Introduction to Scaling in Hydrologic Systems

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ABE 325
http://cobweb.ecn.purdue.edu/~mohtar/ASABE08workshop.htm
Learning Objectives

Successful completion of this Lecture will allow you to:

• Understand the concept and limitation of scaling;
• Analyze the effect of spatial and temporal variability;
• Identify the scaling issues in hydrology and their impact on hydrologic response;
• Demonstrate soil structure and its implication on soil behavior and soil water interaction;
• Understand the hierarchal nested structure of the soil water medium and the concept of pedostructure;
• Distinguish between micro and macro pores and preferential flows and the various scales in the soil water medium;
• Identify major soil characteristic functions (Shrinkage curve, Swelling curve and water potential curve).

This Presentation can be accessed from:
http://cobweb.ecn.purdue.edu/~mohtar/ASABE08workshop.htm

Multiscale Module: Mohtar et al., Purdue University
Spatial and Temporal Scales in Natural Systems

- Large hydrologic Basin
- Small watersheds
- Plot
- Pedostructure REV
- Nano chemical/physical processes

Multiscale Module: Mohtar et al., Purdue University
Questions

• Give examples of short time scale
• … and of long time scale

• Scaling is to multiply the current dimensions by a factor (space/time). Is this true and why?
Models and Scales

• The transfer of information across scales is called **scaling** and the problems associated with it are called **scale issues**.

• Processes are often observed and modeled at short-time scales, but estimates are needed for very long time-scales. Ex. Rainfall events

• Sometimes large-scale models and data are used for small-scale predictions. Ex. Watershed model (CN) is used to predict local processes (infiltration). What are the downside of this?

• The issue of the linkage and integration of formulations at different scales has not been addressed adequately.
Process Versus Observation Scale

Unfortunately, more often than not, the modeling scale is much larger or much smaller than the observation scale. To bridge that gap, ‘scaling’ is needed. 

*To scale*, literally means ‘to zoom’; *upscaling* refers to transferring information from a given scale to a larger scale, Ex. Rainfall excess predicting runoff, whereas *downscaling* refers to transferring information to a smaller scale, Ex. CN used for infiltration prediction. *Regionalization*, on the other hand, involves the transfer of information from one catchment (location) to another. One of the factors that make scaling so difficult is the heterogeneity of catchments and the variability of hydrological processes.

Multiscale Module: Mohtar et al., Purdue University
What scale should we work on?

The type of problem, its sensitivity, and its spatial zone of impact may dictate the time scale to be analyzed in the solution.

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**Source:** Bloschl & Sivapalan, 1995

Multiscale Module: Mohter et al., Purdue University
Moving across scales: maintaining physics!

The concept of transfer of information from small space/time-scales to large space/time-scale with all the variability involved must be well understood.

Source: Bloschl & Sivapalan, 1995

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Moving across scales: maintaining physics!

The concept of *transfer of information* from small space/time-scales to large space/time-scale with all the *variability* involved must be well understood.

| Table 1. Space and Time Scales for Water Properties and Processes in Irrigation Hydrology |
|------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Time**                                 | **Microscale**                  | **Macroscale**                  | **Megascale**                   |
|                                          | \(10^{-5} - 10^{-2}\) m         | \(10^{-2} - 1\) m               | \(1 - 10^4\) m                 |
| Seconds                                  | Water properties                | Porous media flow               | Infiltration                    |
|                                          | Pore-water processes            | Pipe flow                       | Transpiration                   |
|                                          | Geochemical processes           |                                | Precipitation                   |
| **Hour/day**                             | Time average                    |                                 | Surface flow                    |
| **Years**                                |                                 |                                 | Drainage                        |
| **Centuries**                            |                                 |                                 |                                 |
| **Millennia**                            |                                 | Space average                   |                                 |

*Source:* Irrigation Hydrology: Crossing Scales

Wesley W. Wallender\(^1\) and Mark E. Grismer\(^2\)

Multiscale Module: Mohtar et al., Purdue University
Primary soil mapping unit

Pedon

Geomorphological unit

Soil Structure Hierarchy Scaling

CHALLENGE: crossing scales

Pedostructure, primary peds, primary particles, are functionally defined and quantitatively determined using the shrinkage and potential curve measurement.

Horizon = Vertical porosity (cracks, fissures) + Pedostructure

Pedostructure = Interpedal porosity (macro-porosity) + Primary peds and free mineral grains

Primary ped = Clay plasma porosity (micro-porosity) + Primary particles and pedological features

Soil is no longer looked at as a bundle of 1D tubes

Multiscale Module: Mohtar et al., Purdue University
Moving across scales: different views!

Dominant Processes Include:
Infiltration and micro-macro water exchange.

Multiscale Module: Mohtar et al., Purdue University
Moving across scales: different views!

In the *microscopic scale*, particle and aggregate shapes are considered and flow patterns are analyzed within individual pores.

Multiscale Module: Mohtar et al., Purdue University
In the **macroscopic scale**, “each macroscopic differential element must contain a sufficient number of pores that its pertinent properties … can be suitable described by statistical average of many pores”.

*Source: Miller and Miller, Physical theory for capillary flow phenomena, Journal of applied physics, 1956*

**Multiscale Module: Mohtar et al., Purdue University**
Moving across scales: different views!

Higher Variability


Multiscale Module: Mohtar et al., Purdue University
Example: Effect of average response on water and chemical transport

Dry Soil Layer

Dominant Processes:
Darcian Fluxes vs. Preferential Flow Effect

Ground water table

Multiscale Module: Mohter et al., Purdue University
Example: Effect of average response on water and chemical transport

Darcian Fluxes vs. Preferential Flow Effect

Dominant Processes:
Multiscale Module: Mohtar et al., Purdue University
Example: Effect of average response on water and chemical transport

Water Infiltration following a rain event

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Multiscale Module: Mohtar et al., Purdue University
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Multiscale Module: Mohtad et al., Purdue University
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Multiscale Module: Mohtar et al., Purdue University
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Water infiltration following a rain event

Dominant Processes: Darcian Fluxes vs. Preferential Flow Effect

Multiscale Module: Mohtar et al., Purdue University
Heterogeneity and Scale

- Various scales include various levels of details in soil type
Watershed scale and Processes

Additional Processes include: Channeling and Routing

Multiscale Module: Mohtar et al., Purdue University
Watershed scale and Processes

Multiscale Module: Mohtar et al., Purdue University
Temporal Variability

Temp variation: Daily averages vs hourly
Moving across scales: Temporal Variability

Average Monthly Rainfall

Average Rainfall (mm)

Month

January
February
March
April
May
June
July
August
September
October
November
December

Pretipitation (mm)

Four Hour Maximum Rain Event

Precipitation (mm)

Time (Minutes)


Multiscale Module: Mohtar et al., Purdue University
Channel Routing Diagram

Upper Mississippi (LSA-NC) Routing Scheme

Source: AGRY399W

Multiscale Module: Mohtar et al., Purdue University
Hypothetical drainage basins and their effects on runoff hydrographs

Source: AGRY399W

Multiscale Module: Mohtar et al., Purdue University
Change in hydrograph shape with drainage area

Sleepers River near Danville, VT

From Dunne and Leopold (1978)

Source: AGRY399W

Multiscale Module: Mohtar et al., Purdue University
Let's Take A Journey Across Scales Starting With The Watershed...

Multiscale Module: Montar et al., Purdue University
Can we model all this at once?

How many soil types are there in this area? What different landuses it has? How uniform are rainfall and temperature profiles? Est....

Source: http://www.recycleworks.org/images/watershed_475.jpg

Multiscale Module: Mohtar et al., Purdue University
Soil Variability, Why an Issue?

Source: Arkansas Watershed Advisory Group

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Soil Variability, Why an Issue?

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Source: http://www.mnsoils cientist.org/pics/600_Glencoe.jpg
Source: http://www.chuckbrandt.com/mud.jpg
Source: http://www.hnri.co.uk/images/dryearth.jpg

Multiscale Module: Mohtar et al., Purdue University
Soil Variability, Why an Issue?

Soil Variability Takes many Forms:

Texture; Management, Drainage, Surface Condition, …

Multiscale Module: Mohtar et al., Purdue University

Source:
- http://ag.missouristate.edu/Ag_Web_Images/Buried_soil_horizons.JPG
- http://www.chuckbrandt.com/mud.jpg
- http://www.hnri.co.uk/images/dryearth.jpg
We Zoomed from Watershed Scale to Field Scale, then to Horizon Scale, Then What?

Horizon & Column Scale
Core Scale


Multiscale Module: Mohtar et al., Purdue University
We Zoomed from Watershed Scale to Field Scale, then to Horizon Scale, Then What?

Core Scale

Horizon & Column Scale


Aggregate Scale

Multiscale Module: Mohtar et al., Purdue University
We Zoomed from Watershed Scale to Field Scale, then to Horizon Scale, Then What?

See how much we can zoom down! Let’s now think why and when we need that.

Multiscale Module: Mohtar et al., Purdue University
Soil Structure and Functionality

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CHALLENGE: crossing scales

Multiscale Module: Mohtar et al., Purdue University
Soil-Water Interaction

This figure shows the soil-water interactions during drying and wetting cycles.

Microflow region

Macroflow region

Soil-Water Interaction

This figure shows the soil-water interactions during drying and wetting cycles.

Specific structural volume $V$ dm$^3$kg$^{-1}$

Water content $W$ kg kg$^{-1}$

Multiscale Module: Mohtar et al., Purdue University

Braudeau, Frangi and Mohtar (SSSAJ, 2004)
Micro-Macro pore Systems During Drying

Organizational levels:

Pedostructure
- Macro-porosity (Inter-peds porosity)

Primary peds
- Micro-porosity (clay plasma porosity)

Each pore system is characterized by its
- saturation state: empty, unsaturated, saturated
- swelling state: minimum, intermediate, maximum

Braudeau, Frangi, Mohtar (SSSAJ, 2004)

Multiscale Module: Mohtar et al., Purdue University
Material: soil clods withdrawn from B<sub>h</sub> horizons of an oxysol and fractioned through a 2 mm sieve.

1. Immersion (20 seconds)
2. Swelling measurement (20 hours)
3. Gravitational water removal (5 minutes)
4. Shrinkage and weight measurement (10 days)

Braudeau, Mohtar, Chahinian (WRR, 2004)

Multiscale Module: Mohtar et al., Purdue University
Shrinkage: Different Scales, Different Behaviors

Multiscale Module: Mohtari et al., Purdue University
Shrinkage: Different Scales, Different Behaviors

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Shrinkage: Different Scales, Different Behaviors

Field Scale

Core Scale

Aggregate & Particle Scale

Soil

Water

Multiscale Module: Mohtar et al., Purdue University
Shrinkage: Different Scales, Different Behaviors

Field Scale
Core Scale
Multiscale Module: Mohtat et al., Purdue University
Aggregate & Particle Scale
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Shrinkage: Different Scales, Different Behaviors

Field Scale

Core Scale

Soil

Water

Air

Aggregate & Particle Scale

Multiscale Module: Mohtari et al., Purdue University
Shrinkage: Different Scales, Different Behaviors

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Aggregate & Particle Scale
Shrinkage: Different Scales, Different Behaviors

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Aggregate & Particle Scale

Water

Air

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Multiscale Module: Mohtat et al., Purdue University
Shrinkage: Different Scales, Different Behaviors

Multiscale Module: Mohtar et al., Purdue University
Four Basic Measurable Soil-Water Properties Characterize the Pedostructure

Soil Swelling Curve: soil specific volume as a function of time, \( V(t) \)

Soil Shrinkage Curve: specific volume as a function of water content, \( V(W) \)

Unsaturated macropore Hydraulic Conductivity Curve, \( k_{ma}(W_{ma}) \)

Macropore and micropore Water Potential Curves, \( h_{ma}(W_{ma}) \) and \( h_{mi}(W_{mi}) \)

Multiscale Module: Mohtar et al., Purdue University
Field scale application to account for preferential flow, cracks and fissures

Schematic configuration of the soil horizon and a pedostructure showing the open cracks and fissures that opens to air as soil dries. $H$ and $H_D$ are the soil horizon depth at the desired moisture level and point D, respectively.

Multiscale Module: Mohtar et al., Purdue University
Representative Elementary Volume

Medium variables relationships:
\[ dV = K_{\text{in}} \, dw_{\text{in}} + K_{\text{out}} \, dw_{\text{out}} + w_p \]

\[ V_p = V_p_{\text{in}} + V_p_{\text{out}} \]

\[ W = W_{\text{in}} + W_{\text{out}} \]

\[ W_{\text{in}} = w_{\text{in}} + \max(w_{\text{in}}) \]

\[ W_{\text{out}} = w_{\text{out}} + w_p \]

\[ V = V_p + V \]

\[ V_p_{\text{in}} = (\max(w_{\text{in}}) + w_{\text{in}})/\rho \]

Macro-macro water transfer (a):

\[ q_{\text{ma}} = k_{\text{ma}} \frac{\partial h_{\text{ma}}}{\partial x, y, z} \]

Micro-micro water transfer (b):

\[ q_{\text{mi}} = k_{\text{mi}} \frac{\partial h_{\text{mi}}}{\partial x, y, z} \]

Micro-macro water exchange (c):

\[ \frac{dw_{\text{mi}}}{dt} = k_{\text{mi}} (h_{\text{mi}} - h_{\text{eq}}) = \frac{dw_{\text{ma}}}{dt} \]

Braudeau, Mohtar, Chahinian (WRR, 2004)

Multiscale Module: Mohtar et al., Purdue University
Conclusions

1. Scales in hydrology start from the particle scale into the core, column, field, and watershed.
2. Hydrologic processes are nested in a hierarchical structure where every scale has its own dominant processes.
3. What dominates hydrologic response at one scale may not be dominant at other scale.
4. A systematic hierarchical structure and crossing scales processes are essential to transfer information up and down the scale.
5. Soil (spatial), rainfall (spatial and temporal) variability have a significant impact on hydrologic responses.
6. Knowledge of scales and dominant processes is important to solve societal problems such as design dams, pollution, conservation and management infrastructures.