | 0.92 | | |
| Jan | 0.91 | | |
| Oct | 0.90 | | |
| Feb | 0.88 | | 0.28 |
| Aug | 0.84 | 0.37 | |
| Jul | | 0.91 | |
| Mar | | | 0.90 |
| Jun | | 0.84 | -0.40 |
| May | -0.30 | | -0.87 |
| Apr | -0.87 | -0.39 | |
| Expl.Var | 6.72 | 1.92 | 1.87 |
| Prp.Totl | 0.56 | 0.16 | 0.16 |

The monthly runoff in MN as Factor Loading structure

Factor Loadings, Factor 1 vs. Factor 2 vs. Factor 3

Rotation: Varimax normalized

Extraction: Principal components

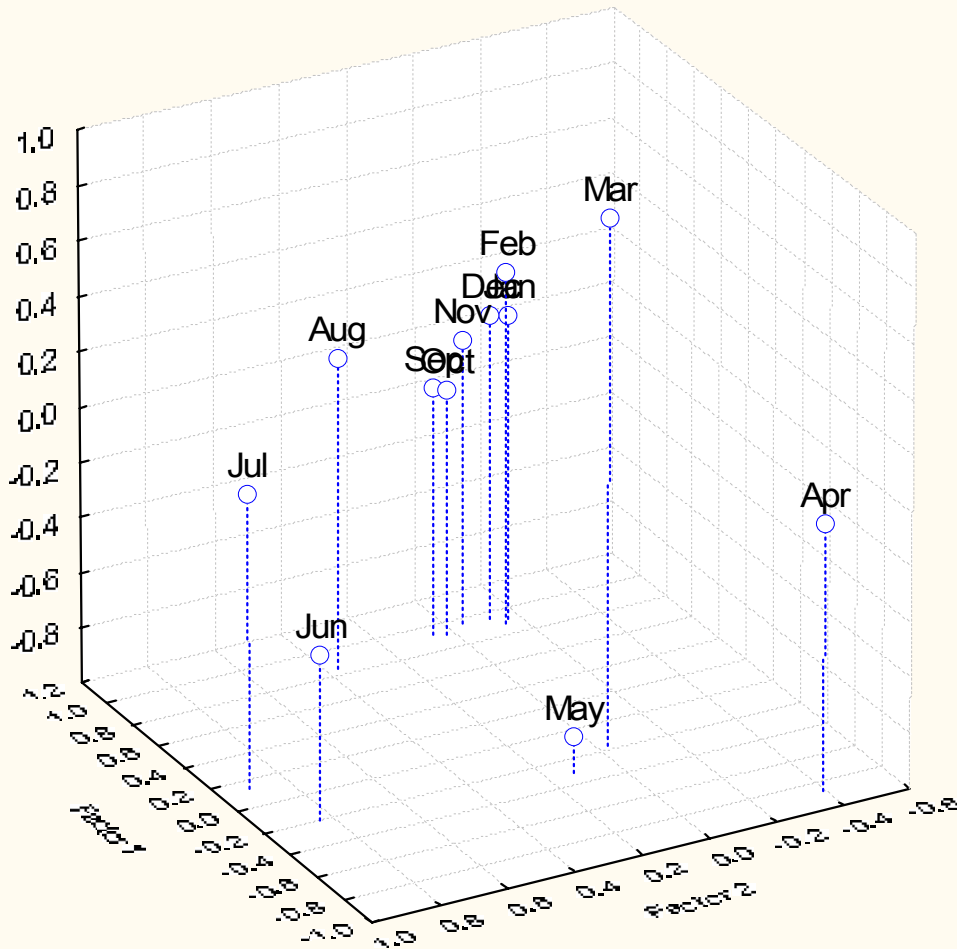


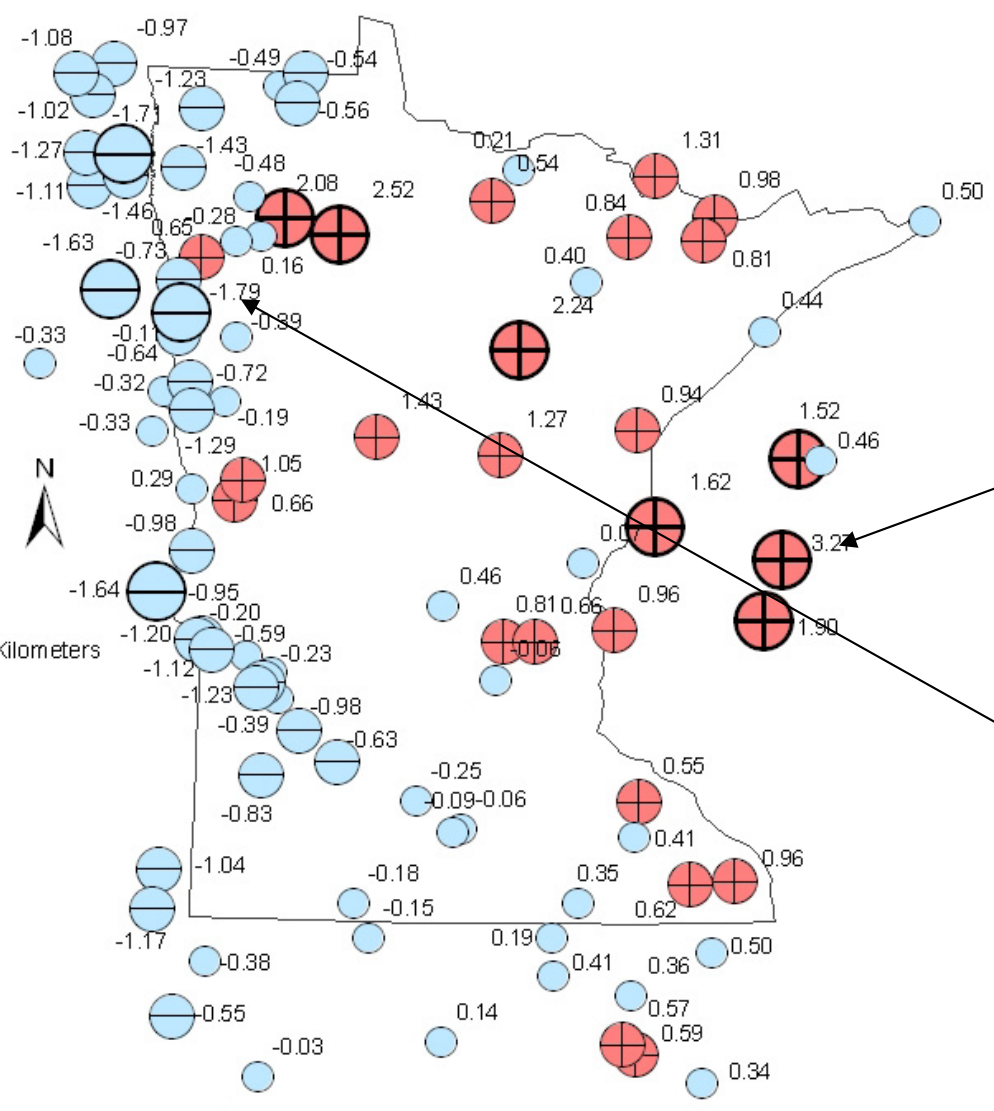
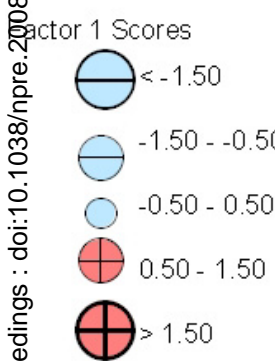
Table of Factor Loading
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Factor 1 Scores of watersheds in MN

Nature Precedings : doi:10.1038/npre.2008.1311 : Posted 8 Oct 2008

Monthly Proportion
for Period 1955-1979



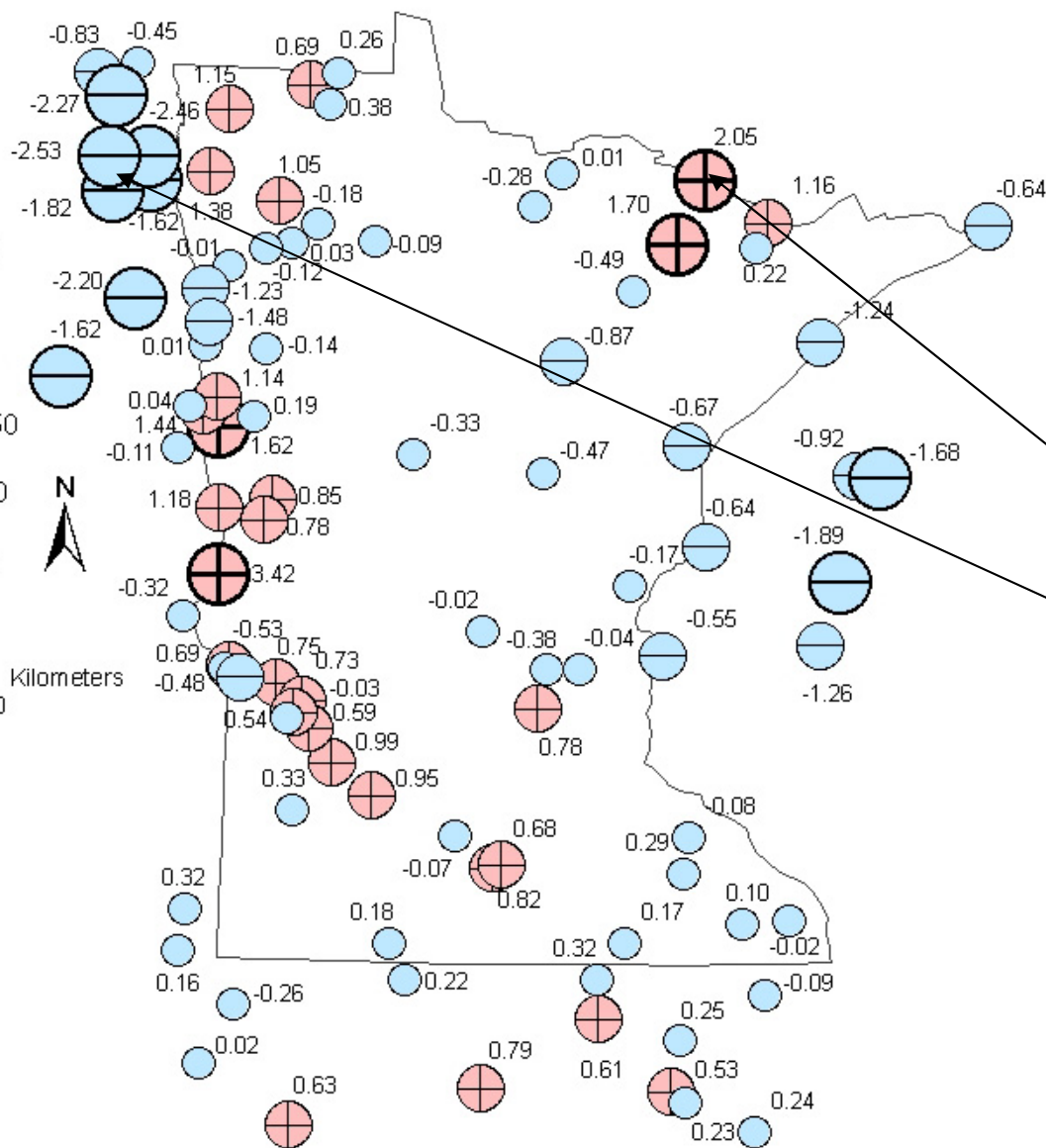
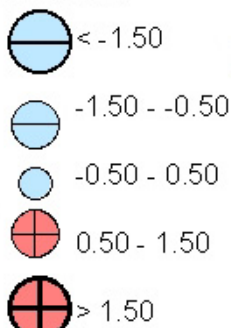
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Factor 2 Scores of watersheds in MN

Nature Precedings : doi:10.1038/npre.2008.23781

Monthly Proportion
for Period 1955-1979

Factor 2 Scores



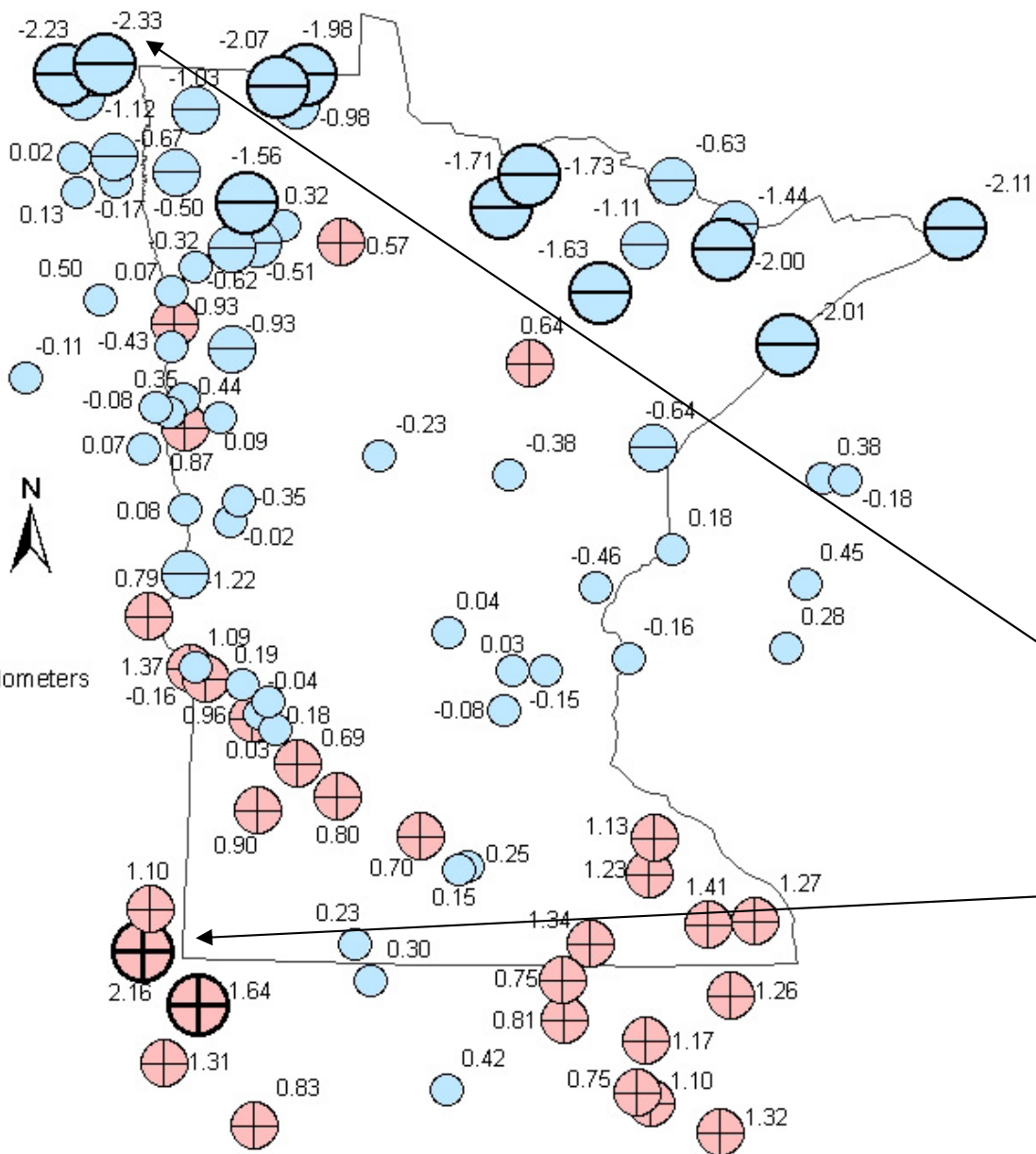
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Factor 3 Scores of watersheds in MN

Nature Precedings : doi:10.1038/npre.2008.23781 : 8 Oct 2008

Monthly Proportion
for Period 1955-1979

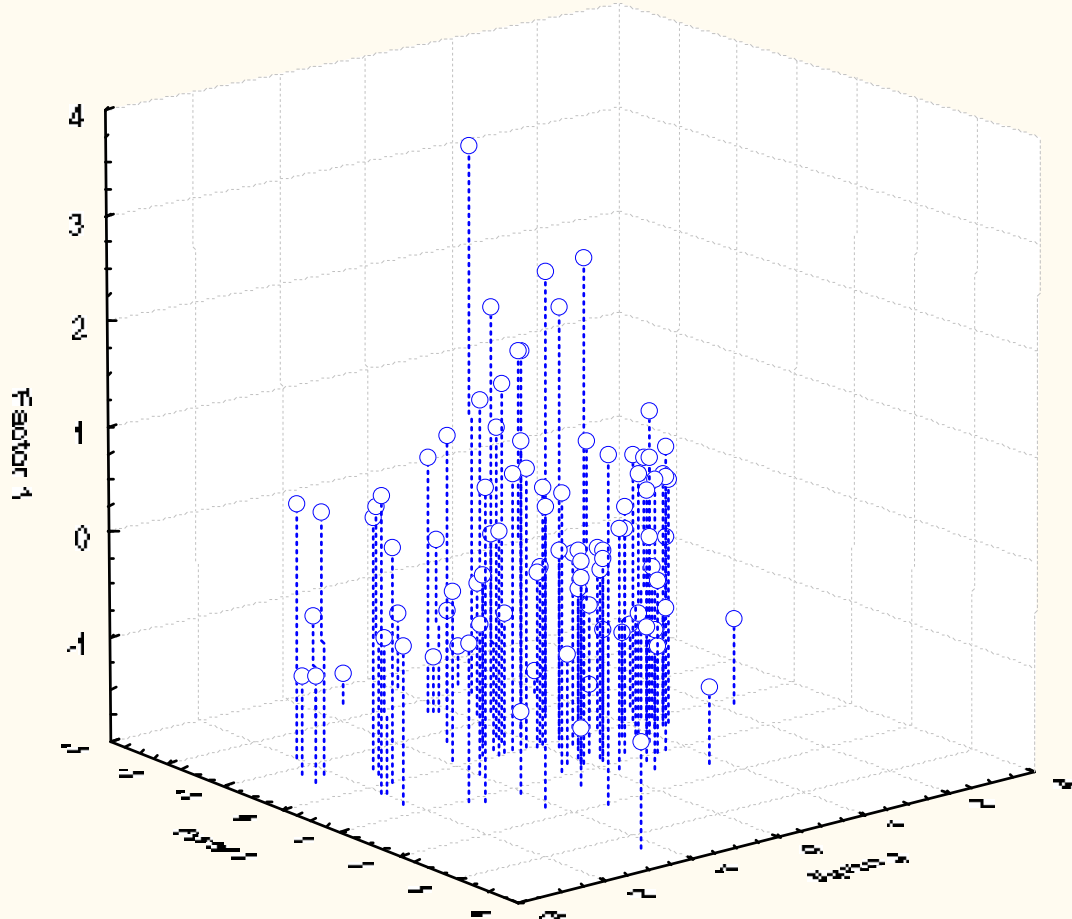
Factor 3 Scores



| | Factor 1 | Factor 2 | Factor 3 |
|----------|--------------|-------------|--------------|
| Nov | 0.96 | | |
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Factor Scores of watersheds in coordinates of streamflow monthly proportions in MN

3D Scatterplot



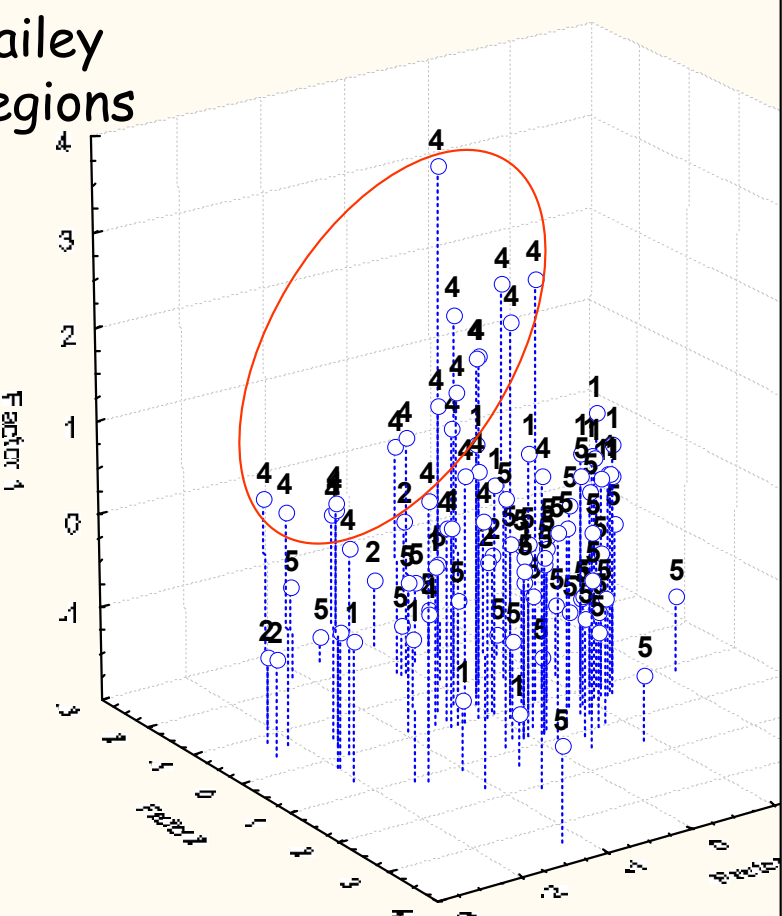
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Factor Scores of watersheds in coordinates of streamflow monthly proportions in MN

Nature Precedings : doi:10.1038/npre.2008.23781v1 [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46] [47] [48] [49] [50] [51] [52] [53] [54] [55] [56] [57] [58] [59] [60] [61] [62] [63] [64] [65] [66] [67] [68] [69] [70] [71] [72] [73] [74] [75] [76] [77] [78] [79] [80] [81] [82] [83] [84] [85] [86] [87] [88] [89] [90] [91] [92] [93] [94] [95] [96] [97] [98] [99] [100] [101] [102] [103] [104] [105] [106] [107] [108] [109] [110] [111] [112] [113] [114] [115] [116] [117] [118] [119] [120] [121] [122] [123] [124] [125] [126] [127] [128] [129] [130] [131] [132] [133] [134] [135] [136] [137] [138] [139] [140] [141] [142] [143] [144] [145] [146] [147] [148] [149] [150] [151] [152] [153] [154] [155] [156] [157] [158] [159] [160] [161] [162] [163] [164] [165] [166] [167] [168] [169] [170] [171] [172] [173] [174] [175] [176] [177] [178] [179] [180] [181] [182] [183] [184] [185] [186] [187] [188] [189] [190] [191] [192] [193] [194] [195] [196] [197] [198] [199] [200] [201] [202] [203] [204] [205] [206] [207] [208] [209] [210] [211] [212] [213] [214] [215] [216] [217] [218] [219] [220] [221] [222] [223] [224] [225] [226] [227] [228] [229] [230] [231] [232] [233] [234] [235] [236] [237] [238] [239] [240] [241] [242] [243] [244] [245] [246] [247] [248] [249] [250] [251] [252] [253] [254] [255] [256] [257] [258] [259] [260] [261] [262] [263] [264] [265] [266] [267] [268] [269] [270] [271] [272] [273] [274] [275] [276] [277] [278] [279] [280] [281] [282] [283] [284] [285] [286] [287] [288] [289] [290] [291] [292] [293] [294] [295] [296] [297] [298] [299] [300] [301] [302] [303] [304] [305] [306] [307] [308] [309] [310] [311] [312] [313] [314] [315] [316] [317] [318] [319] [320] [321] [322] [323] [324] [325] [326] [327] [328] [329] [330] [331] [332] [333] [334] [335] [336] [337] [338] [339] [340] [341] [342] 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[841] [842] [843] [844] [845] [846] [847] [848] [849] [850] [851] [852] [853] [854] [855] [856] [857] [858] [859] [860] [861] [862] [863] [864] [865] [866] [867] [868] [869] [870] [871] [872] [873] [874] [875] [876] [877] [878] [879] [880] [881] [882] [883] [884] [885] [886] [887] [888] [889] [890] [891] [892] [893] [894] [895] [896] [897] [898] [899] [900] [901] [902] [903] [904] [905] [906] [907] [908] [909] [910] [911] [912] [913] [914] [915] [916] [917] [918] [919] [920] [921] [922] [923] [924] [925] [926] [927] [928] [929] [930] [931] [932] [933] [934] [935] [936] [937] [938] [939] [940] [941] [942] [943] [944] [945] [946] [947] [948] [949] [950] [951] [952] [953] [954] [955] [956] [957] [958] [959] [960] [961] [962] [963] [964] [965] [966] [967] [968] [969] [970] [971] [972] [973] [974] [975] [976] [977] [978] [979] [980] [981] [982] [983] [984] [985] [986] [987] [988] [989] [990] [991] [992] [993] [994] [995] [996] [997] [998] [999] [1000]

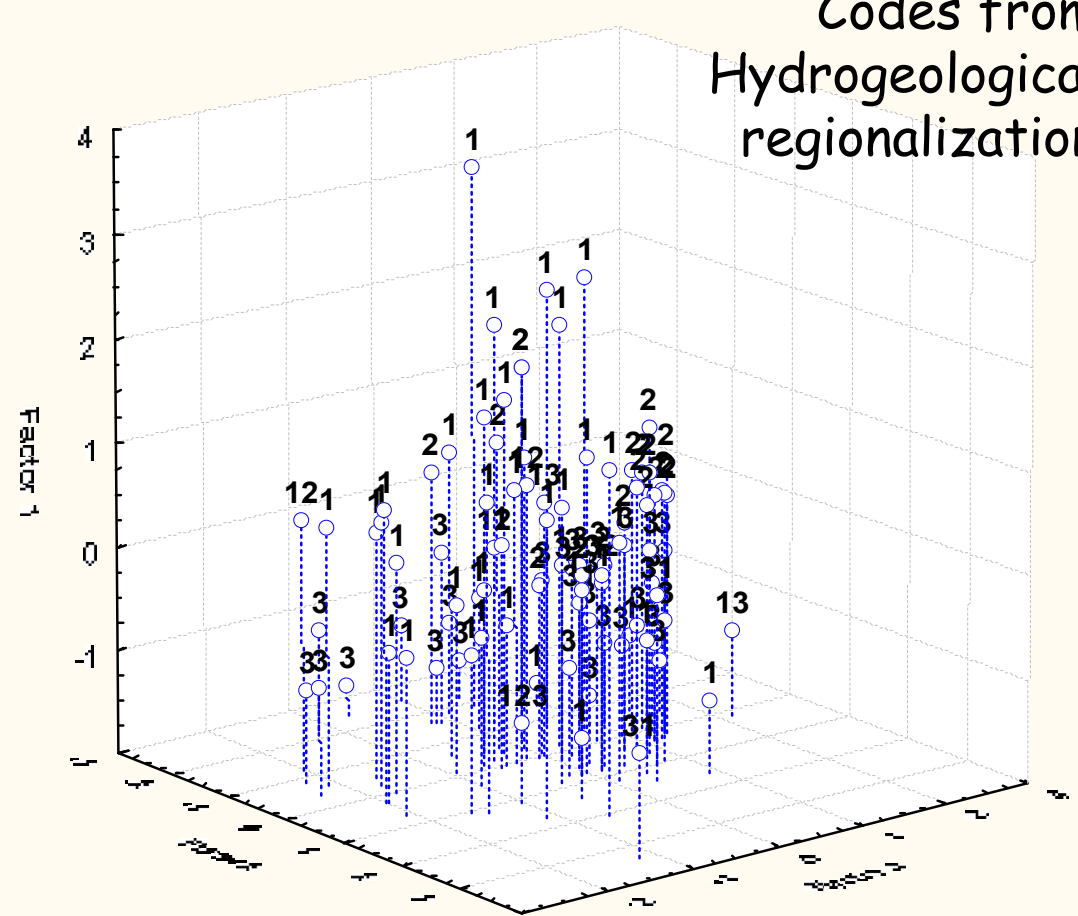
Codes from
Bailey
Regions

3D Scatterplot



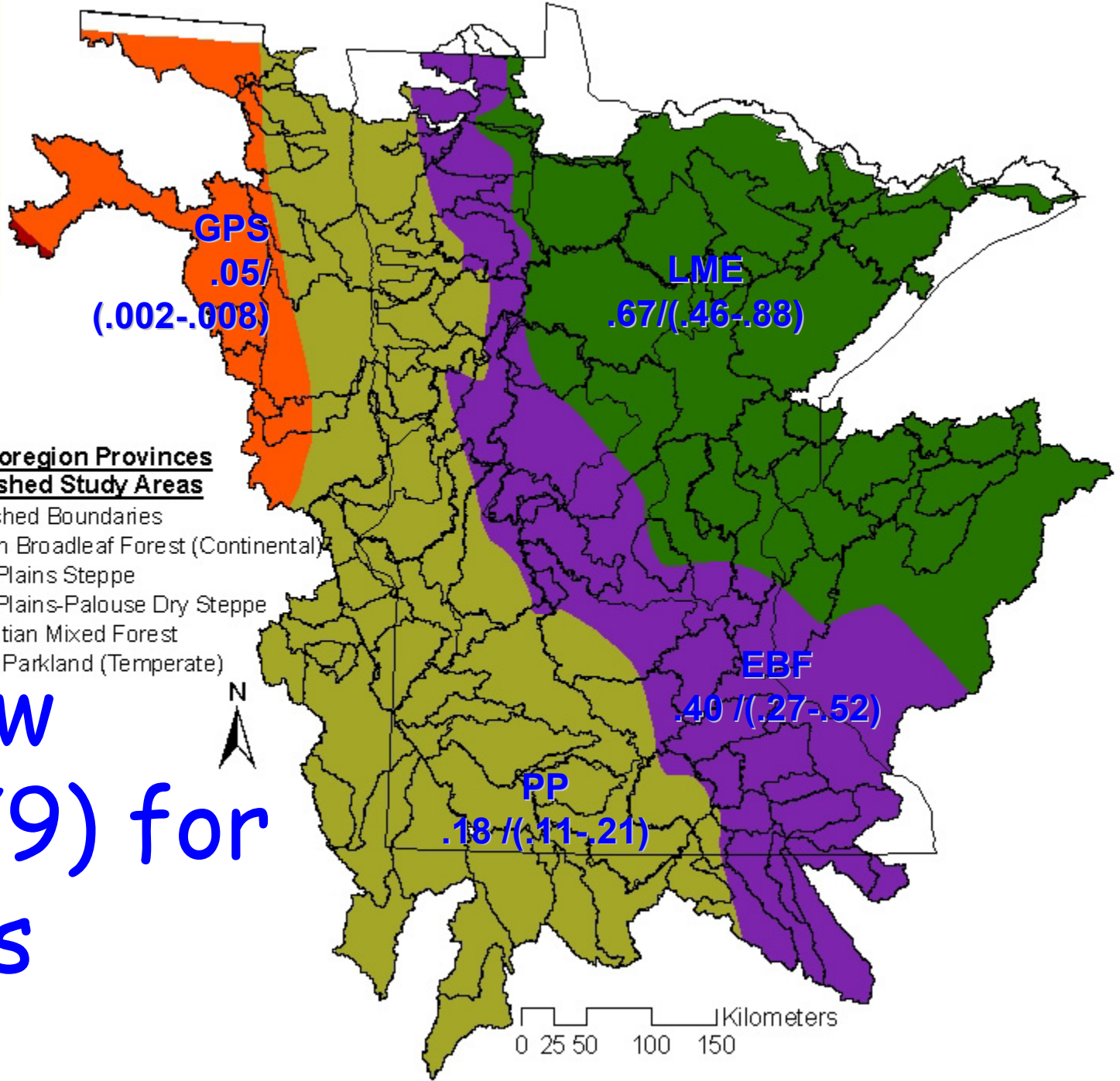
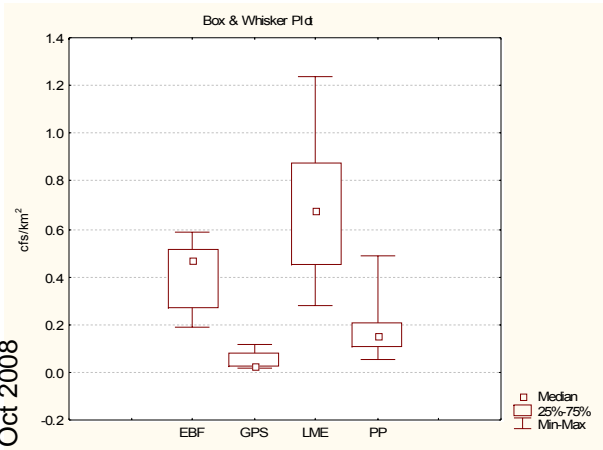
3D Scatterplot

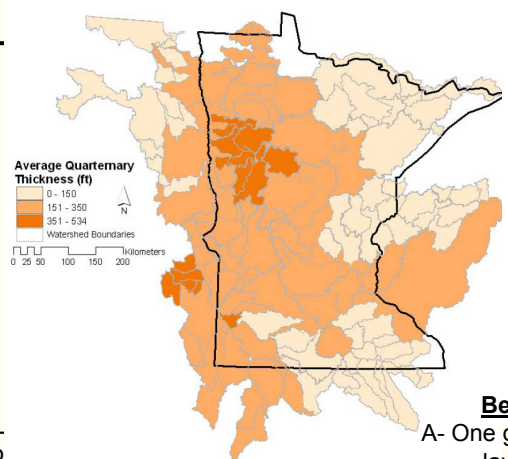
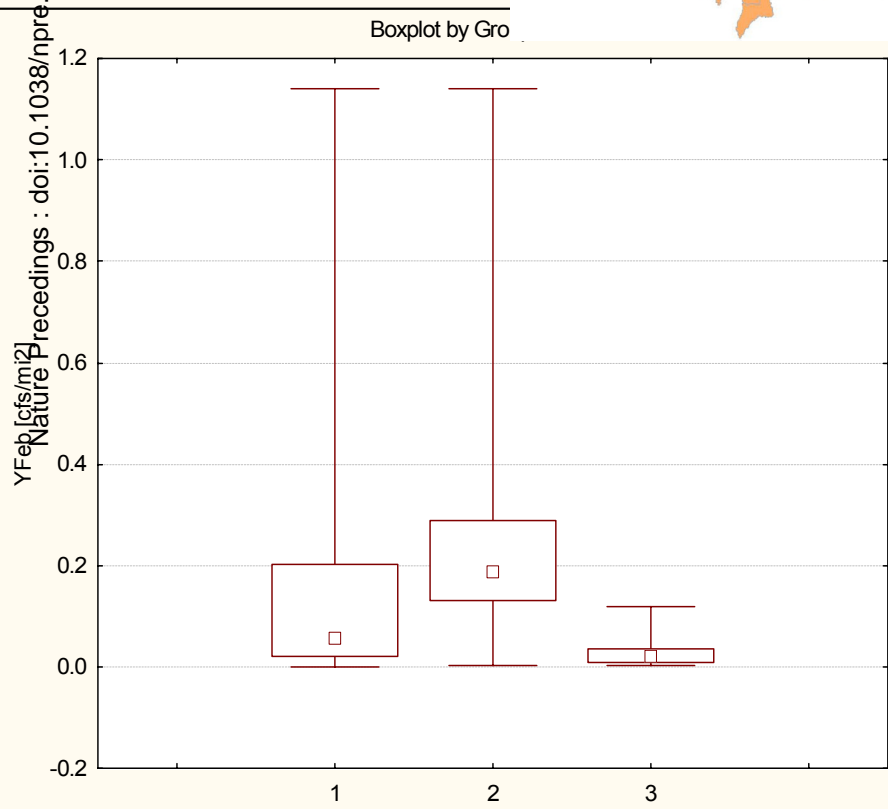
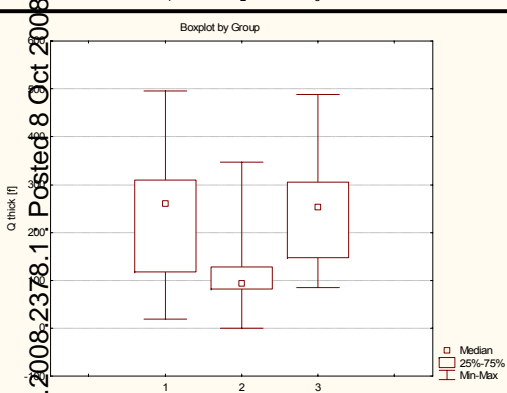
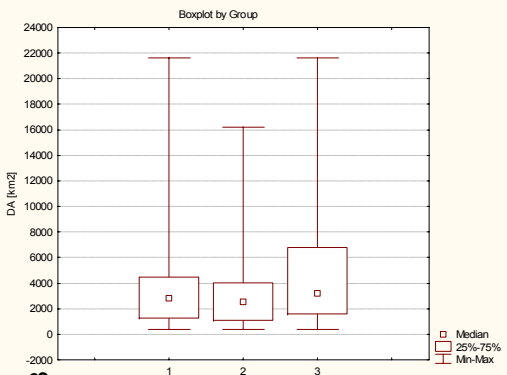
Codes from
Hydrogeological
regionalization



Mean annual streamflow (1955-1979) for Ecoregions

Numbers show:
average yield [cfs/mi²]/
(quartile lower- quartile upper)



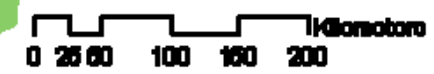
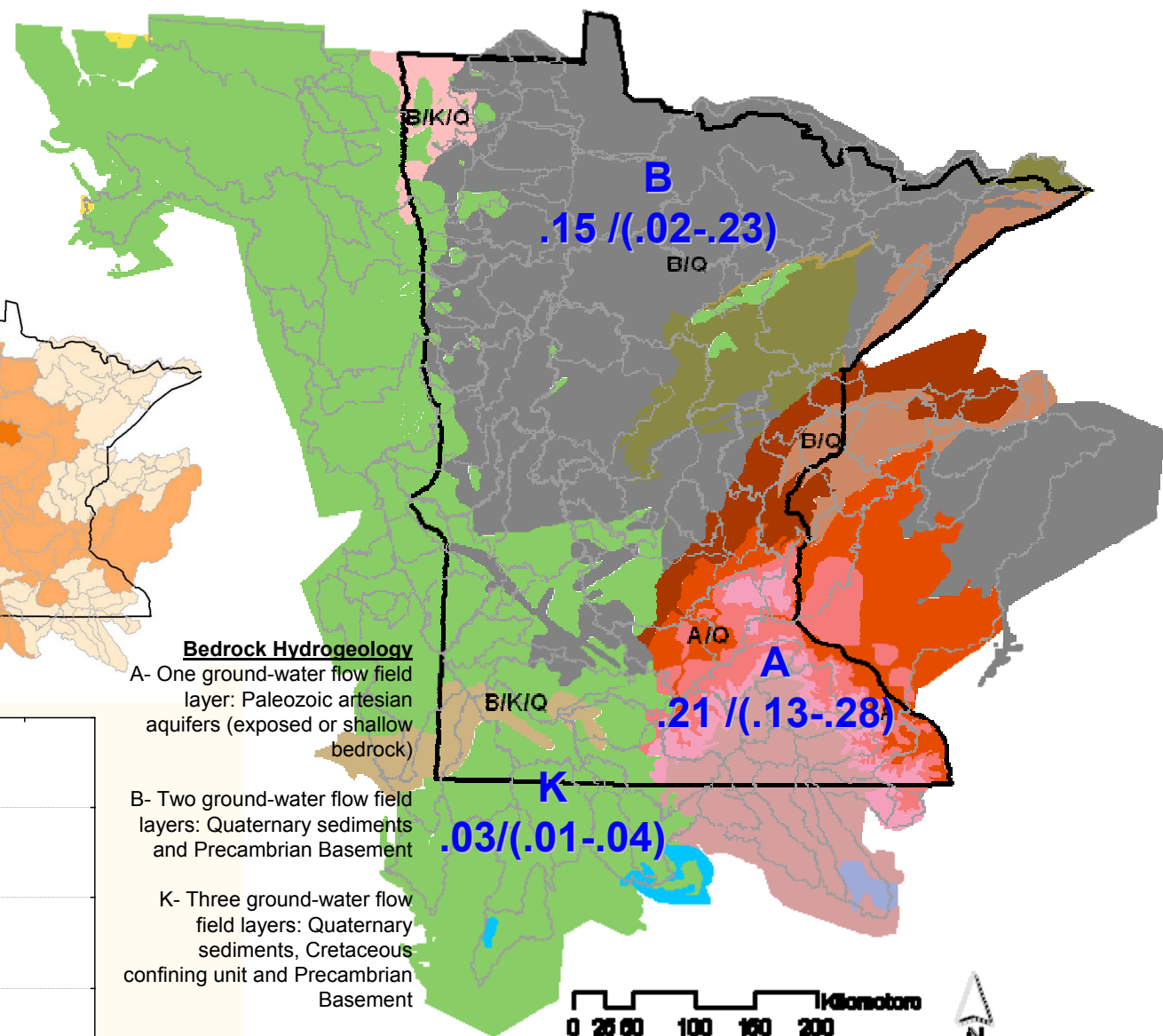


Bedrock Hydrogeology

A- One ground-water flow field layer: Paleozoic artesian aquifers (exposed or shallow bedrock)

B- Two ground-water flow field layers: Quaternary sediments and Precambrian Basement

K- Three ground-water flow field layers: Quaternary sediments, Cretaceous confining unit and Precambrian Basement



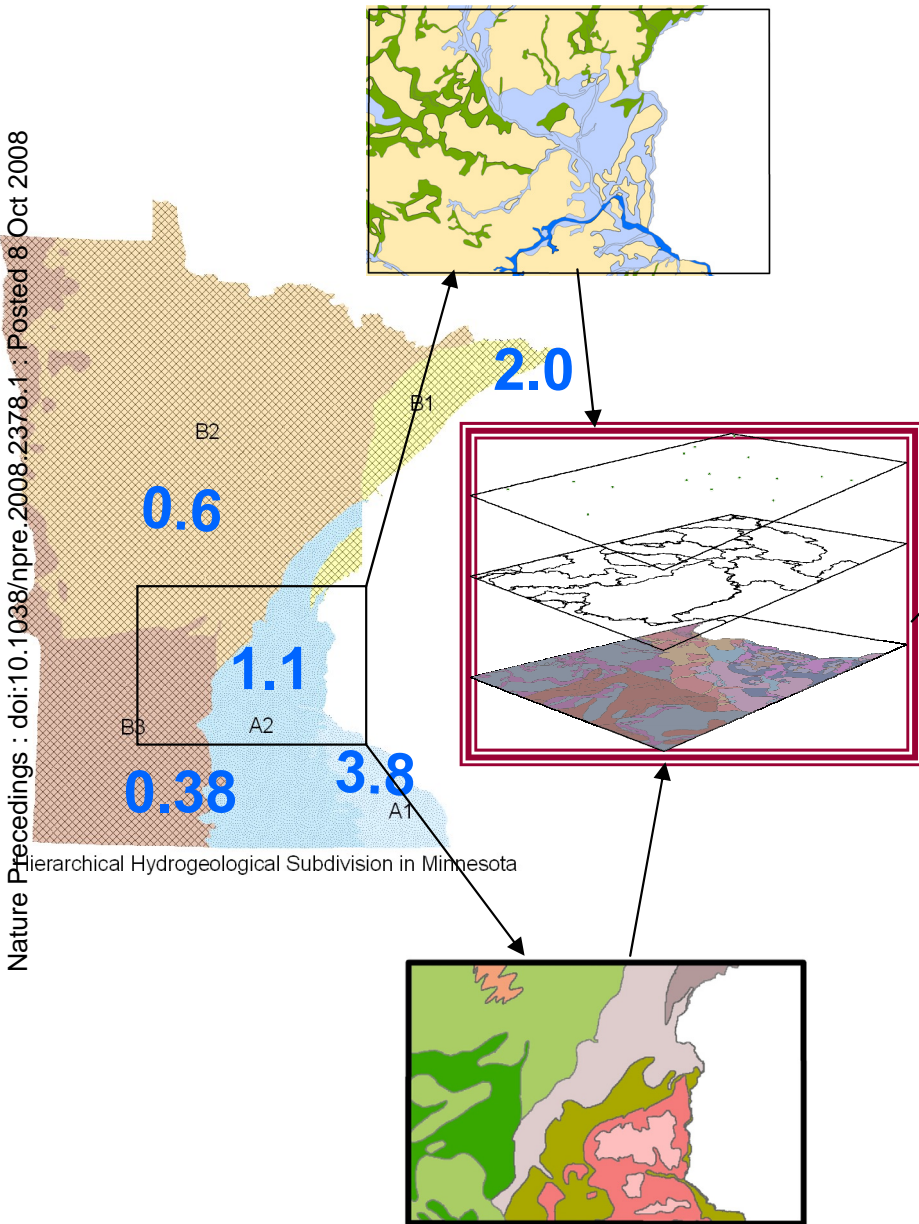
Mean February streamflow (1955-1979) for HG regions

Numbers show: mean yield [cfs/mi²] / (quartile lower- quartile upper)

YFeb [cfs/mi²] Nature Precedings : doi:10.1038/npre.2008.2378.1 Posted 8 Oct 2008

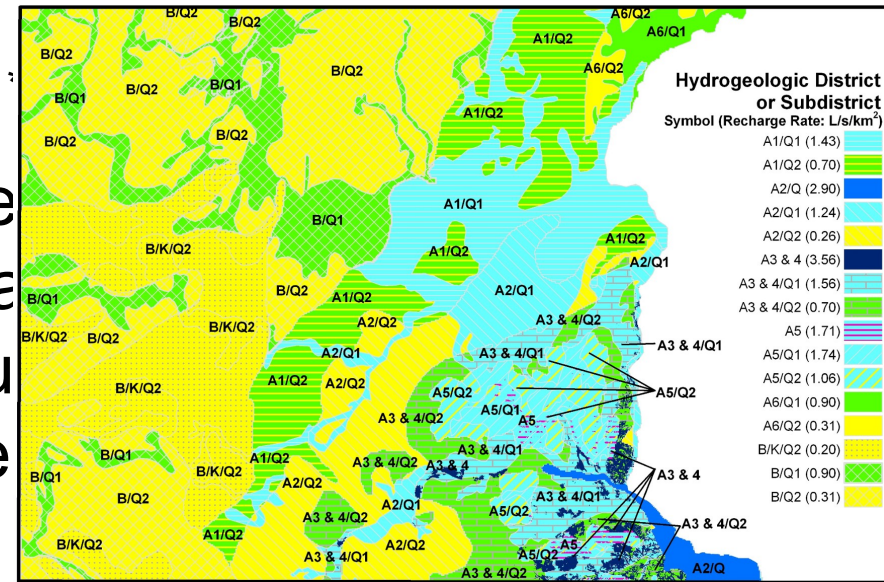
Two maps with GW recharge in MN

Nature Precedings : doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008



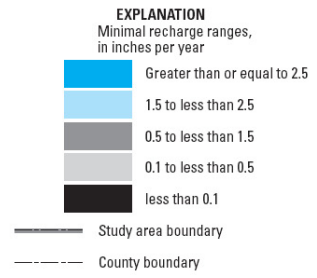
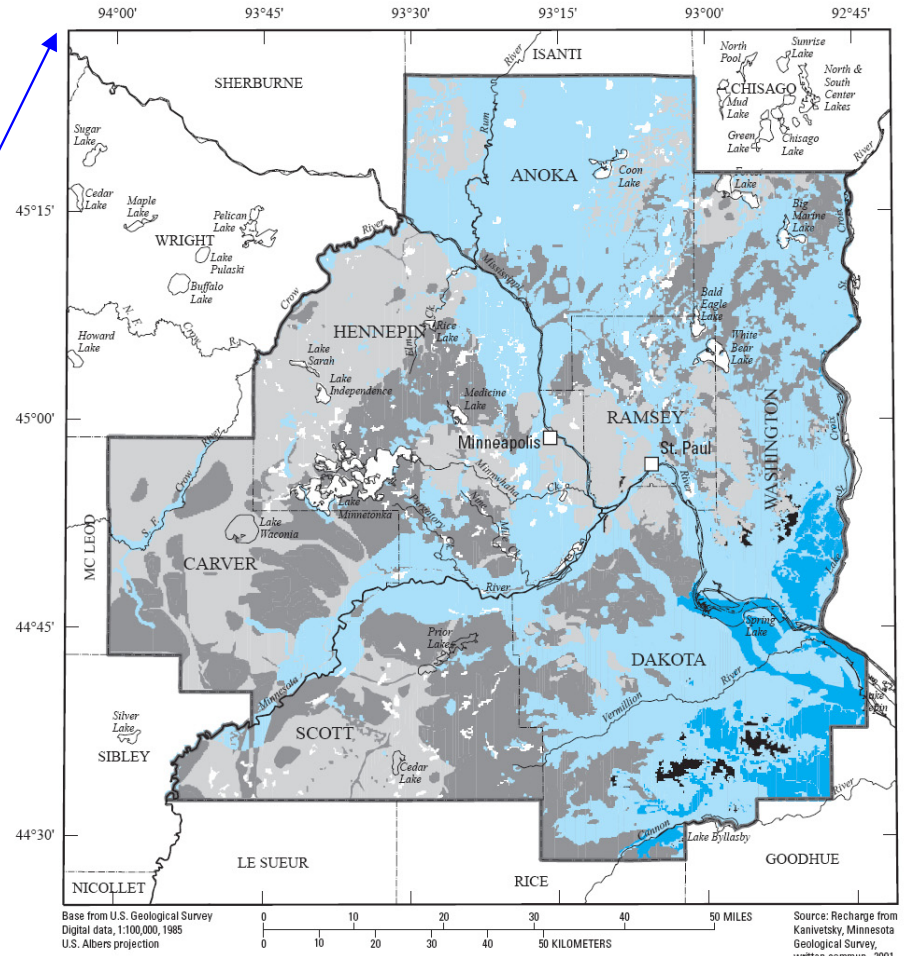
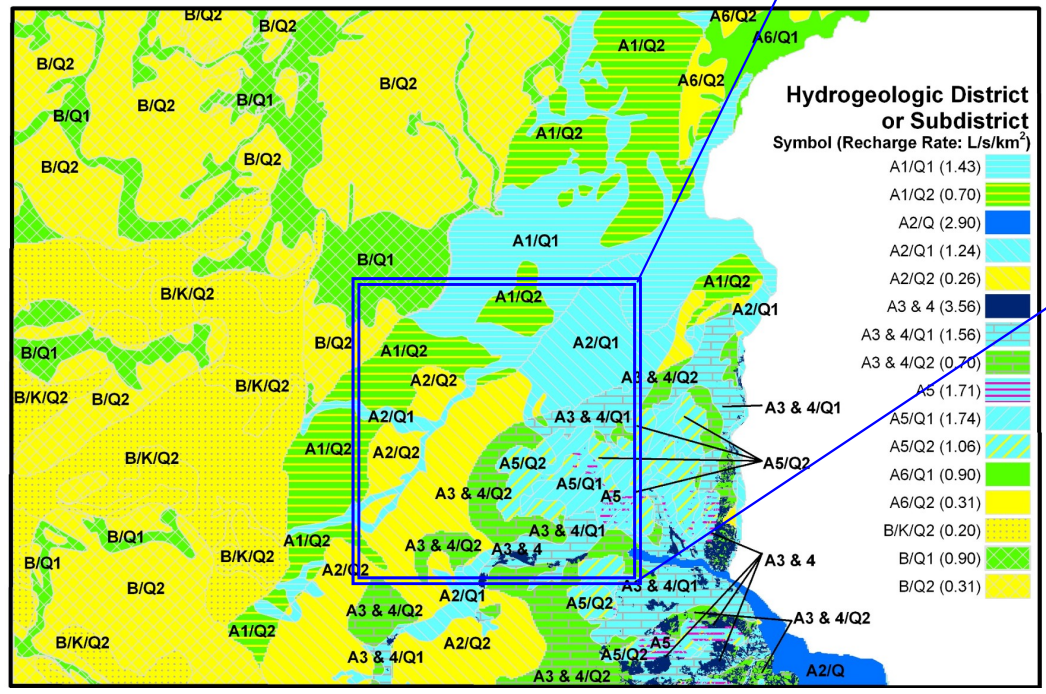
Initial matrix:

$Q_{(101)}$
there
of wa
annu
code



Minimal ground-water recharge based on statistical analyses of watershed characteristics for Eastern Central Minnesota

Two maps with GW recharge



Minimal ground-water recharge based on statistical analyses of watershed characteristics in the TC metropolitan study area, MN

Maps & regime - units & boundaries

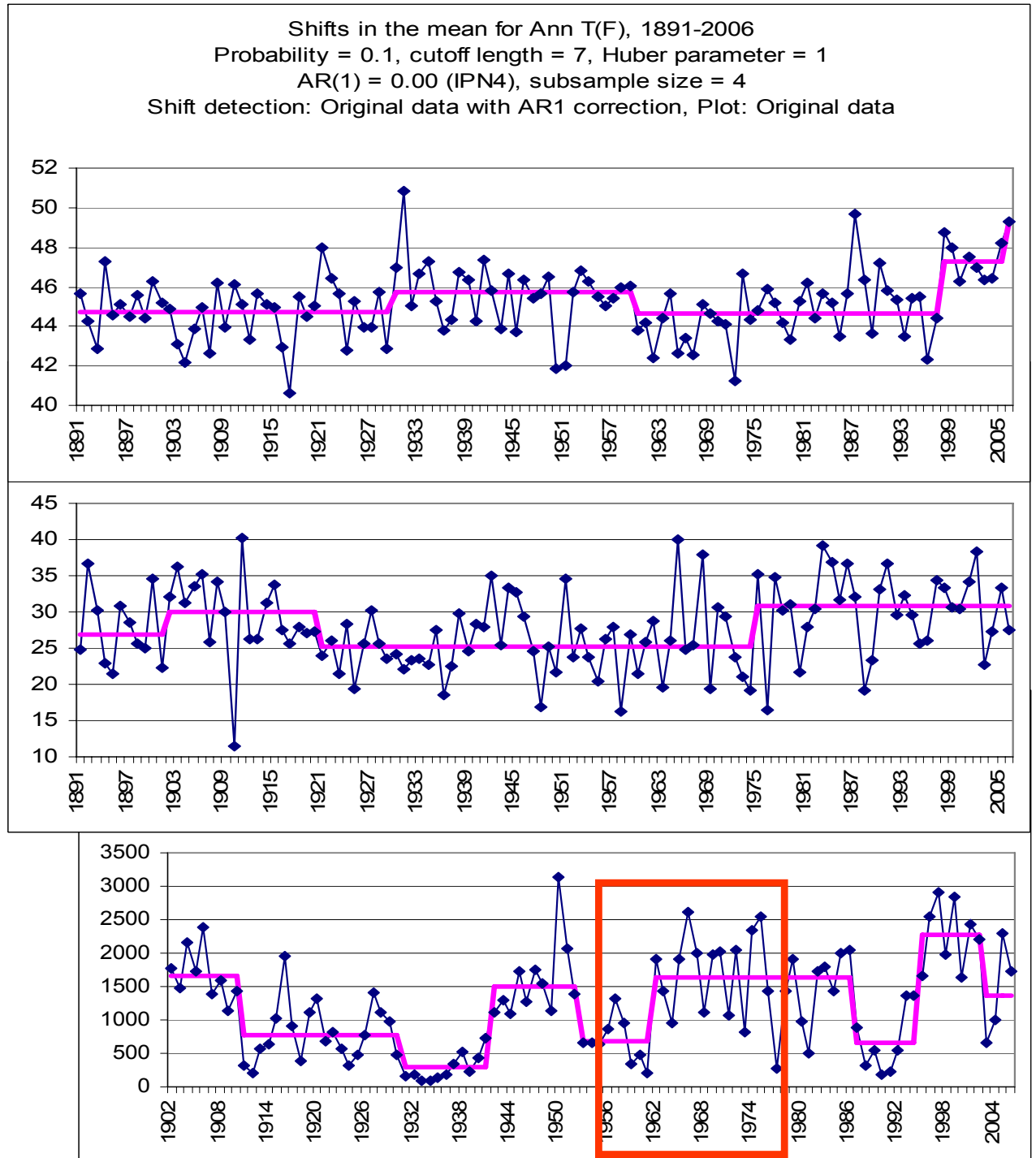
- Groups of watersheds recognized by mutual landscape properties with statistical proven influence on hydrologic characteristics provide base for regionalization
- The units on a map reflect regionalization with average hydrologic characteristics for those kind of groups or its range
- The values of characteristics on the map reflect the interval of observation (presented case 1955-1979) & have to be placed in long time perspective

Regime for long time interval

Air temperature
(Minneapolis)

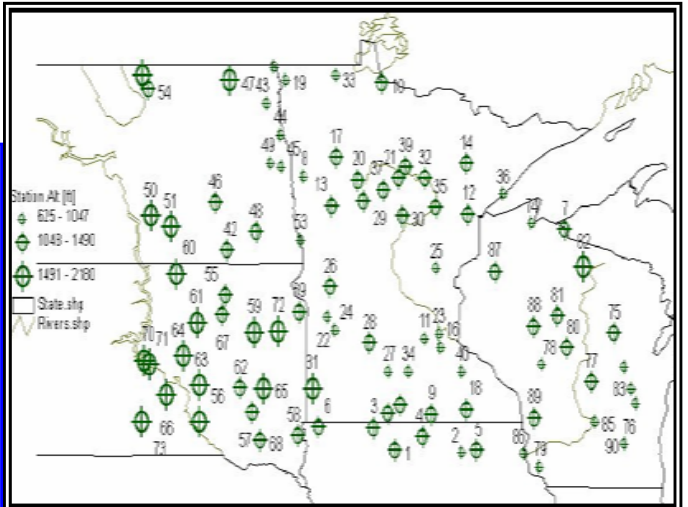
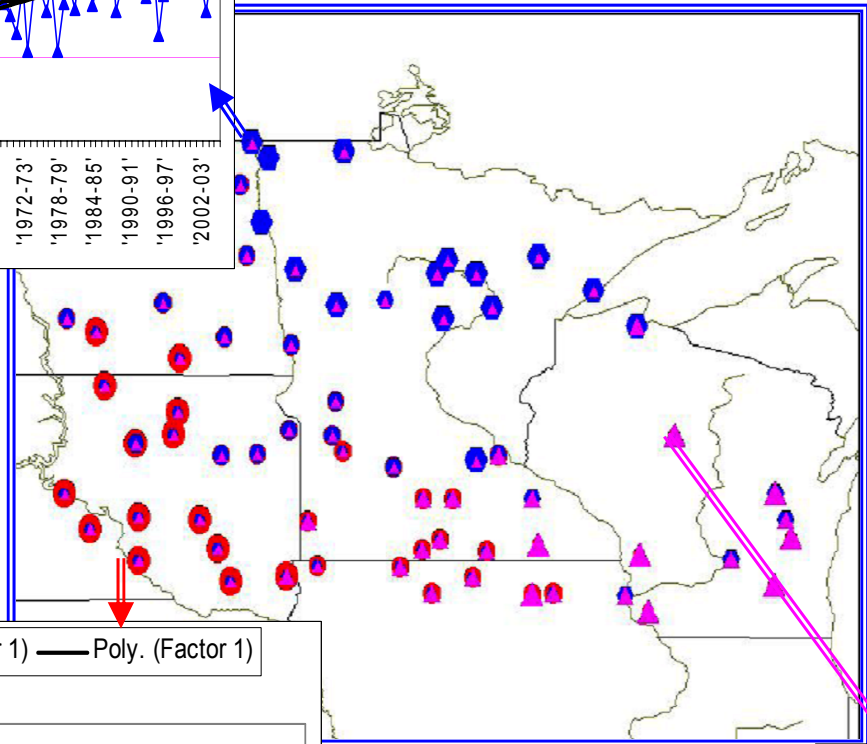
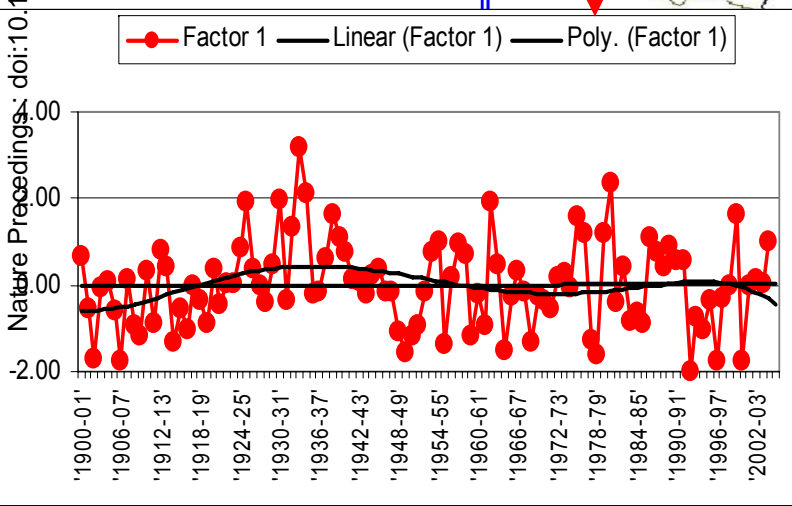
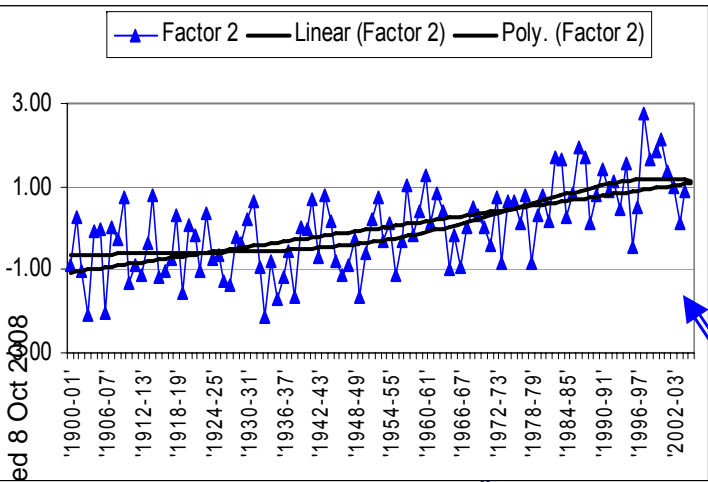
Precipitation
(Minneapolis)

Streamflow
(Red Lake River)

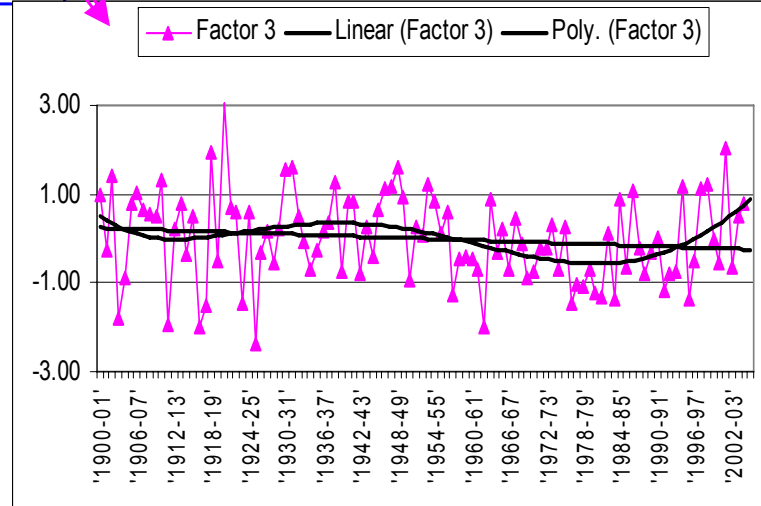


doi:10.1038/npre.2008.2378.1 : Posted 8 Oct 2008

Nature Precedings

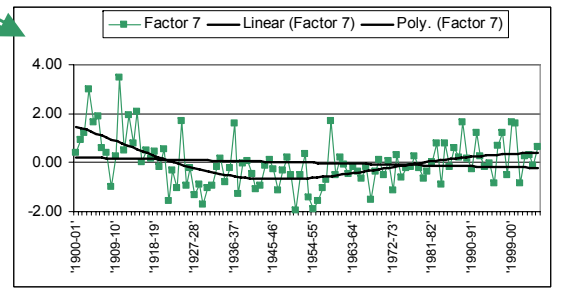
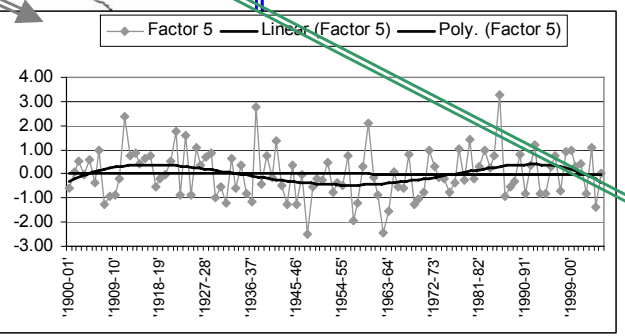
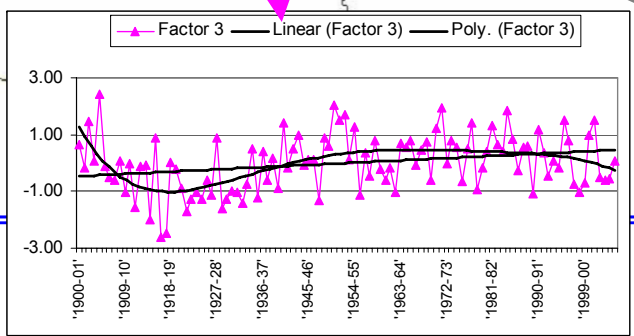
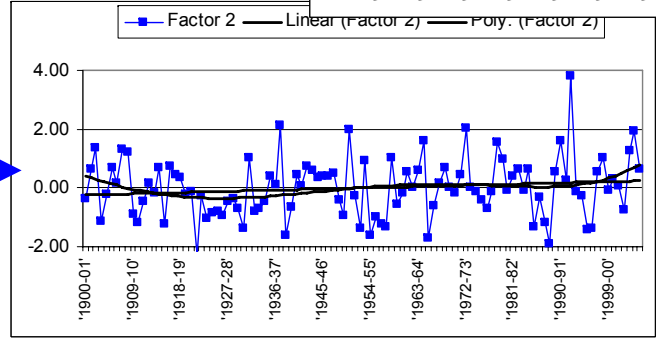
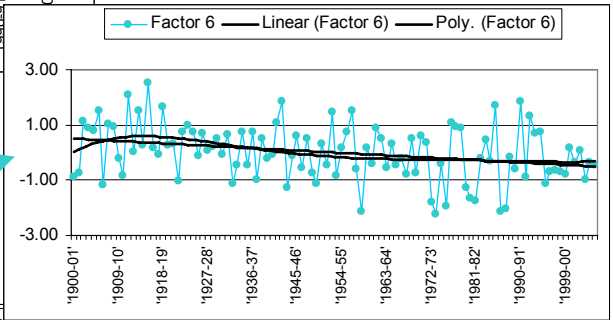
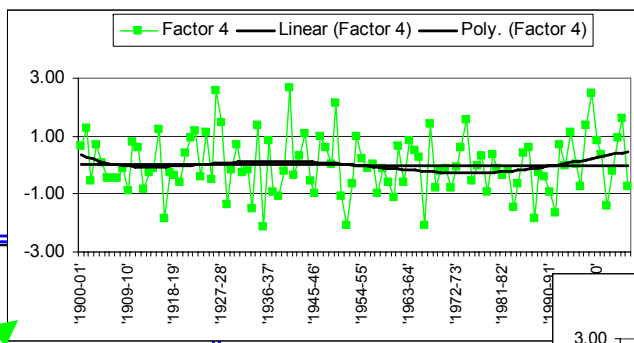
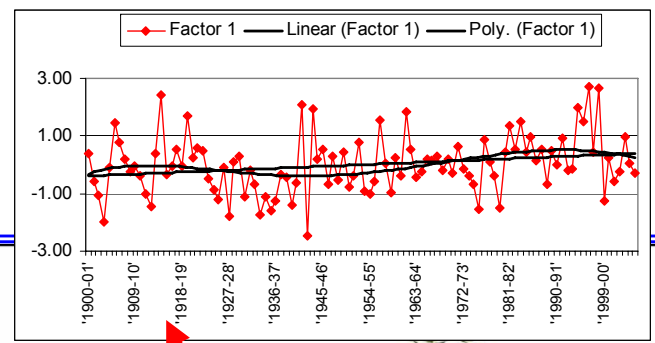


Spatial temporal structure of annual air temperature regime in MN for 1900-01 – 2004-05 hydrologic years (70 meteorological stations). The arrows point from the stations with highest Factor Loading to the corresponding chart of Factor Scores



Air temperature

Spatial temporal structure of annual precipitations regime in MN for 1930-31 – 1984-85 hydrologic years (87 meteo stations)

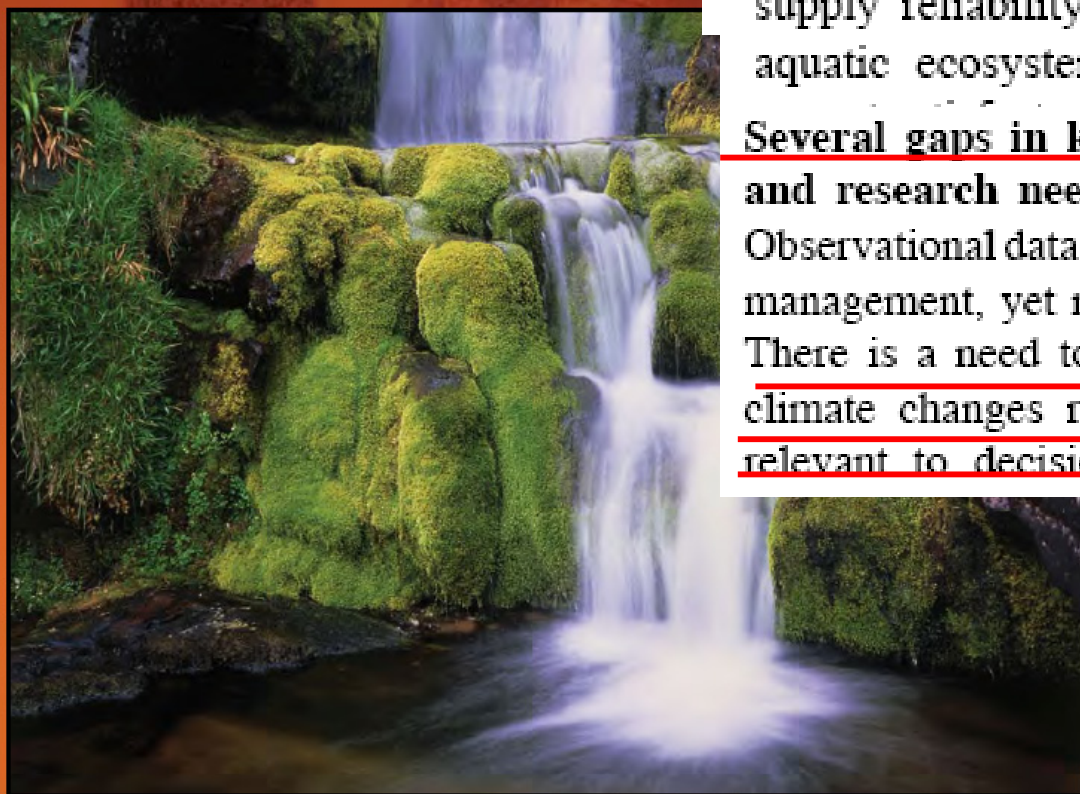


- Factor 7
 - -0.43 - 0.25
 - 0.25 - 0.5
 - 0.5 - 0.68
- Factor 6
 - 0.25 - 0.5
 - 0.5 - 0.66
- Factor 5
 - 0.25 - 0.5
 - 0.5 - 0.7
- Factor 4
 - 0.25 - 0.5
 - 0.5 - 0.7
 - 0.7 - 0.82
- Factor 3
 - ▲ 0.25 - 0.5
 - ▲ 0.5 - 0.7
 - ▲ 0.7 - 0.83
- Factor 2
 - 0.25 - 0.5
 - 0.5 - 0.7
 - 0.7 - 0.86
- Factor 1
 - 0.25 - 0.5
 - 0.5 - 0.7
 - 0.7 - 0.86
- State.shp
- Rivers.shp

Precipitation

CLIMATE CHANGE AND WATER

IPCC Technical Pa



Observed warming over several decades has been linked to changes in the large-scale hydrological cycle such as: increasing atmospheric water vapour content; changing Current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability, flood risk, health, agriculture, energy and aquatic ecosystems. In many locations, water management Several gaps in knowledge exist in terms of observations and research needs related to climate change and water. Observational data and data access are prerequisites for adaptive management, yet many observational networks are shrinking. There is a need to improve understanding and modelling of climate changes related to the hydrological cycle at scales relevant to decision making. Information about the water-

From
Reports'
conclusions



Intergovernmental Panel on Climate Change



For discussion

- Watershed as hydrological object has a time-spatial scaled structure of interaction (straight & feedback connections) with other components of landscape
- System model (cyber model) of landscape allows to formulate research tasks, develop methods of analysis, create databases, interpret results & present them as a map
- For results of analysis for MN number of factor's axis create seasonal characteristic space dimensions & distribution of watersheds in this space depends upon its hydrologic characteristics
- Map of water resources reflect structure of connection in landscape & statistical proven boundaries
- Atlas for region fully represents scaled diversity of hydrological time-spatial structure

Questions

Up to date information about the project can be found at:

https://wiki.umn.edu/twiki/bin/view/Water_Sustainability/WebHome

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