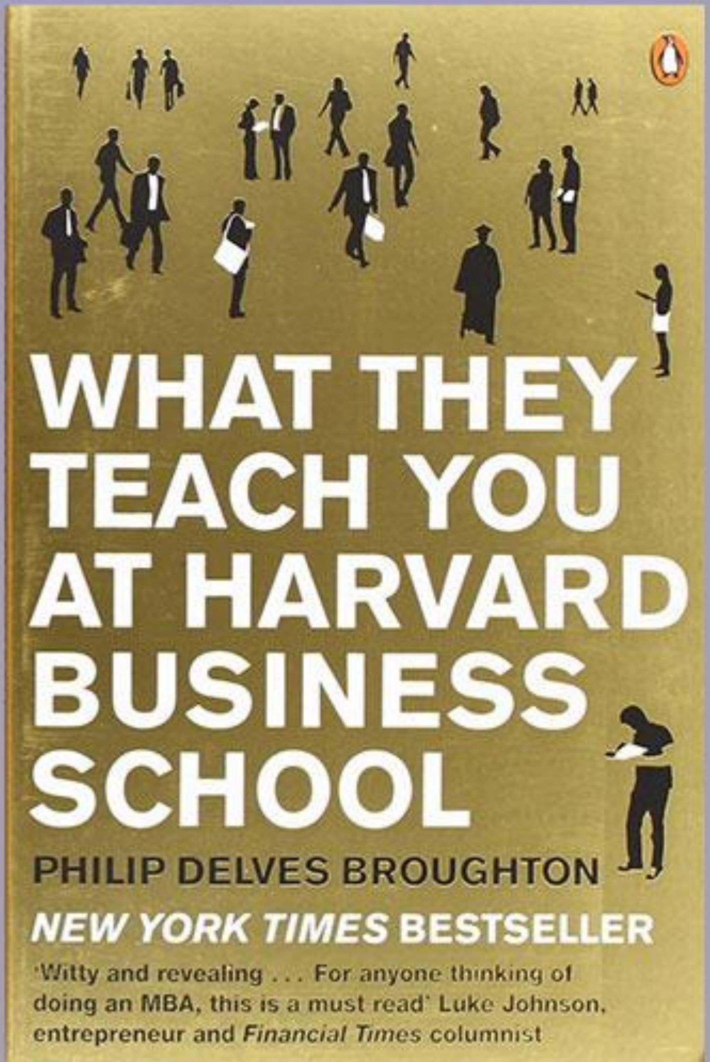
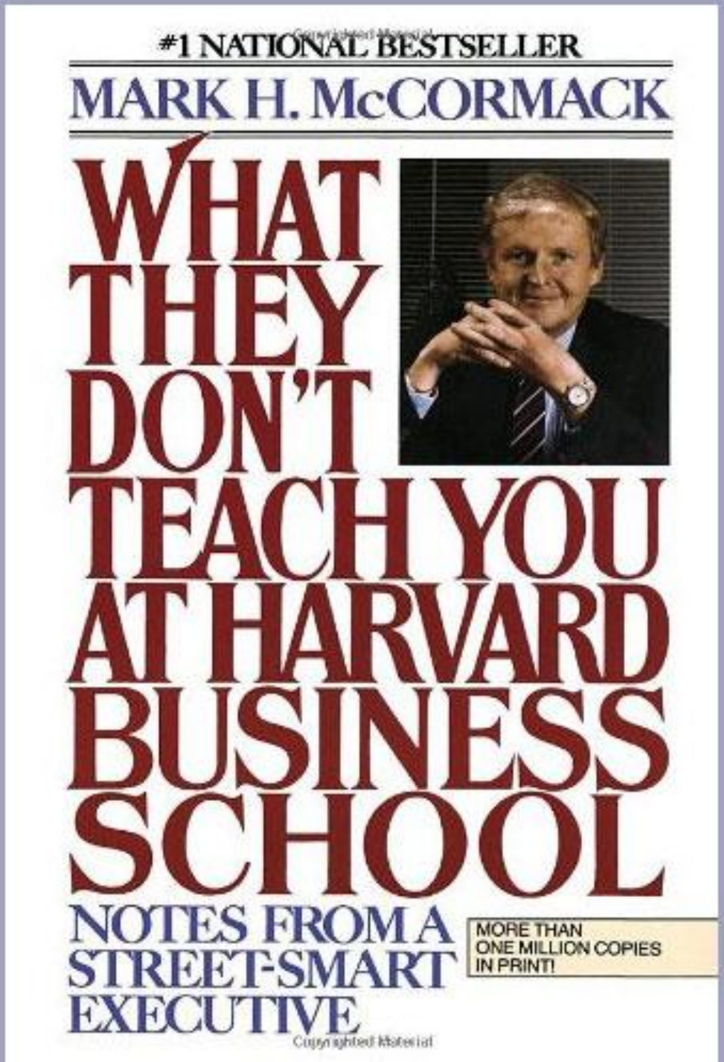
Integrated Modelling of Groundwater Interaction with Channels, Wetlands and Lakes in GSFLOW

Watertech 2013

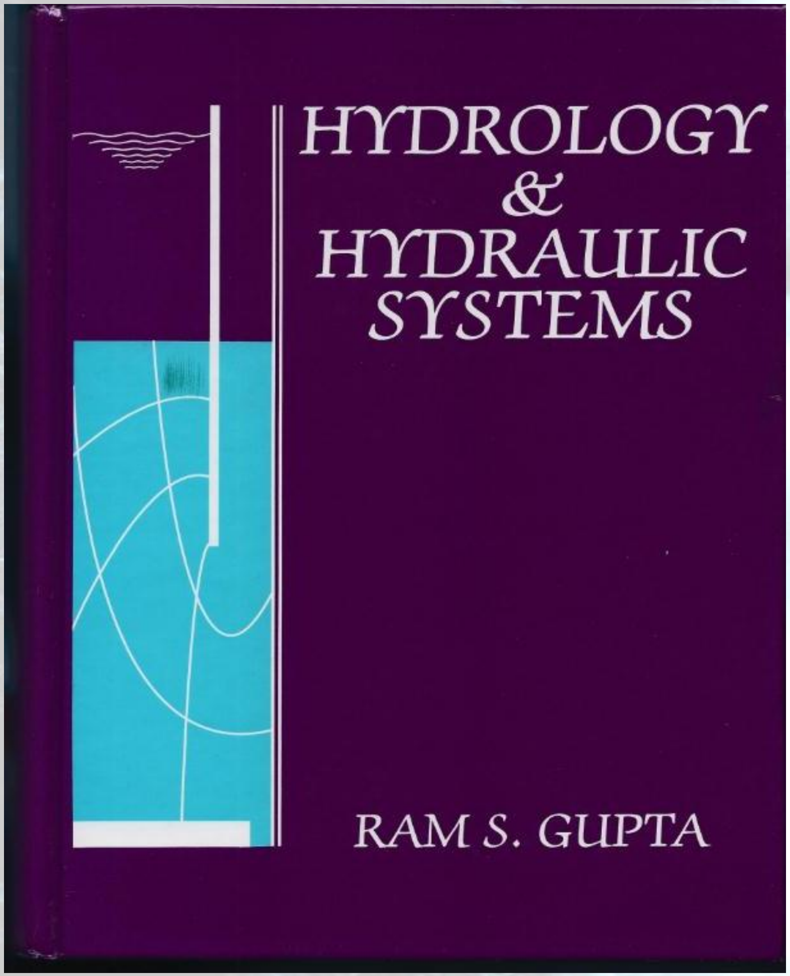
Dirk Kassenaar, E.J. Wexler,
P.J. Thompson, M.A. Marchildon
Earthfx Inc.

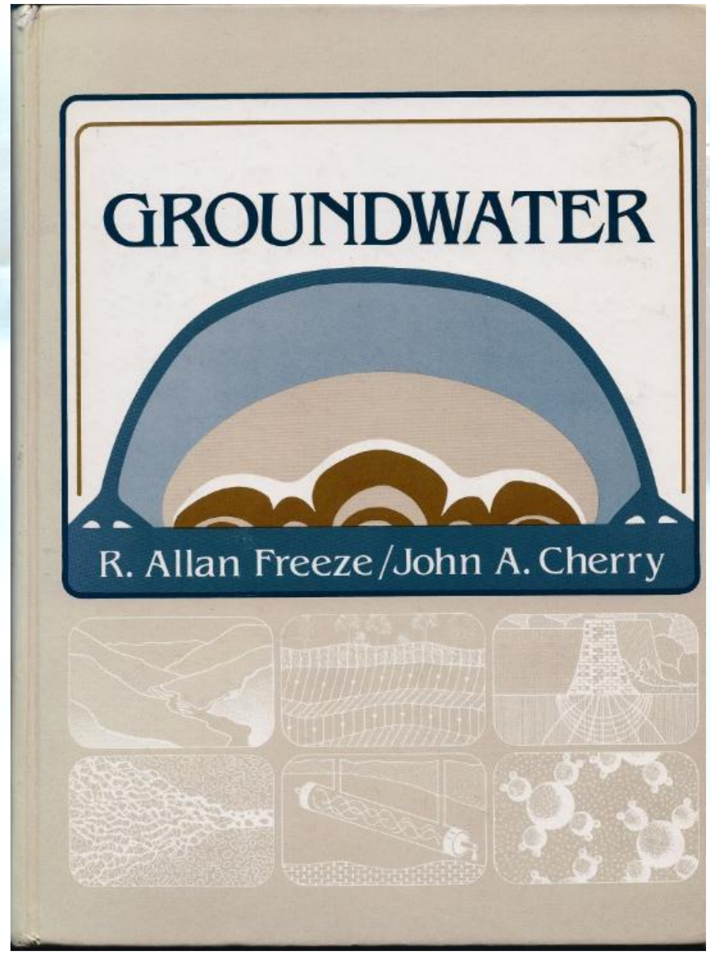
These two books contain the sum total of all human knowledge





Therefore, these two books should contain the sum total of all water systems knowledge





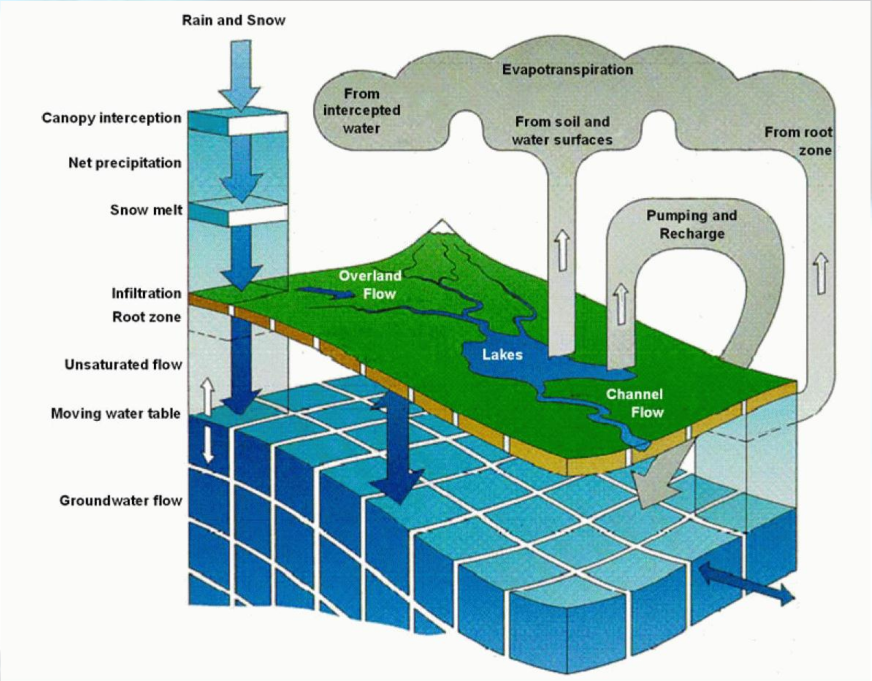
Earthfx Incorporated **SW** **/** **GW**

GW/SW or SW/GW Modelling?

- Is the order important?
- Does the water know or care where it is?
  - Bloods and Crips?
  - Romeo and Juliette?
  - Night and Day?
- When can the two systems be considered disconnected?
- Perhaps what happens in the "**/**" zone is quite important…

Current Conceptual Models of GW/SW Interaction

- Processes:
  - Vertical flow downwards through the unsaturated zone
    - Richard's Equation!
  - Vertical flow through streambed
    - Head dependent discharge
- Modelling:
  - "Loosely" coupled models
  - Fully integrated models

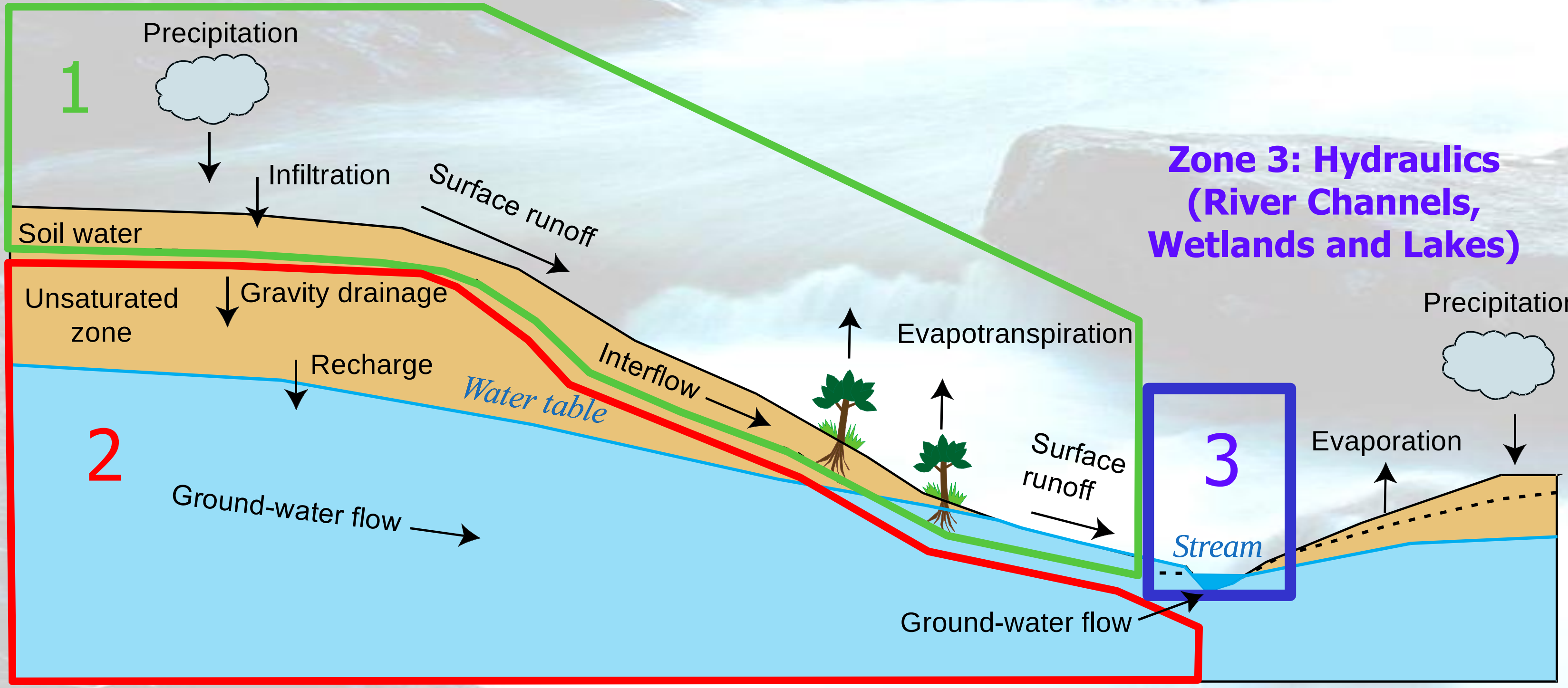


After DHI Software, 2007

SW/GW/SW Modelling

Zone 1: Hydrology (Vegetation, Snow and Soil)

Zone 3: Hydraulics (River Channels, Wetlands and Lakes)



Zone 2: Groundwater (Unsaturated and Saturated aquifer layers)

Note, however, that there are inputs and outputs from each zone

Zone of aeration

Zone of saturation

------ Soil-zone base

Earthfx Incorporated

Trouble: The "Old Water Paradox"

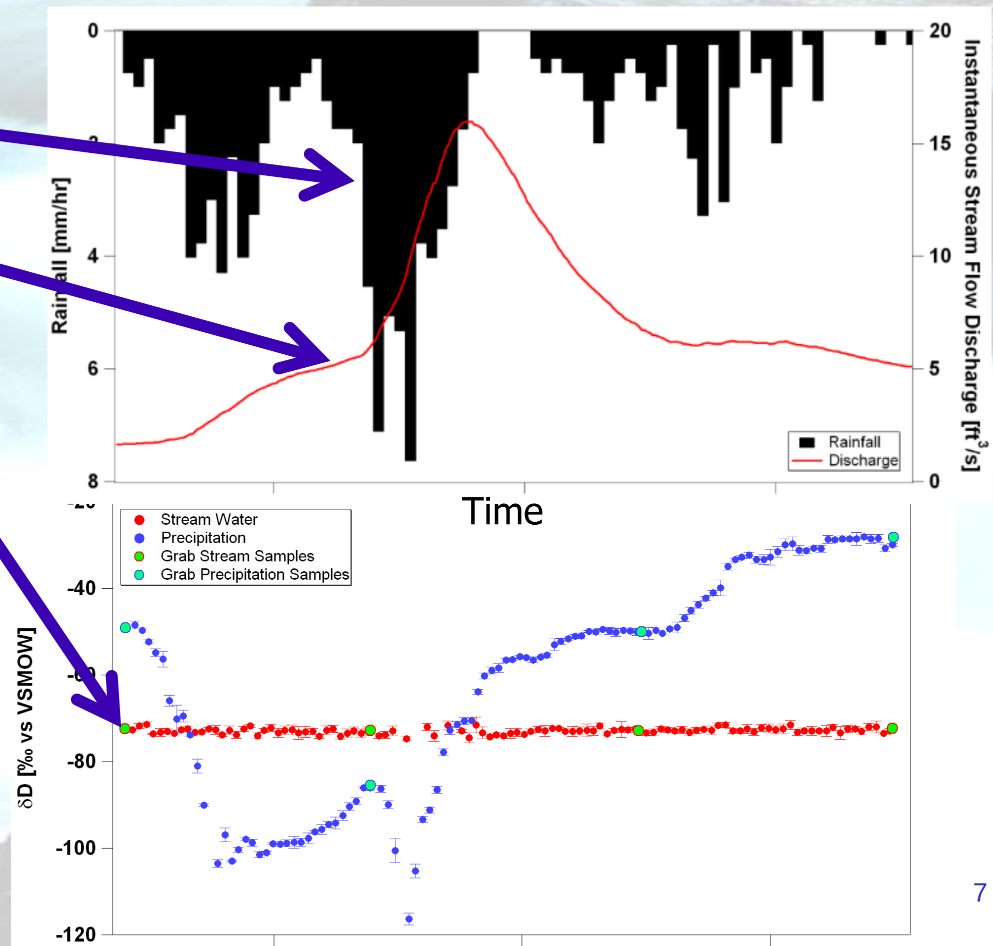
- Hydrologists are re-evaluating basic SW processes
  - **Jeff McDonnell, 2011 Birdsall-Dreiss Lecture**

Rainfall Event

Increase in Streamflow

Deuterium isotope profile shows that streamflow is predominantly "old" water (i.e. water that has been subject to ET processes)

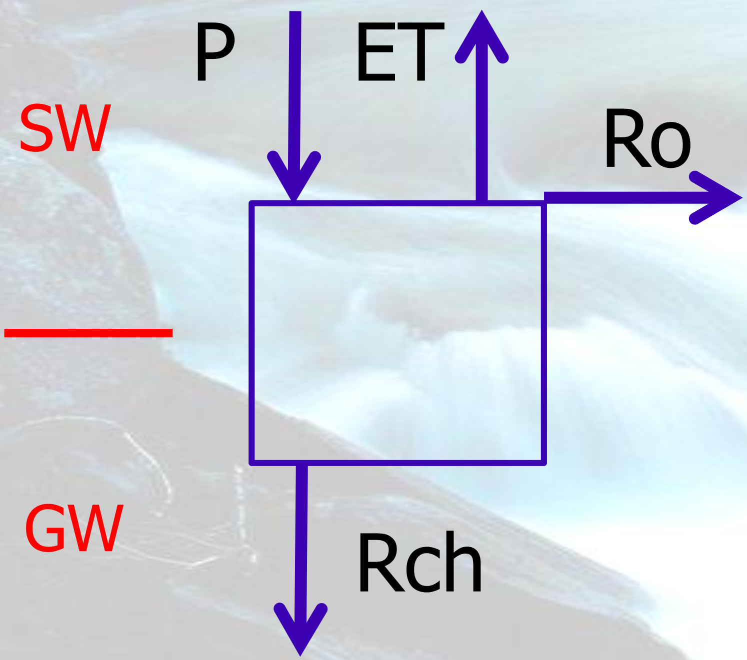
Conclusion: Storm event streamflow is primarily mobilized shallow groundwater!!!



Earthfx Incorporated

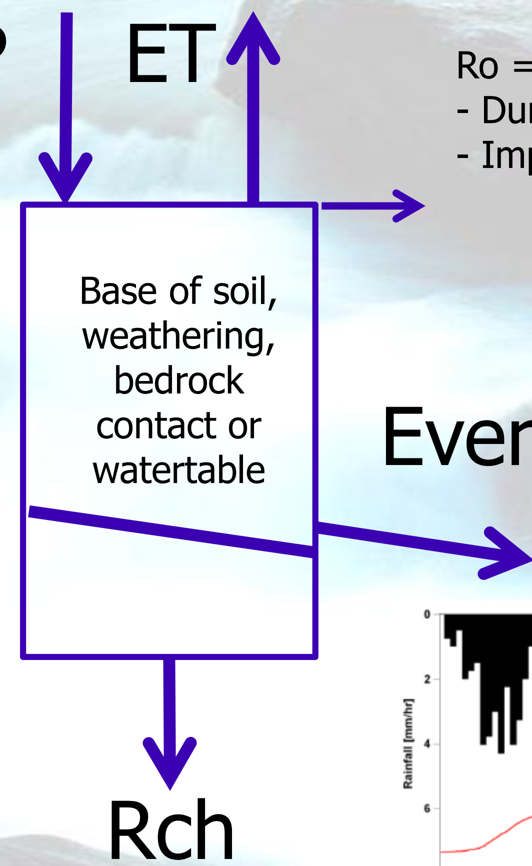
Revised Conceptual Model

Old Conceptual Model



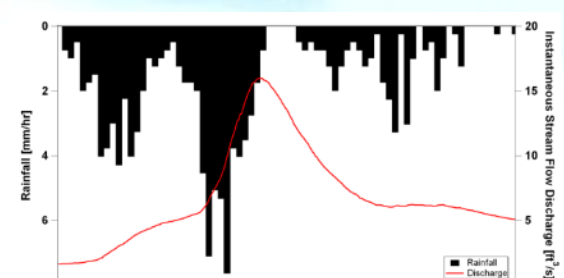
Clear separation of GW and SW

New Conceptual Model



Ro = Special cases:
- Dunnian processes
- Impervious/paved surfaces

Event Mobilized GW



Old Water Paradox: Implications

- Old concepts (and emphasis) on overland runoff should be discounted
  - Sheet flow is not the dominant precipitation event response process
  - The unsaturated zone is not dominated by 1D vertical ("Richards equation") type flow
    - Too simplistic a model in areas where there is GW/SW response
    - There is significant lateral flow in the unsat zone!
- **We need to re-think/re-conceptualize both recharge and the shallow zone flow system as a set of 3D processes**
  - The concept of **event mobilized groundwater** response is analogous to interflow, but the mobilized water is primarily "old" groundwater
  - Evidence suggests this is not even Darcy flow
- **If runoff is GW, then the distinction between SW and GW is blurred!**

Earth*fx* Incorporated

Old Water Paradox: What does this mean to hydrogeology/modelling?

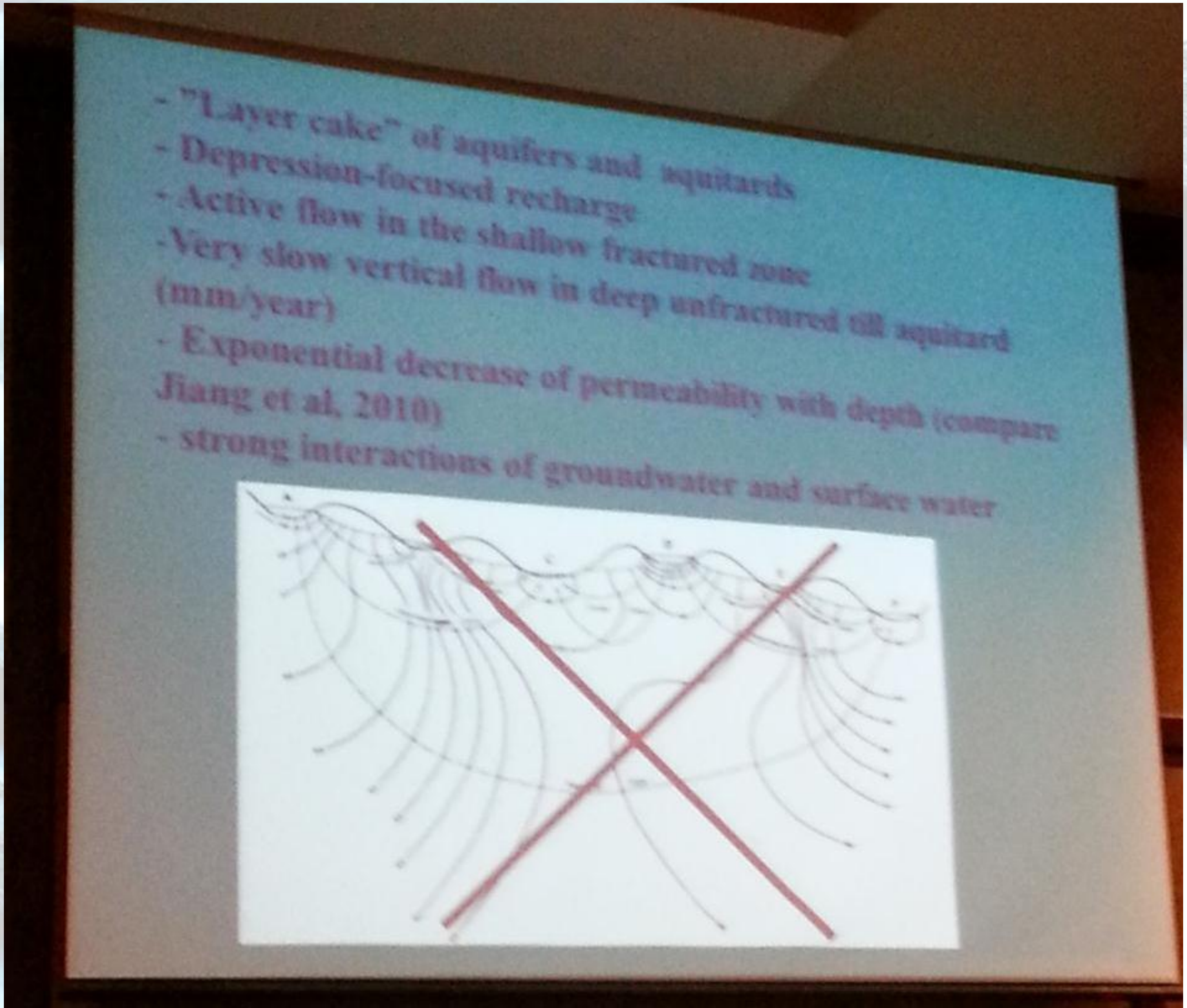
- The shallow groundwater system is responding much faster, and with greater volumes, than we might ever have thought
- We need to spend more time understanding and representing the soil/weathered zone and shallow geologic layers
  - Storage and mobilization of soil zone water and shallow groundwater need to be simulated if we are to truly understand both recharge and streamflow response
- Concepts of focused recharge (hummocky topography, potholes, etc.) and groundwater feedback (Dunnian processes and the contributing area concept) are broadly more important
- We already have 3D models – we need 3D recharge and fast GW

Earthfx Incorporated

What do the GW Scientists think?

- **Garth van der Kamp**, Research Scientist (Groundwater and surface water interactions), National Hydrology Research Centre, Saskatoon, SK
- Slide from Garth's IAH 2012 World Congress Keynote Presentation:

- Conceptual flownet models are wrong
- Much more active flow in the shallow zone
- **Garth agrees with Jeff McDonnell's event mobilized groundwater theory**



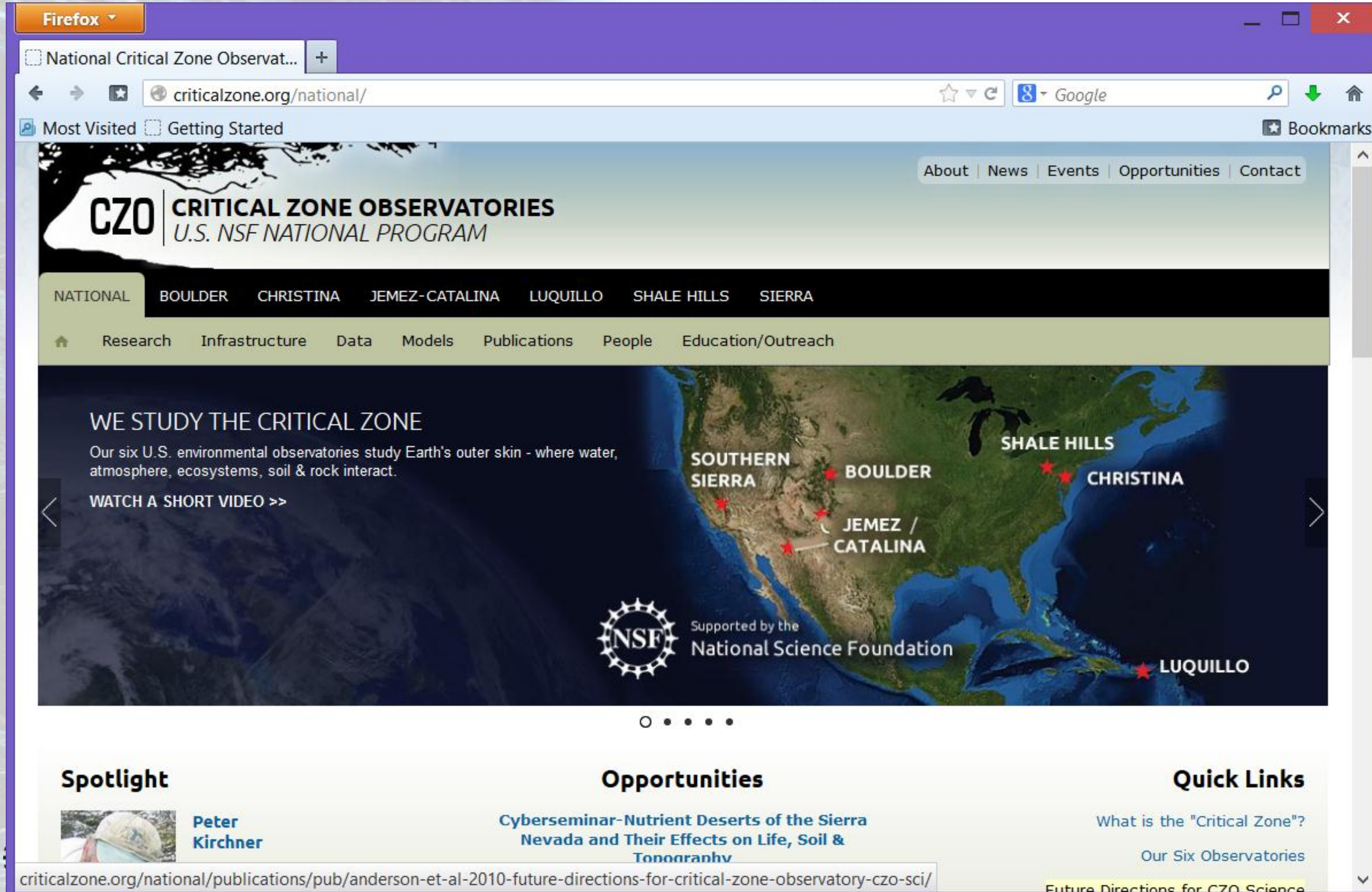
Earthfx Incorporated

NSF "Critical Zone" Conceptual Approach

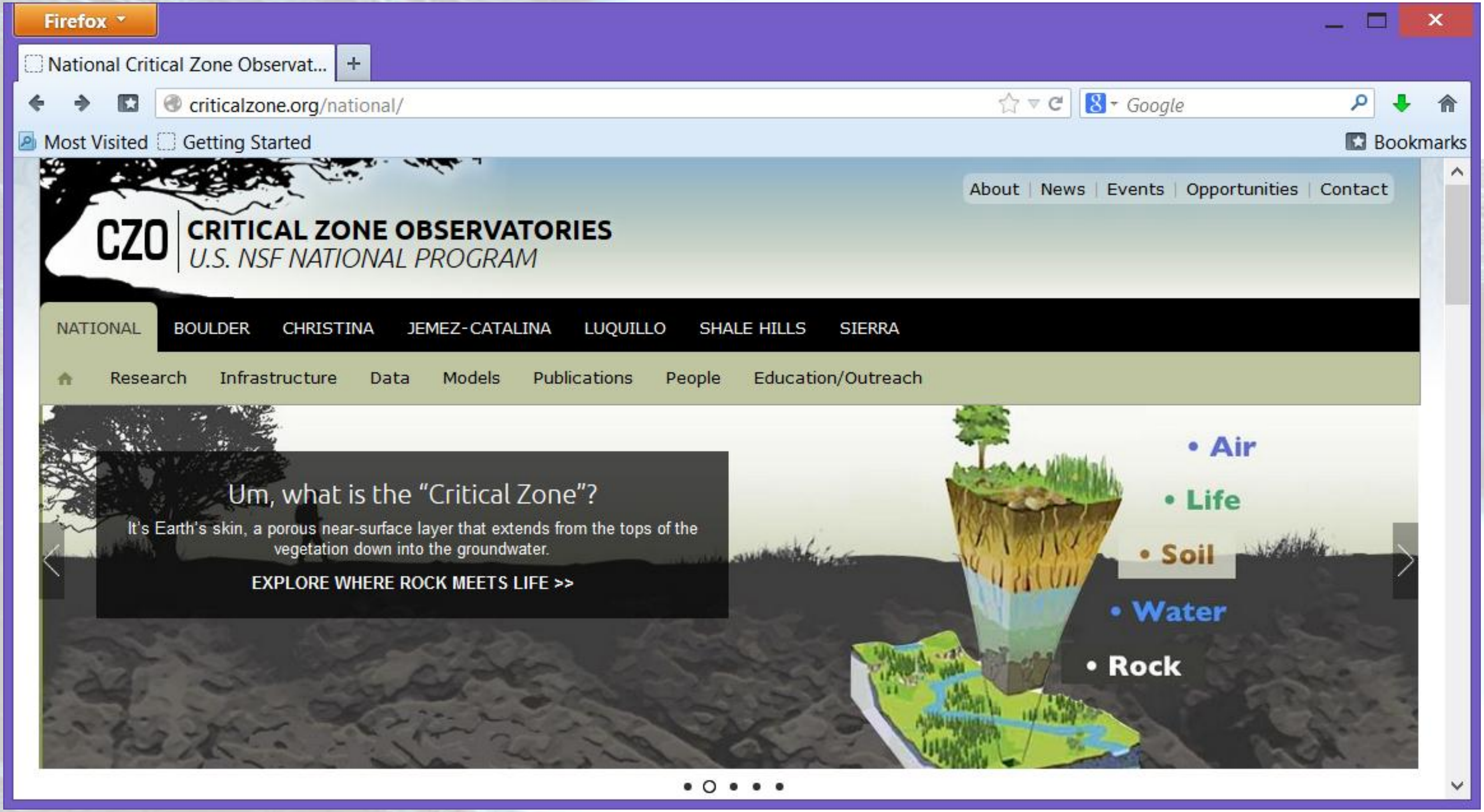
- In 2001 the US National Science Foundation (NSF) began work on a new "framework" for shallow earth science research
  - More comprehensive approach than just GW/SW, unsat flow, etc.
  - Includes water, climate, vegetation (carbon cycle), energy processes
- New terminology: the "Critical Zone"
  - Definition: **"where rock meets life"**
  - CZ = "From the tops of the vegetation down into the groundwater"
- NSF funding of "Critical Zone Observatories" (CZOs)
  - Multiple research sites set up to study CZ processes
  - http://www.criticalzone.org

Earthfx Incorporated

NSF "Critical Zone" Observatories



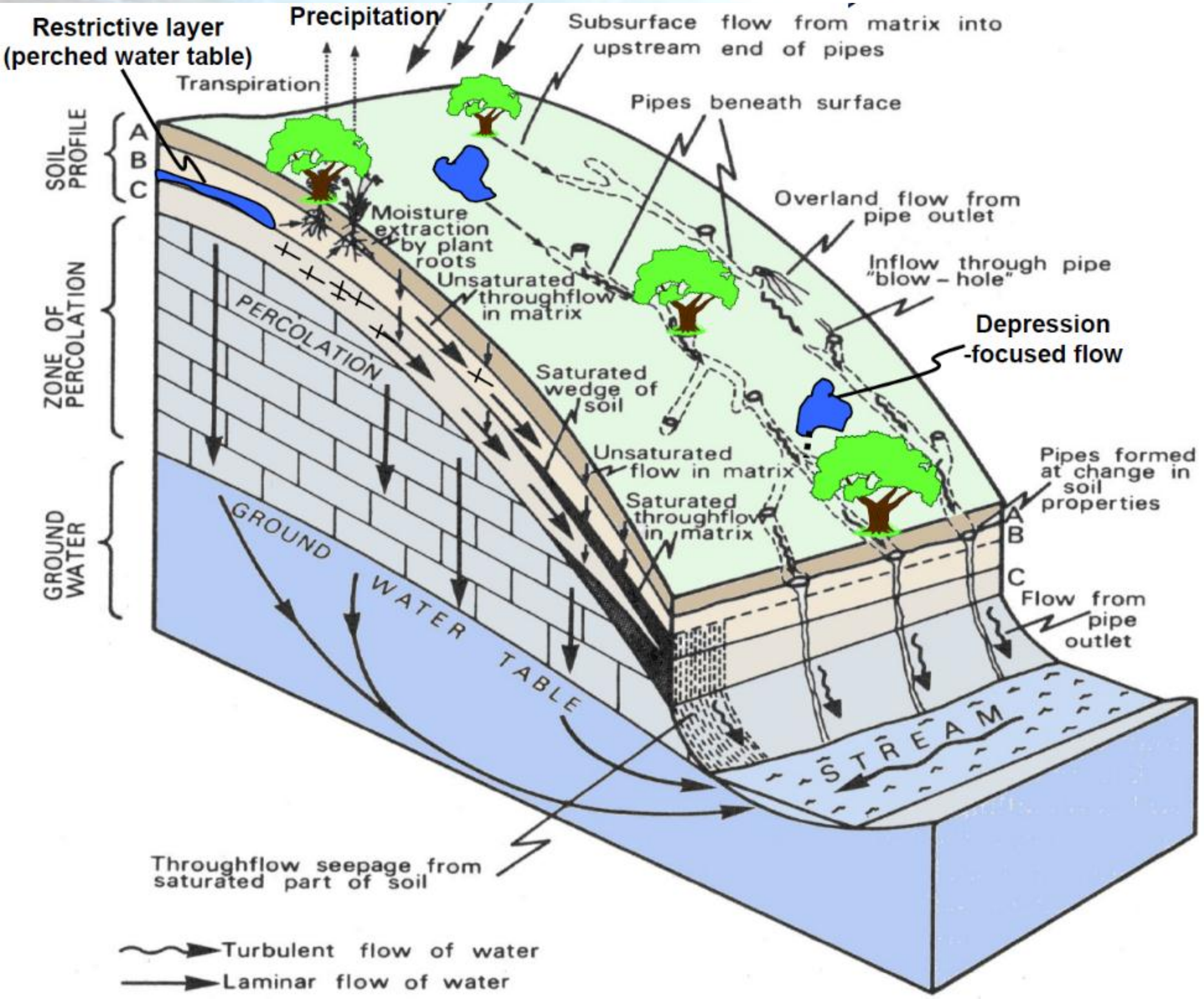
NSF "Critical Zone" Research Portal



Earthfx Incorporated

Critical Zone Flow Processes

- Macropores
- Interflow
- Throughflow
- Seepage faces
- Event mobilized GW
- Note: no wetlands or lakes shown..



from Lin, 2010

Earthfx Incorporated

Ideal location where uncoupled SW/GW models can be used

- 2-D diffusive wave overland runoff
  - (i.e. sheetflow)
- Known GW Recharge
  - (zero)

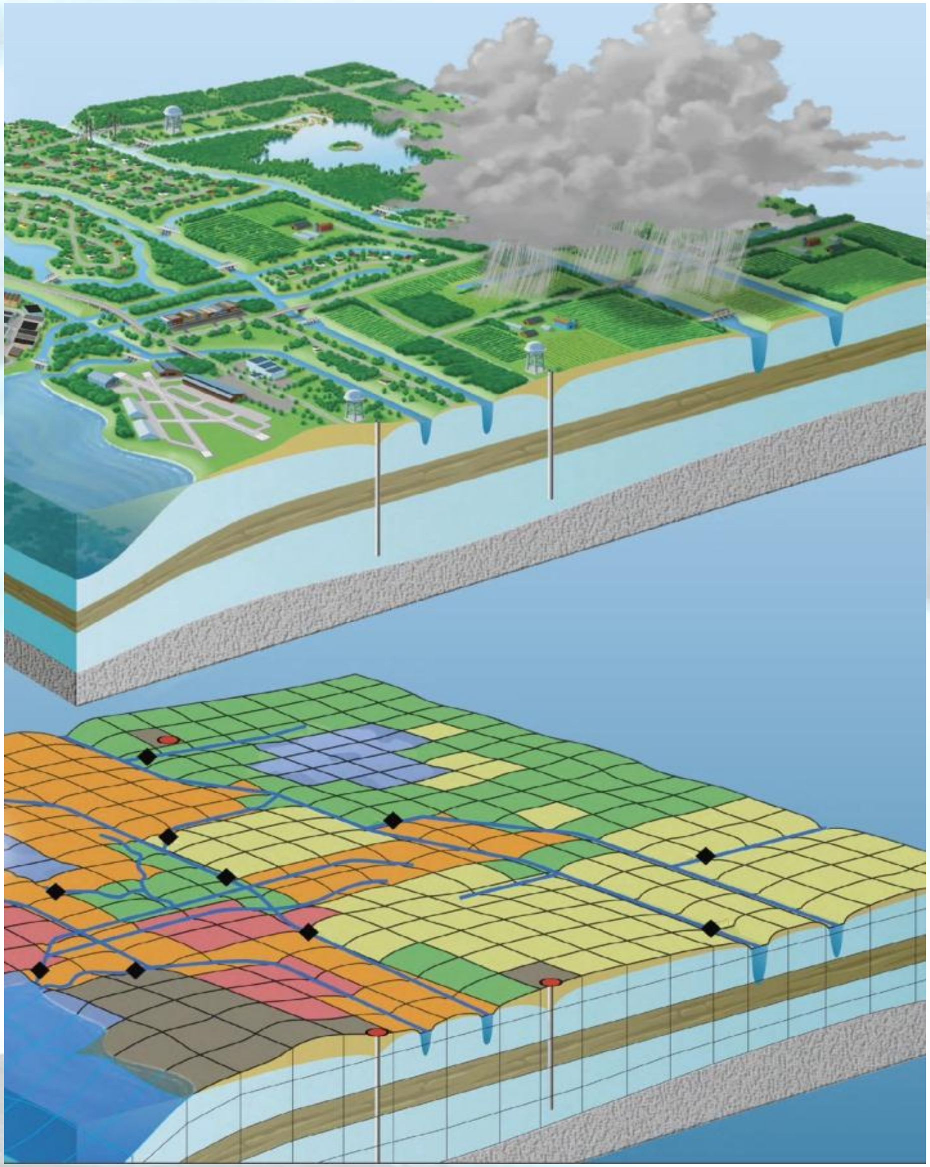
USGS GSFLOW

~~Integrated SW/GW Model~~

"A Critical Zone Model?"

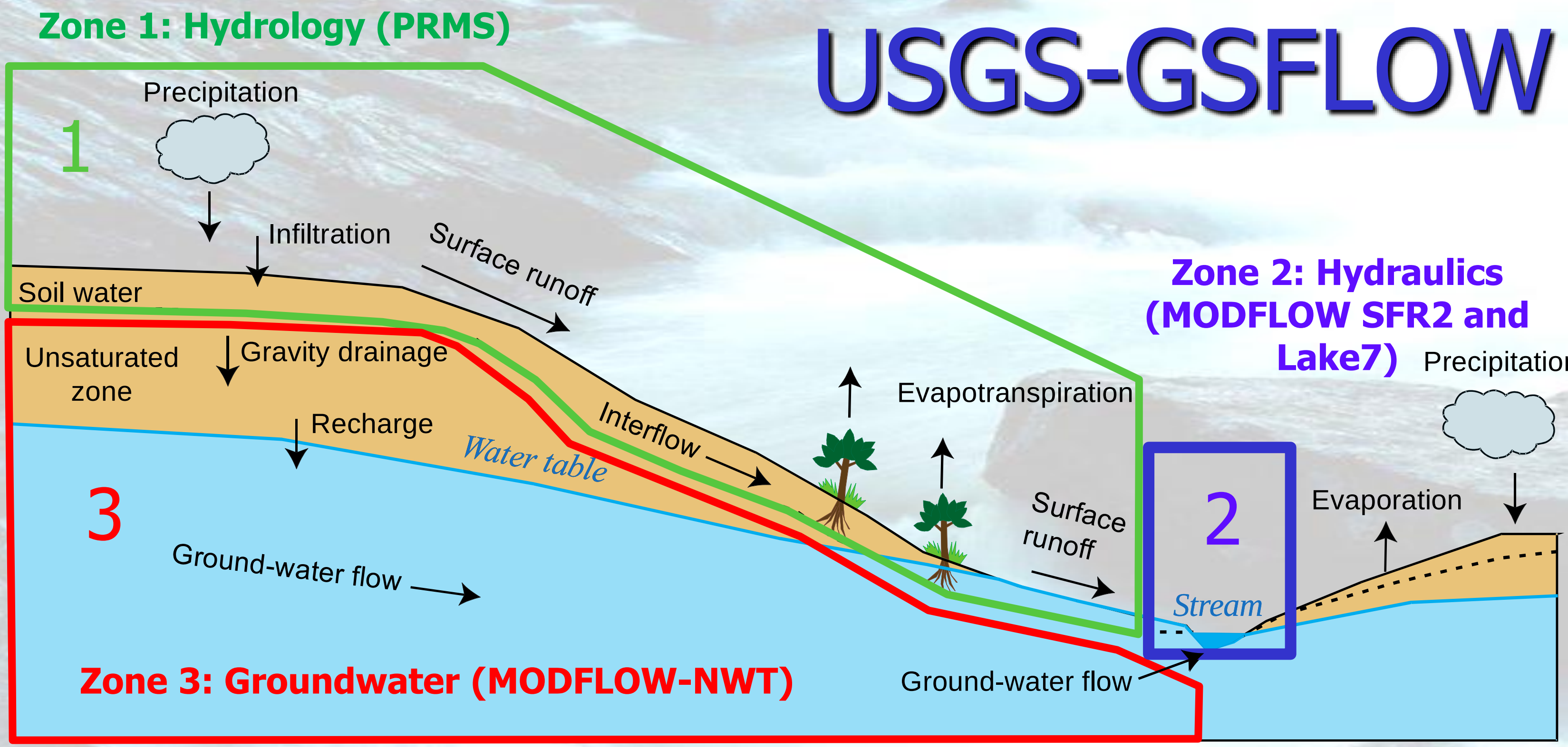
USGS GSFLOW Integrated Model

- Balanced: Based on two very established models (MODFLOW NWT and PRMS)
- Fully distributed (cell based) GW and Hydrology processes
- Channel network for hydraulics
- Multi-mesh
  - Can use different grids for GW and SW processes



Earthfx Incorporated

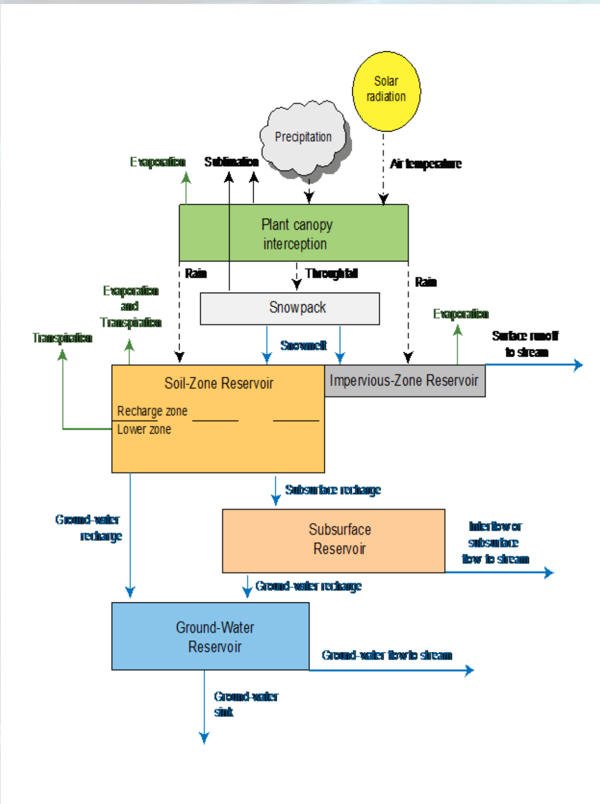
USGS-GSFLOW

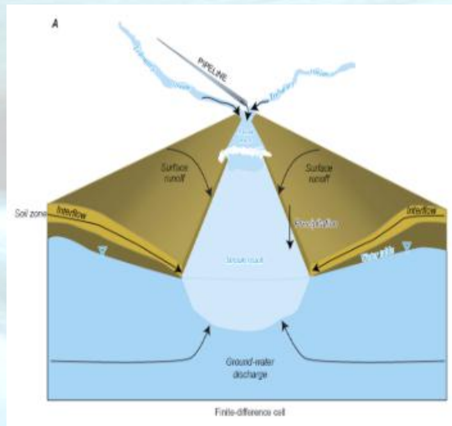


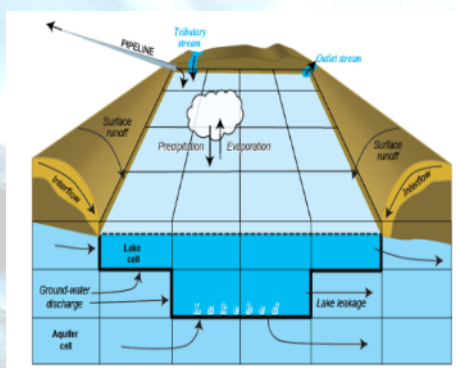
- GSFLOW is a new USGS integrated GW+SW model
  - Based on MODFLOW-NWT and USGS PRMS (Prepitation-Runoff Modelling System)
  - Both models fully open source, proven and very well documented
- GSFLOW Model Integration- design by expert committee:
  - First author is a SW modeller, but there is strong evidence that the GW modellers were quite persuasive (2 of the 3 zones are based on MODFLOW)…

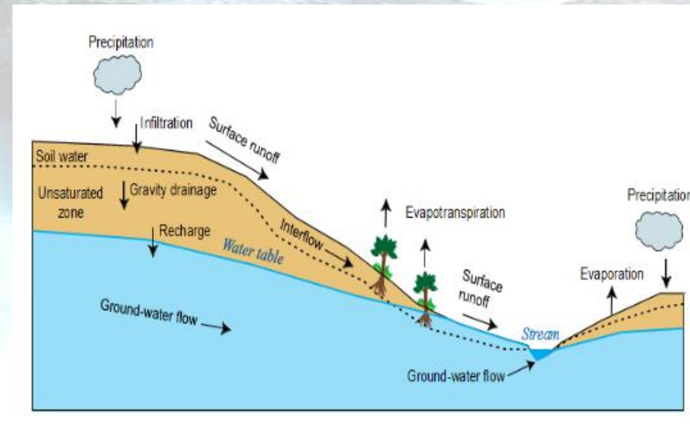
GSFLOW Components

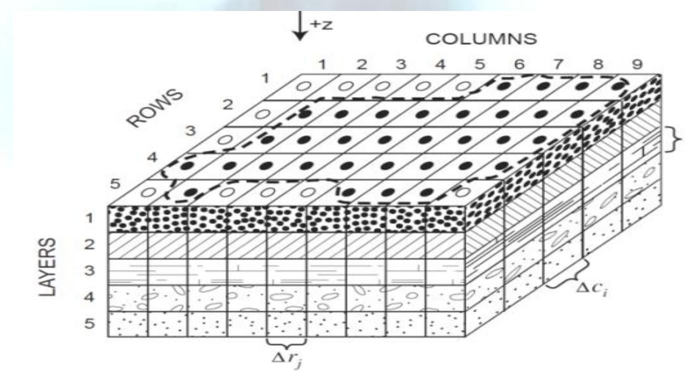
- Hydrology (PRMS) Hydraulics (SFR2) GW (MODFLOW-NWT)











Earthfx Incorporated

GSFLOW Hydraulics: Stream Channel Routing

GSFLOW Channels

- Streams are represented as a network of linear segments or channels
- Streams can pick up precipitation, runoff, interflow, groundwater and pipe discharges
- Stream losses to GW, ET, channel diversions and pipelines
- GW leakage/discharge is based on head difference between aquifer and river stage elevation
  - An extra stream bed conductance layer exists under each river reach
  - Similar to MODFLOW rivers, but the head difference is based on **total flow** river level

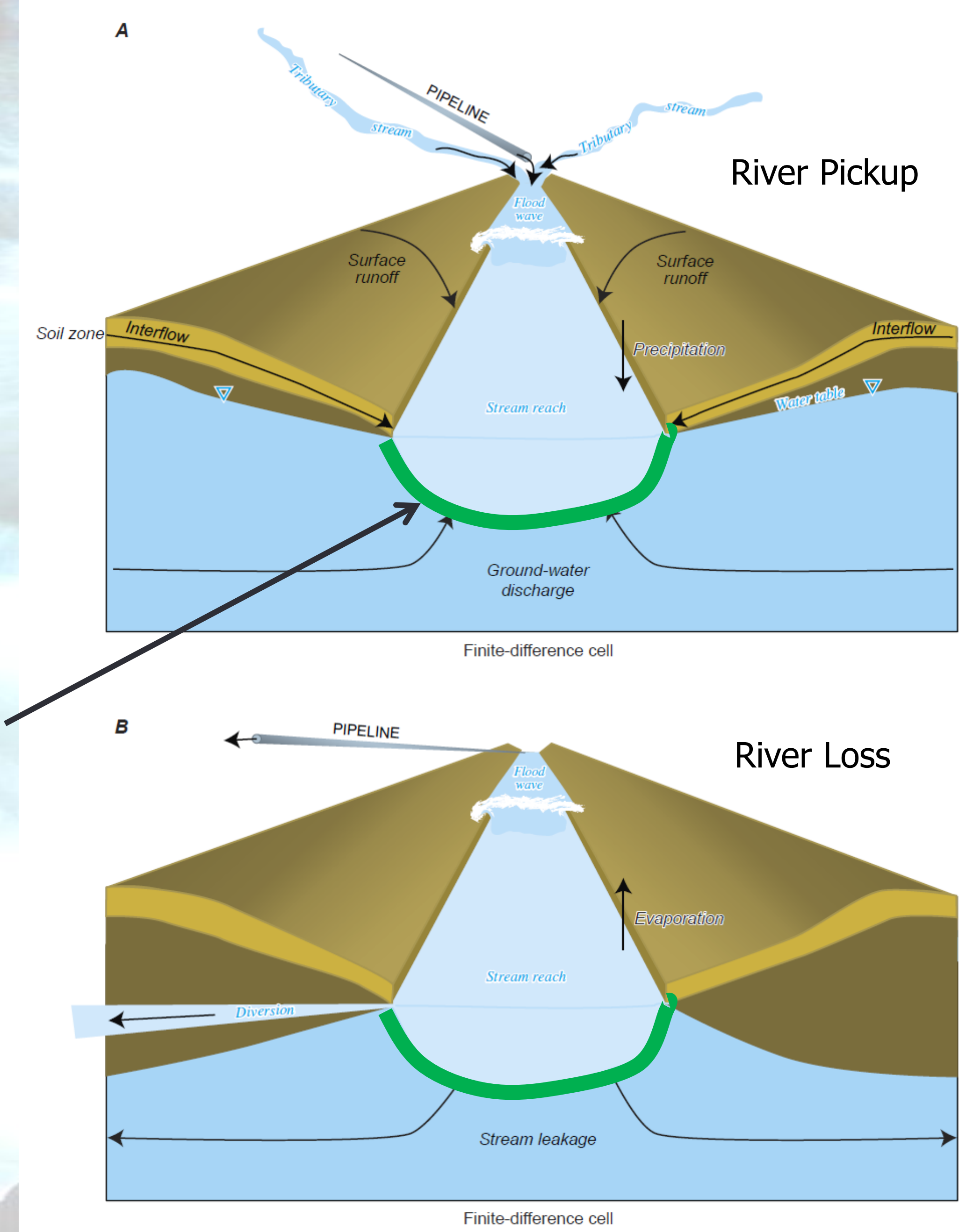
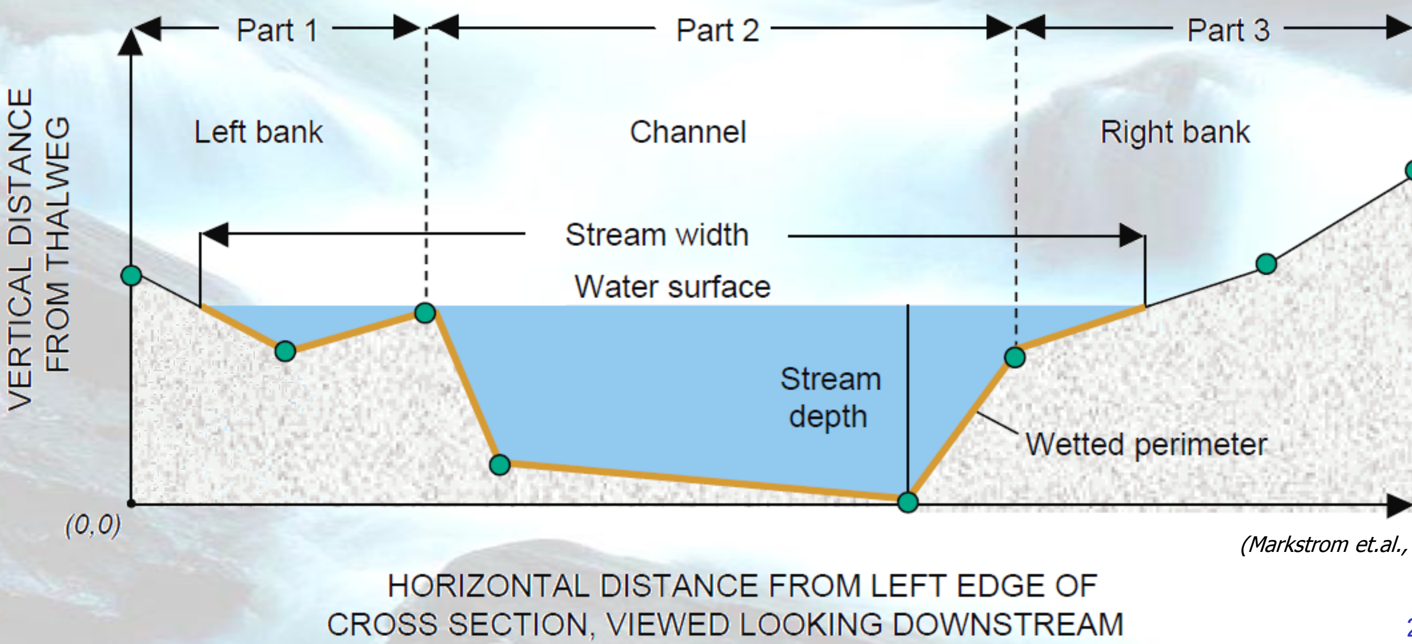


Figure 22. (*A*) Inflows to and (*B*) outflows from a stream reach.

Earthfx Incorporated

GSFLOW: Stream Channel Geometry

- The Stream Flow Routing package (SFR2) represents stream channels using an 8-point cross-section in order to accommodate overbank flow conditions
- Streamflow depths are solved using Manning's equation
- Different roughness can be applied to in-channel and overbank regions
- SFR2 incorporates sub-daily 1D kinematic wave approximation if analysis of longitudinal flood routing is required



(Markstrom et.al., 2008)

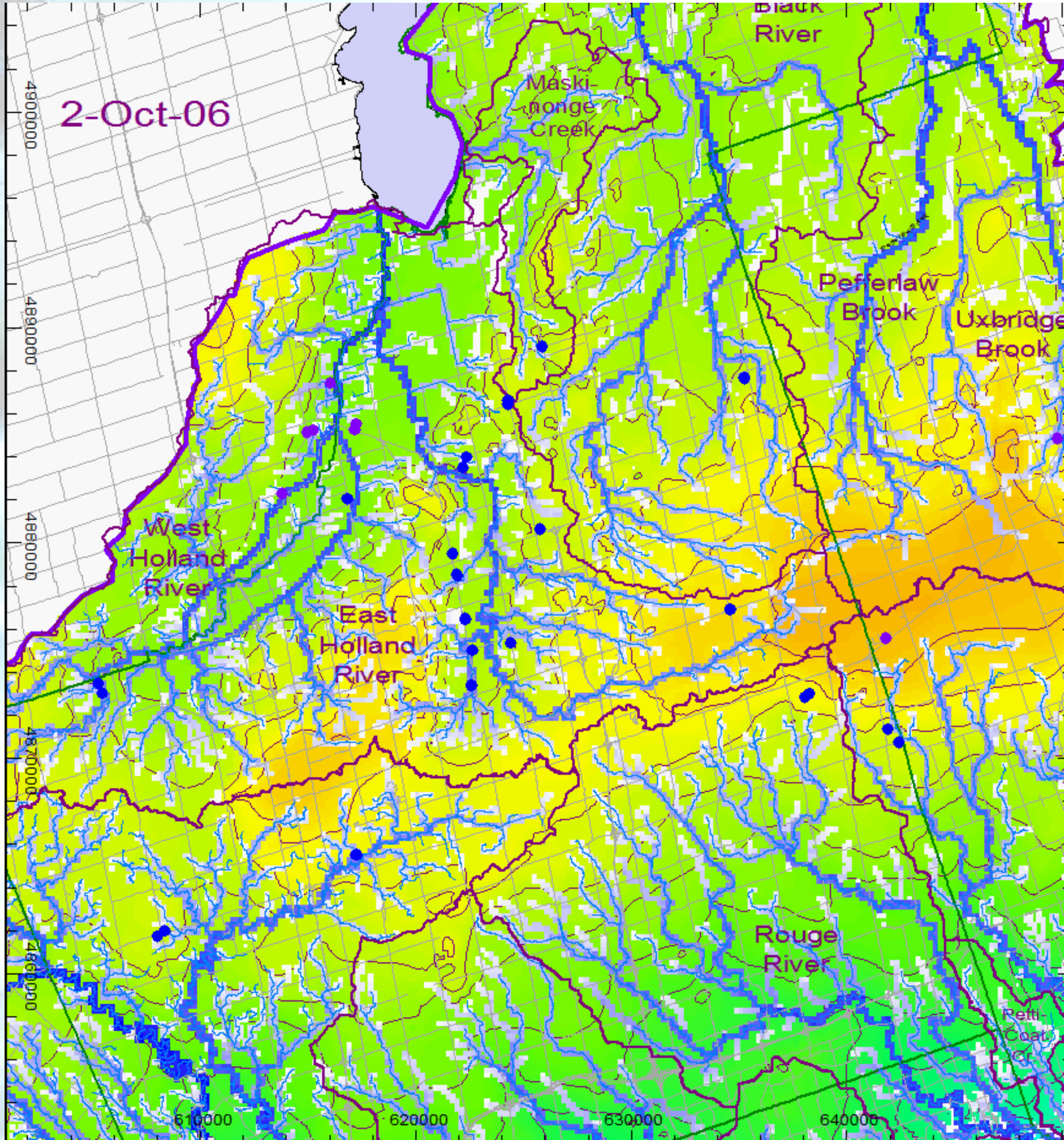
Earthfx Incorporated

GSFLOW Stream Routing Benefits

- Full open channel hydraulic representation
  - Variable channel x-section geometry with overbank
- Streams channels need not conform to the grid cell or element boundaries
  - No requirement to refine the model mesh around streams
  - No need to “straighten” the streams to conform to an element edge
  - All streams can be represented, including springs and intermittent headwaters
- Stream controlling elevations can be set independent of grid cell elevation
  - Streams can also incise through multiple GW layers
  - (real-world streams have a nasty habit of eroding)

GSFLOW Total Flow Routing

- White-blue gradation indicates total streamflow
  - Green-orange gradation indicates topography
- All streams, including key headwater springs are simulated

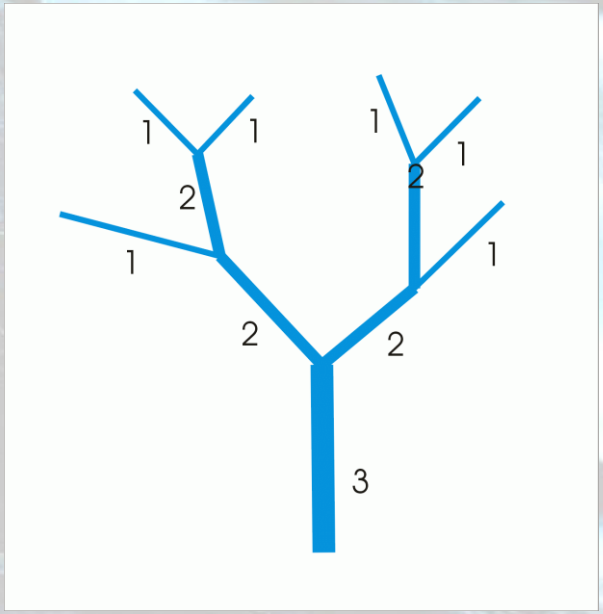


Earthfx Incorporated

Why model the small streams?

- The smallest Strahler Class 1 streams represent the greatest total stream length and have the greatest baseflow pickup (i.e. from springs and seeps)

Strahler Classes



Baseflow Pickup

Strahler Class	No. of Segments	Total Length (km)	% of Total Length	Total Discharge (m3/s)	% of Total Discharge
1	4213	2185	43%	3.65	26%
2	2118	1186	23%	2.75	19%
3	1083	832	16%	3.15	22%
4	529	431	8%	2.07	15%
5	29	266	5%	1.43	10%
6	16	112	2%	0.61	4%
7	7	66	1%	0.6	4%
Total	7995	5078		14.26	

Earthfx Incorporated

Benefits of Integrated Stream Routing

- Head dependent leakage based on total flow stream levels
  - In a GW only model, the leakage is based on baseflow levels only
  - High stream levels after a storm can drive SW into the GW system
- Upstream flow can infiltrate downstream to the GW system
  - Full 3D "routing" of both SW and GW
- Analysis of the entire water budget, including SW takings, SW discharges and stream diversions
- **Model calibration to a field measurable parameter (total streamflow)**
  - No need to guesstimate baseflow
    - Direct baseflow measurement is nearly impossible (seepage meters?)
    - Baseflow separation is, at best, an unscientific empirical estimate

Earthfx Incorporated

GSFLOW

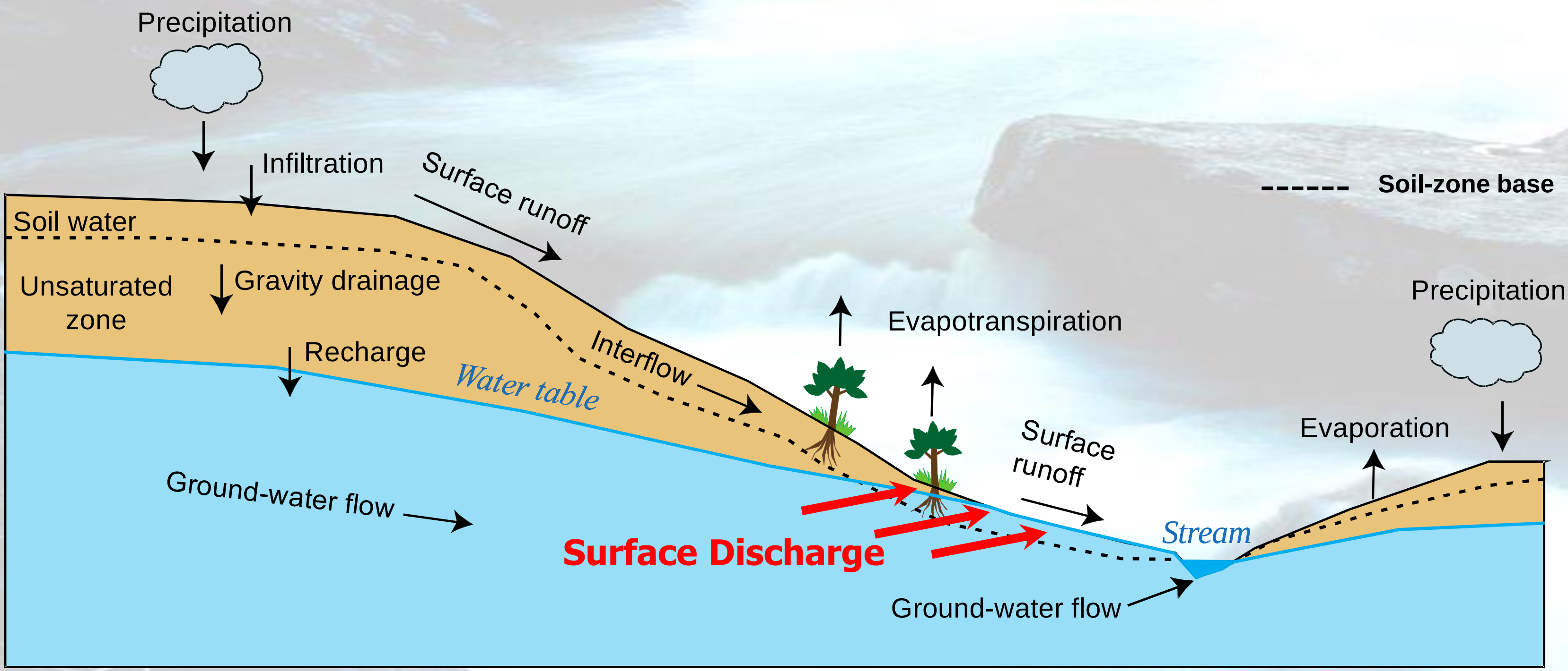
Wetland Modelling

Wetland Representation

- Wetlands have a wide range of water content (bogs, fens, marshes, etc.), and can be represented in GSFLOW in multiple zones
- Soil zone wetlands:
  - Partially or fully saturated soils, with surface ponding
  - Benefits – seasonal ET modelling, complex topography with cascade overland flow and interflow, GW leakage or discharge
- Open water wetlands:
  - The portion of a wetland that generally has standing water
  - Represented as a lake that can penetrate one or more GW layers
  - Benefits: Dams, weirs, and control structures can all be simulated

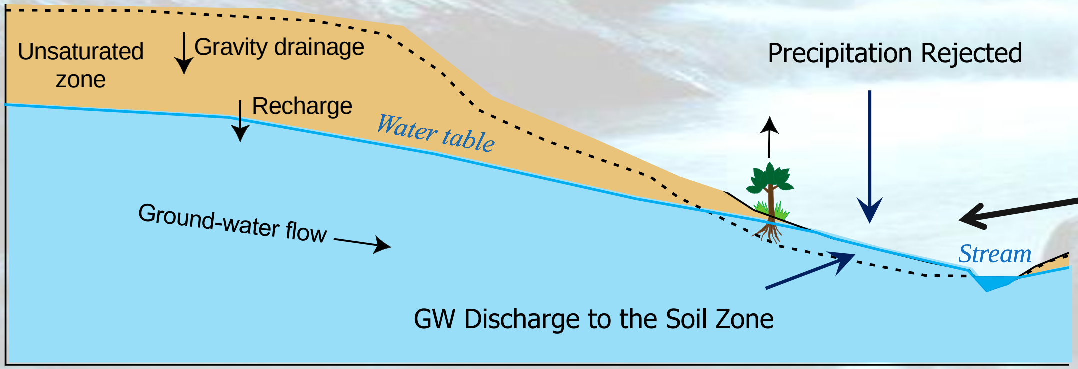
Earth*fx* Incorporated

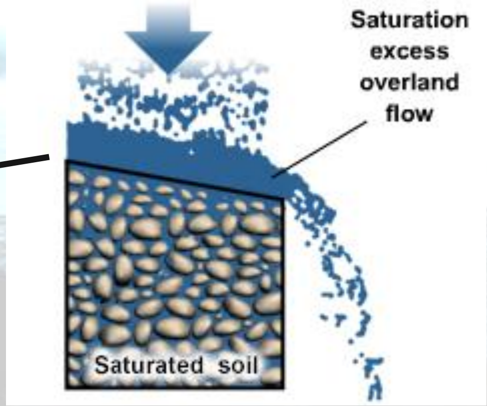
GSFLOW "Surface Discharge"



- Surface Discharge is the movement of water between the GW and Soil Zones

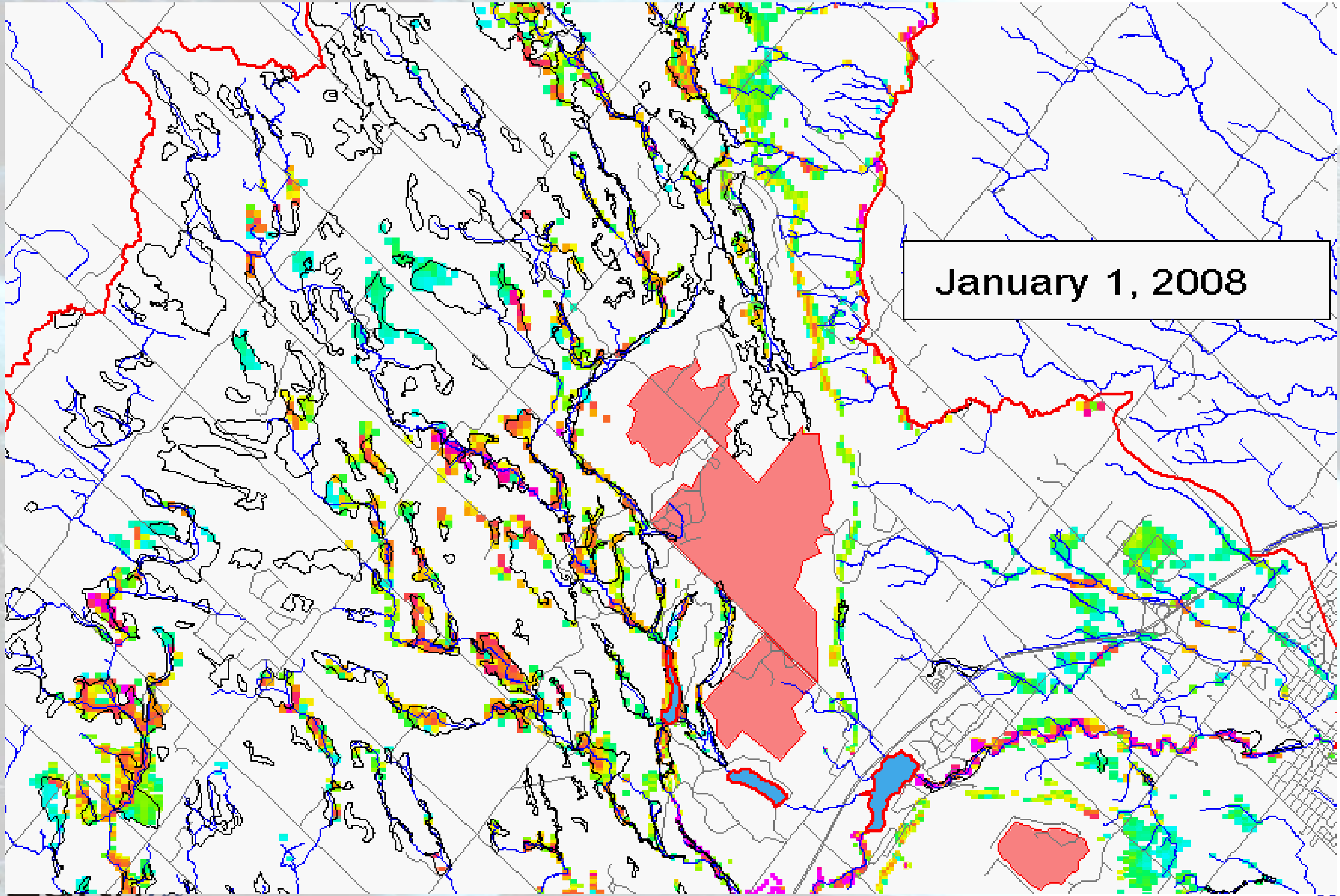
Wetland Dunnian Rejected Recharge





- Precipitation on fully saturated soils is rejected and becomes runoff
  - Insensitive to surficial material K: Runoff from saturated gravels!
  - Spatially controlled: Tends to occur in stream valley areas
  - Seasonally controlled: Tends to occur in spring when water table is higher
- **The is the critical "Groundwater Feedback" process that makes estimating recharge so difficult**
  - Occurs when the water table is at or near surface or soils are saturated

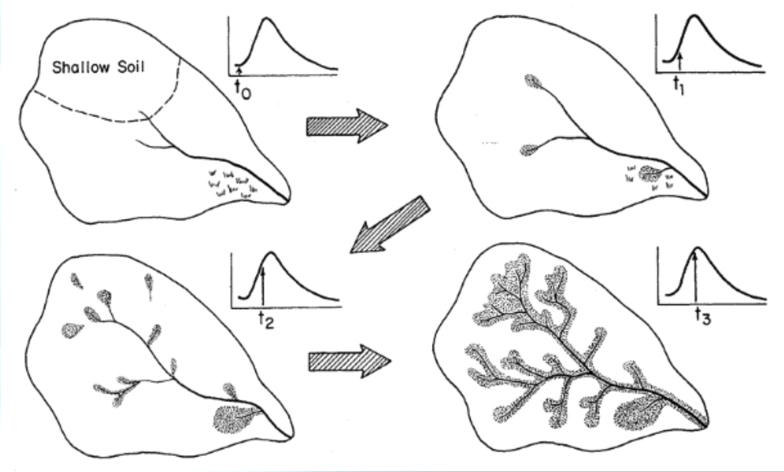
GSFLOW Surface discharge to wetlands

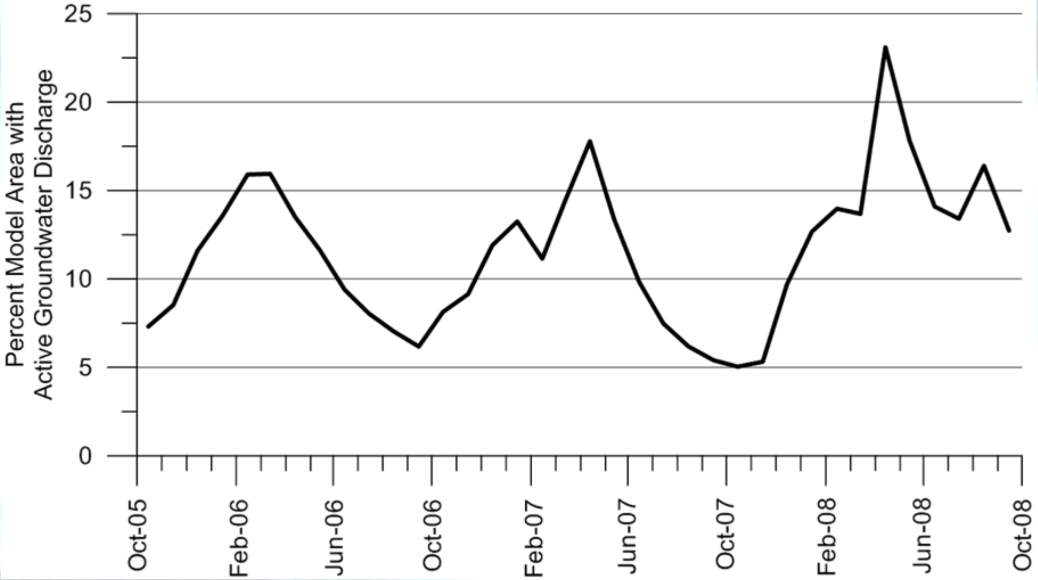


Daily GW discharge to soil zone

Time-varying GW Feedback

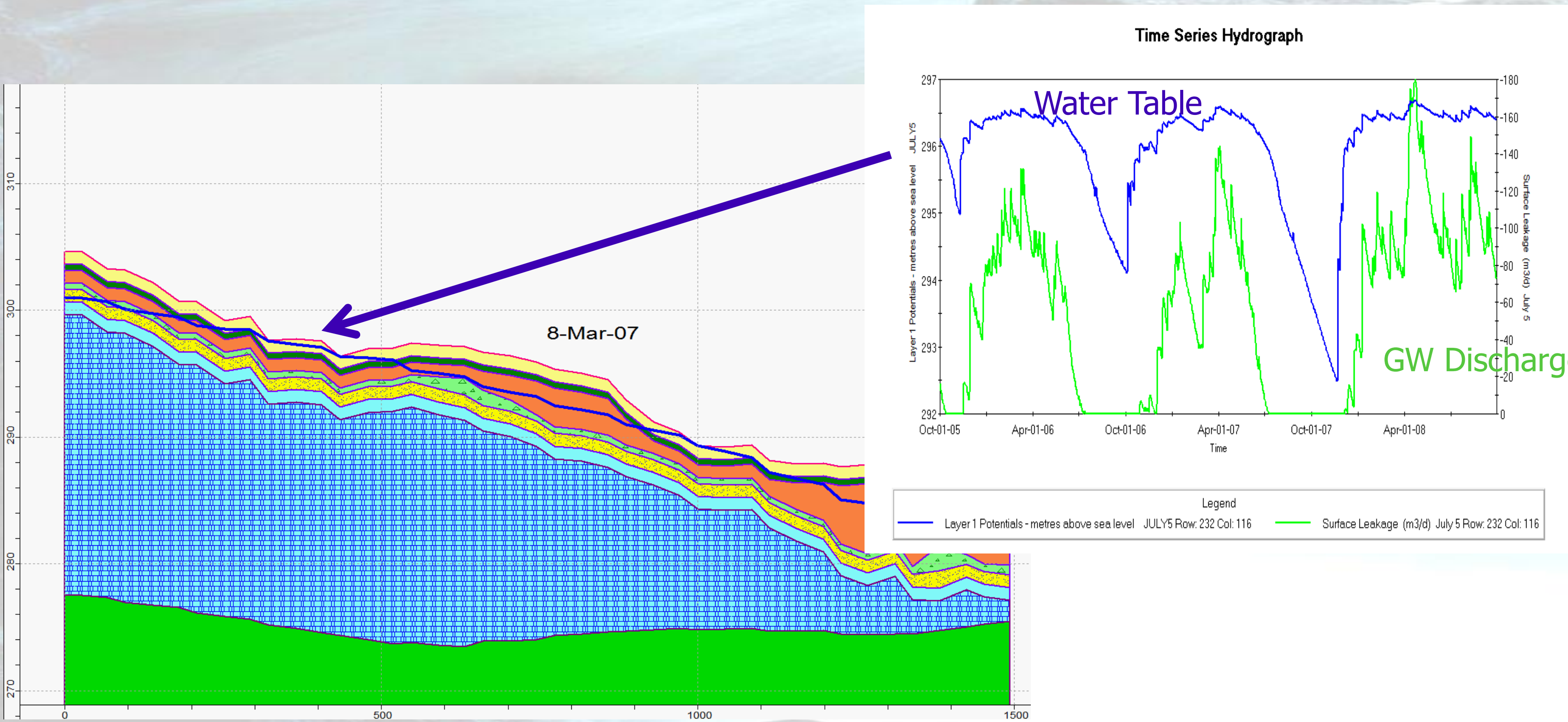
- The "contributing area" that generates true runoff depends on the time-varying position of the water table
- **Surface discharge wetland area varies seasonally between 5 and 25% of the study area**





GW Discharge to Wetland

- Water table rises and falls through multiple thin, variably saturated, layers
  - Highly variable response to precipitation events
- GSFLOW NWT Solver – no dry cell problems!



Earthfx Incorporated

GSFLOW

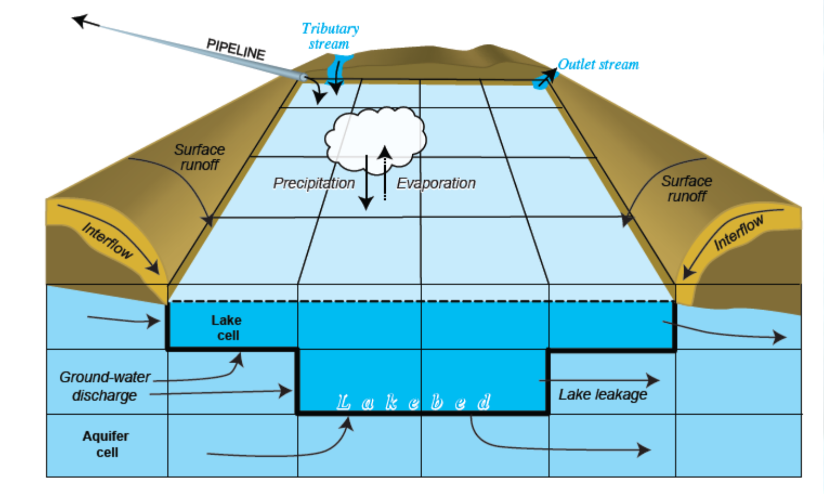
Lake Modelling

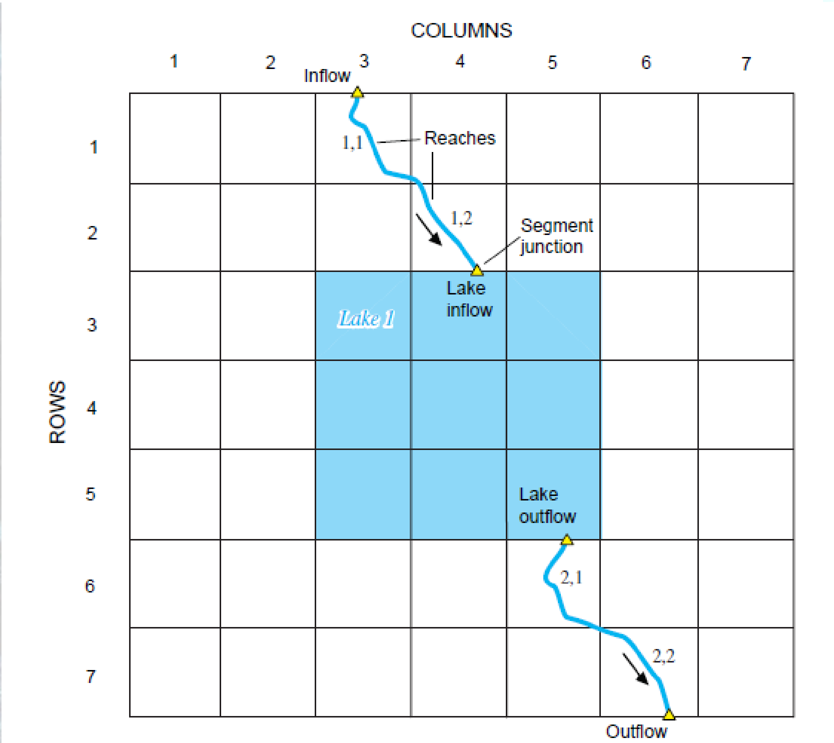
Lake and Reservoir Modelling

- The GSFLOW Lake Package allows pits, lakes and reservoirs to penetrate one or more aquifer layers
- A single lake can both pickup and loose water to multiple aquifers in the the GW system

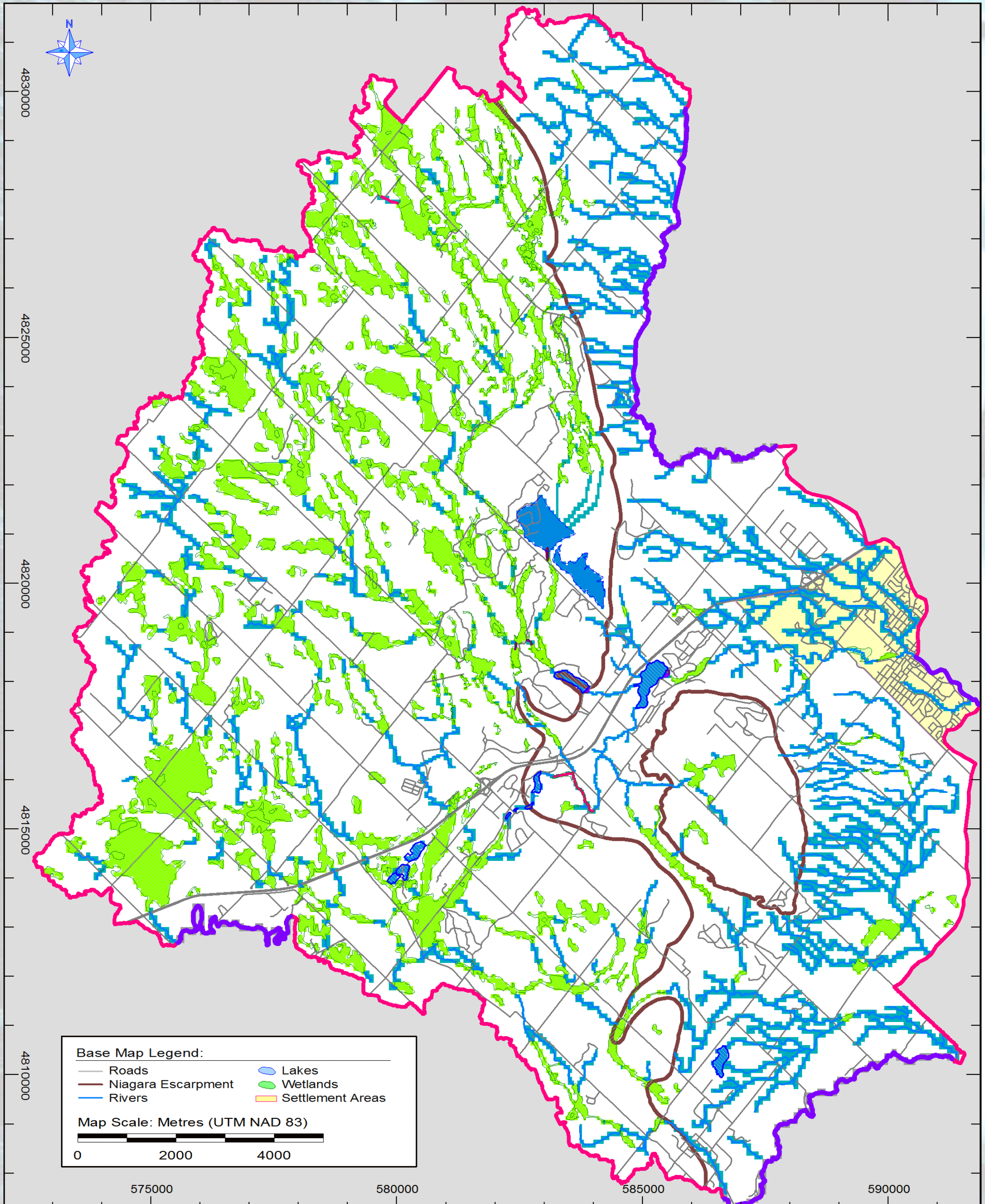
Earthfx Incorporated

GSFLOW Lakes and Wetlands



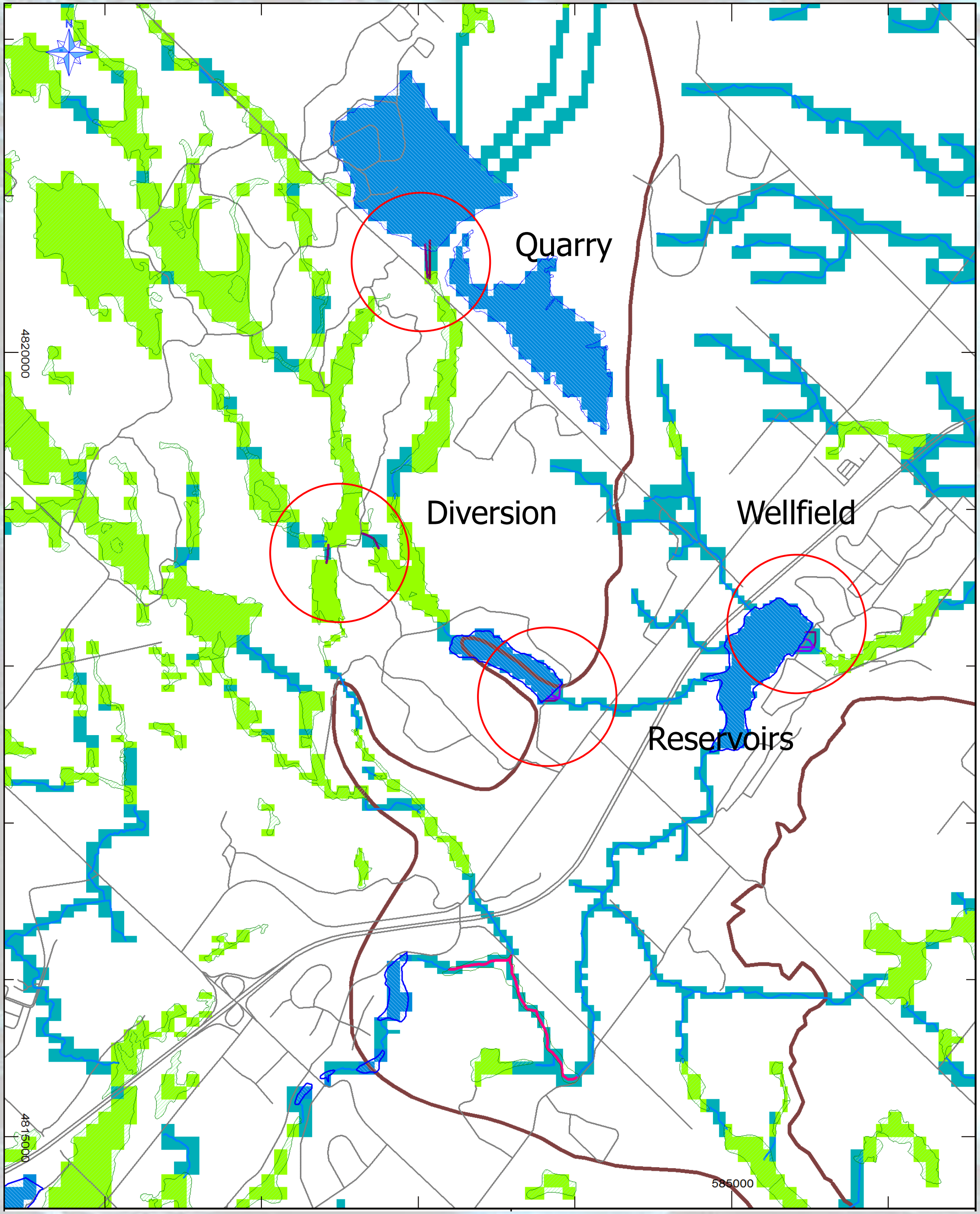


- Separate water balance done for each lake to determine y:
  - $Q_{IN} + P - E - Q_{LEAK}(y) = Q_{OUT}(y)$
- Wetlands and lakes can penetrate multiple aquifer layers
- SFR2 handles lake inflows and outflows.
- Outflow can be a fixed rate or determined by stage-discharge
- Multiple inlets and outlets are allowed



Example: Surface Water Features

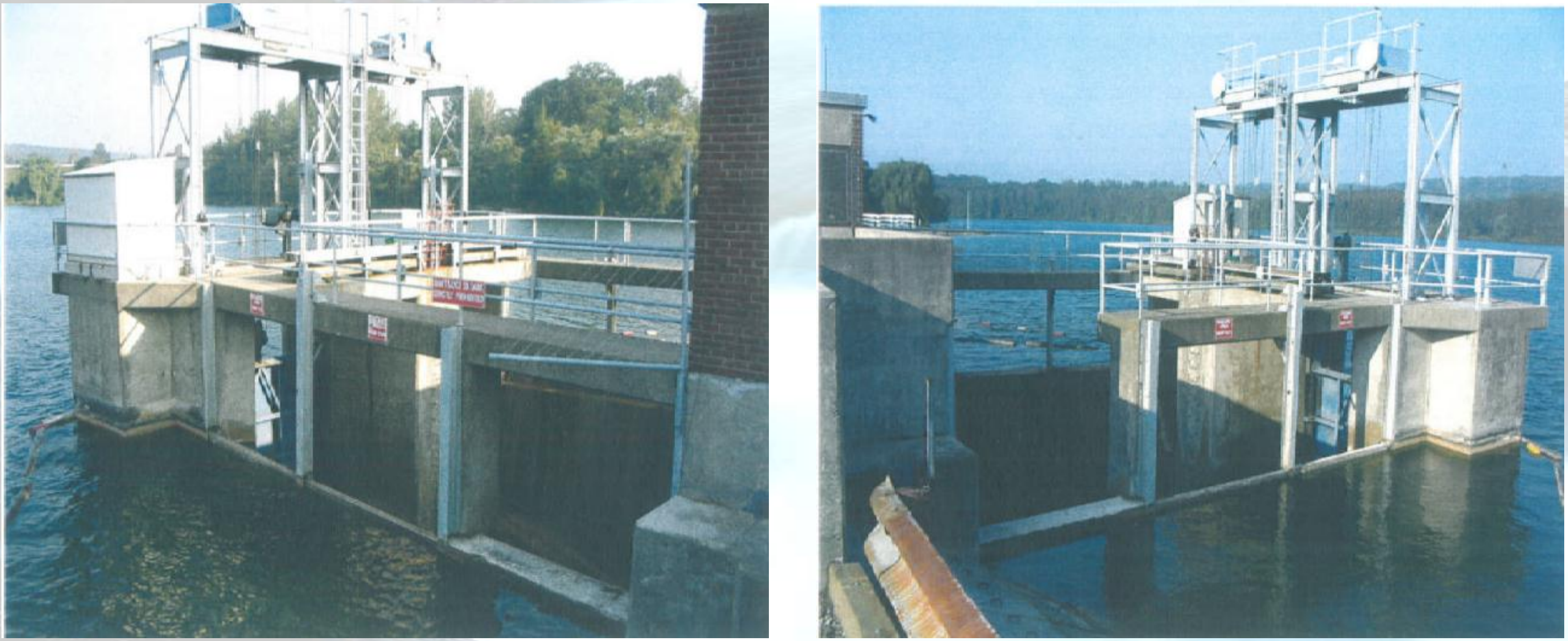
- 475 km of mapped streams
  - Many reaches are actually riparian wetland complexes
- 338 Wetlands
- 12 Lakes and ponds



Surface Water Features

- 2 Reservoirs with multiple structures
  - Gates, stop logs, intakes, and spillways
- 1 Diversion
- 1 Quarry Discharge Point
- Surface Water Takings from permit and water use databases

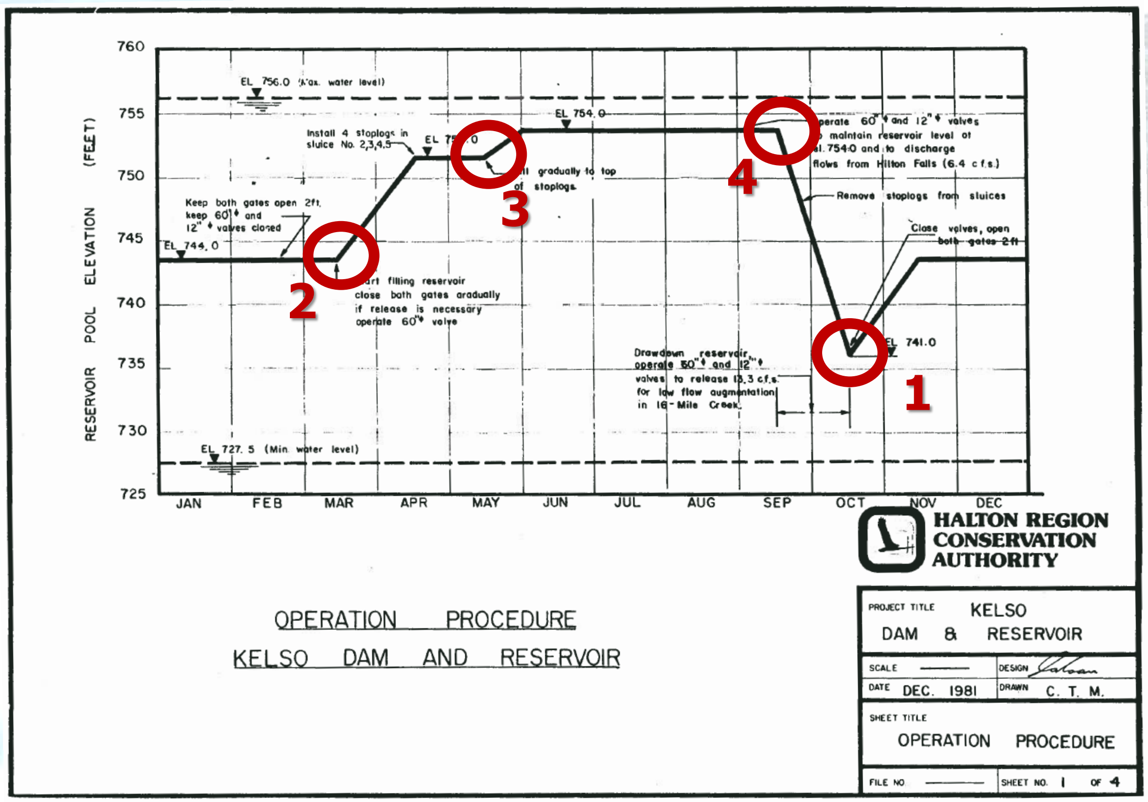
Reservoir Operation: Kelso Reservoir



Kelso Reservoir Control Structure *(Hatch, 2007)*

Reservoir Operation: Kelso Reservoir

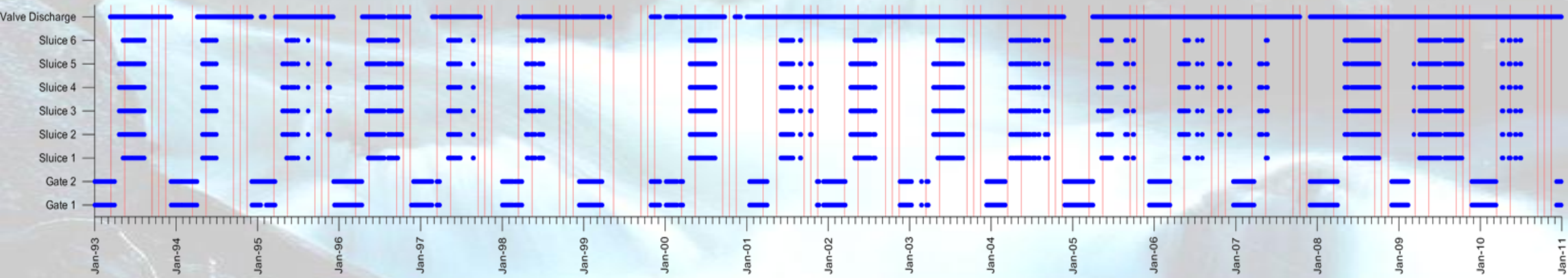
1. **Oct-Mar:** valves closed, gates open
2. **Mar-May:** gates closed
3. **May-Sep:** install stoplogs in sluice gates 2, 3, 4, 5
4. **Sep-Oct:** remove stoplogs



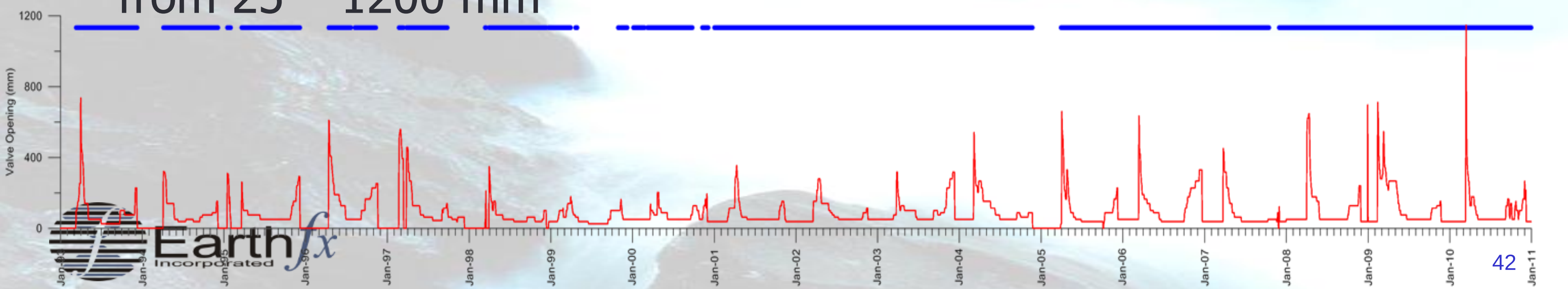
Earthfx Incorporated

Reservoir Gate and Valve Operations: Mathematically "inelegant"

- Operation rules not followed exactly (again, as expected)
  - Blue lines indicate when discharge is occurring from each specific outlet
  - Red lines indicate rule curve operation dates (from previous slide)



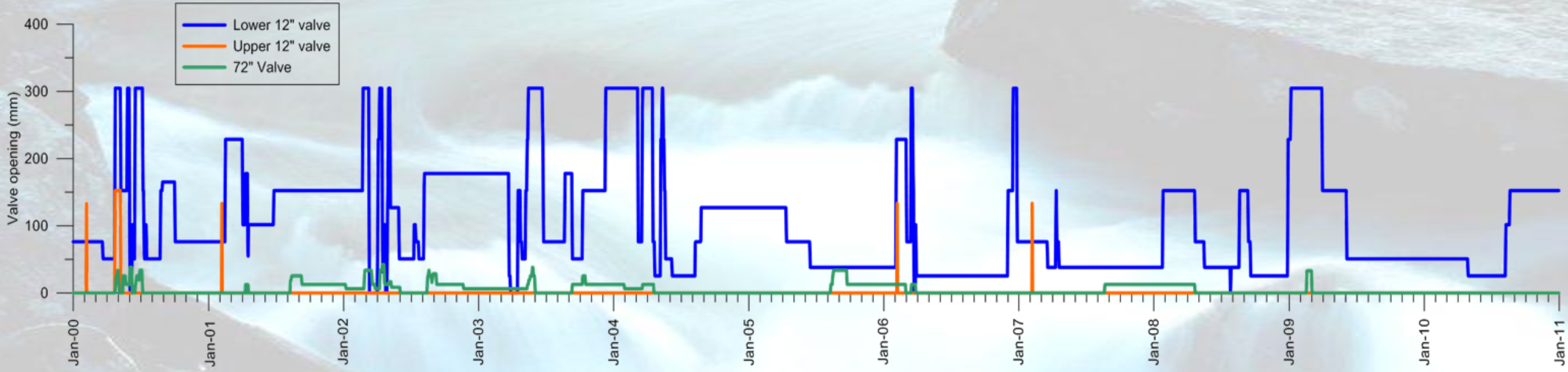
- 1.5 m ϕ valve operation varies widely: valve openings range from 25 – 1200 mm



Earthfx Incorporated

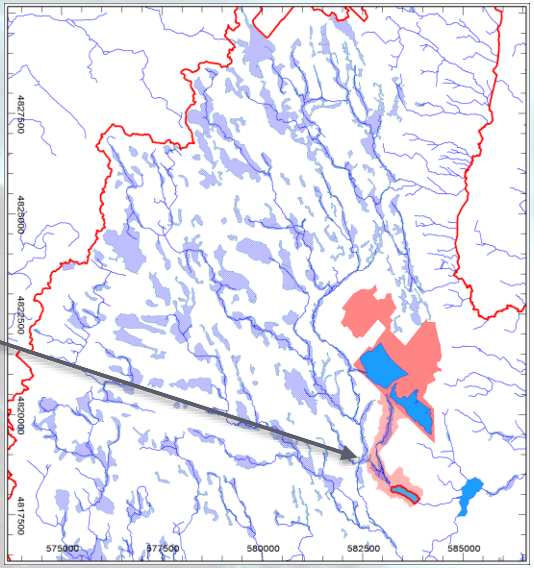
Reservoir Valve Operations

- Large variation in valve operation

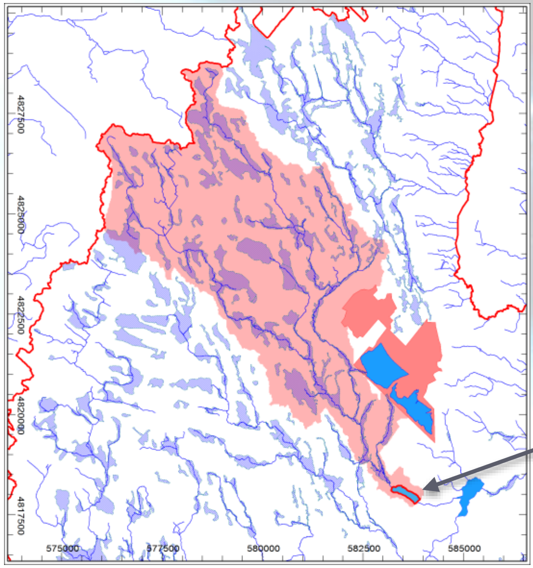


- Diversion is used to augment flows into Hilton Falls Reservoir in addition to the Dufferin Quarry discharge

Diversion Location



Contributing area without diversion

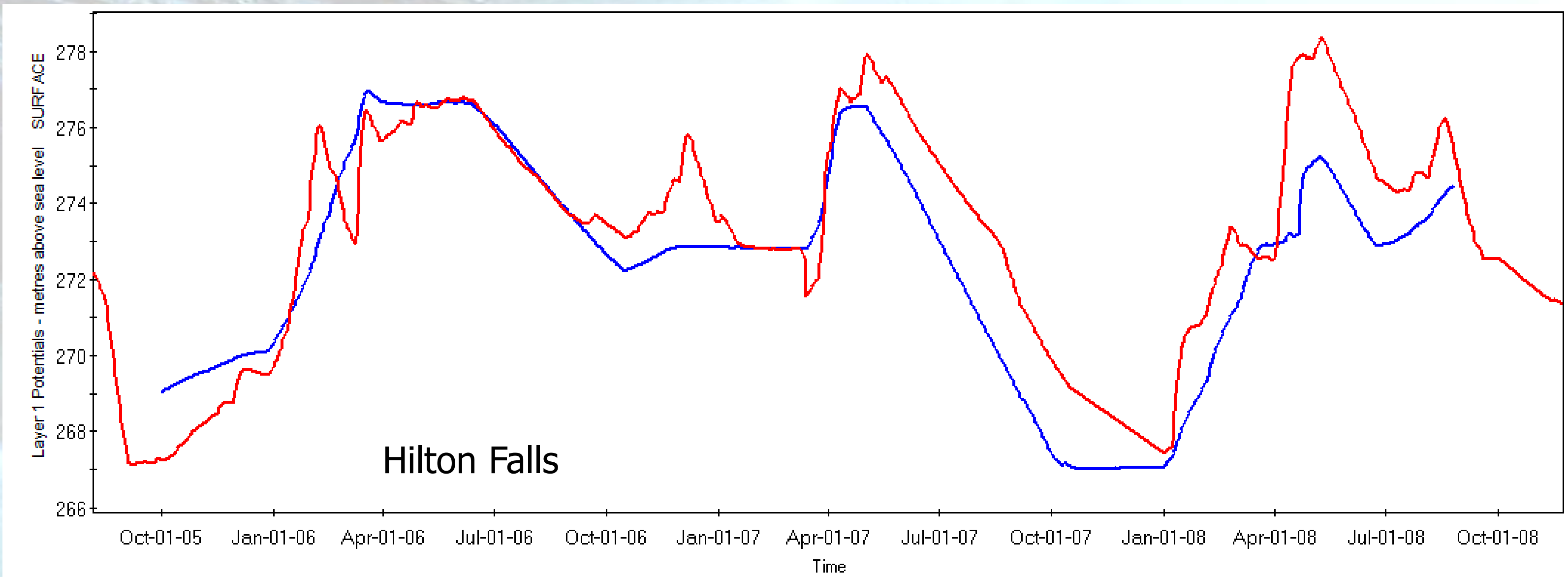


Hilton Falls Reservoir

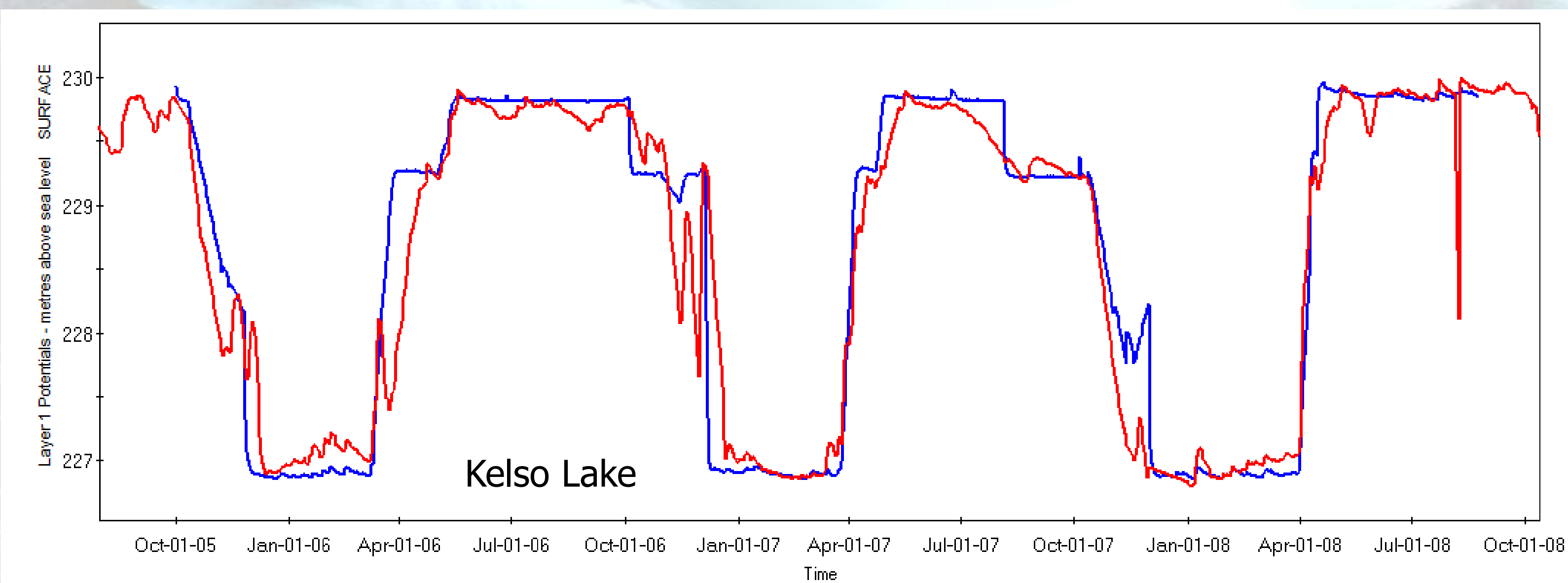
Contributing area with diversion

Earthfx Incorporated

Simulated Stage in Reservoirs

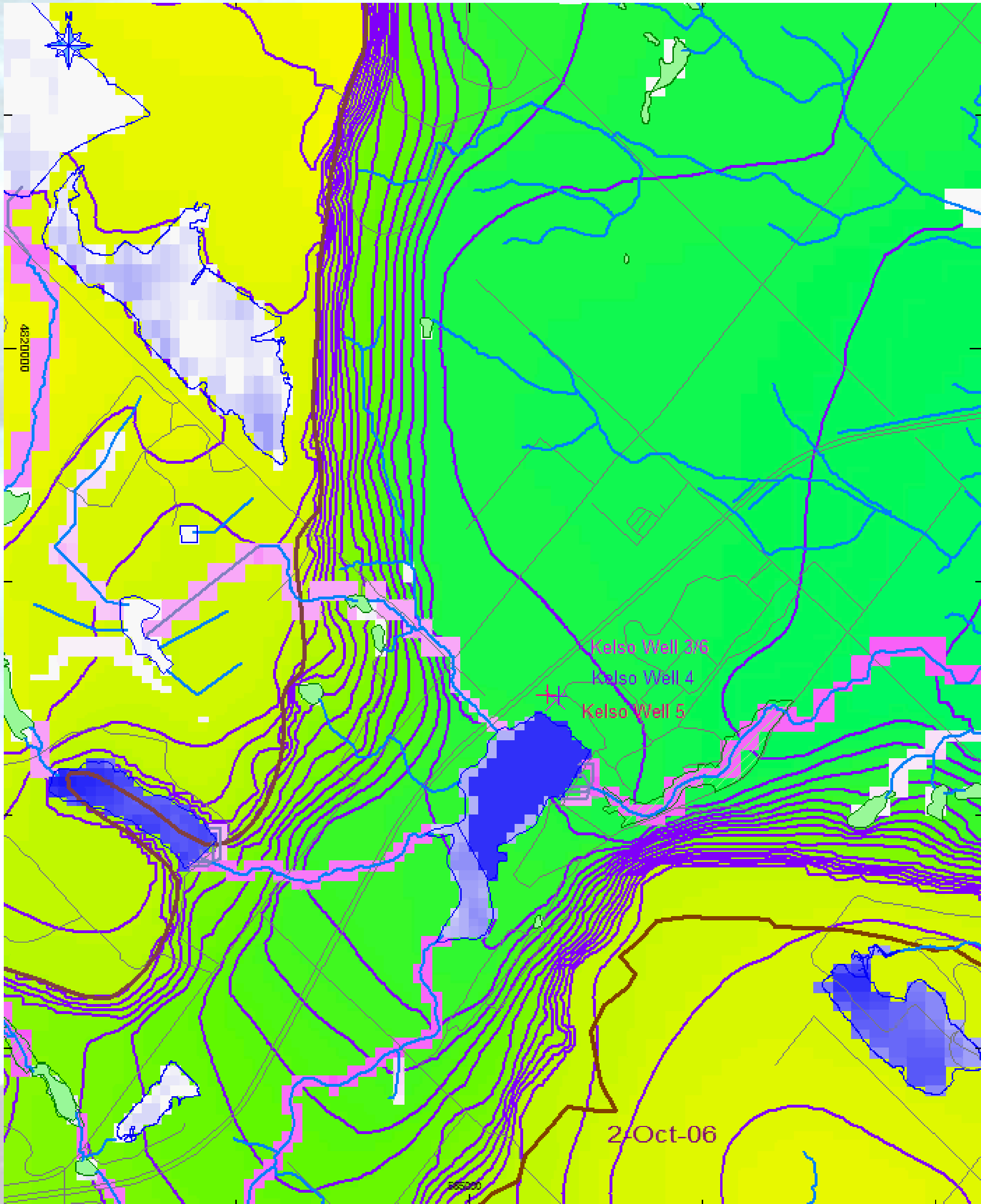


OBSERVED PREDICTED



Wellfield Levels in vicinity of reservoir

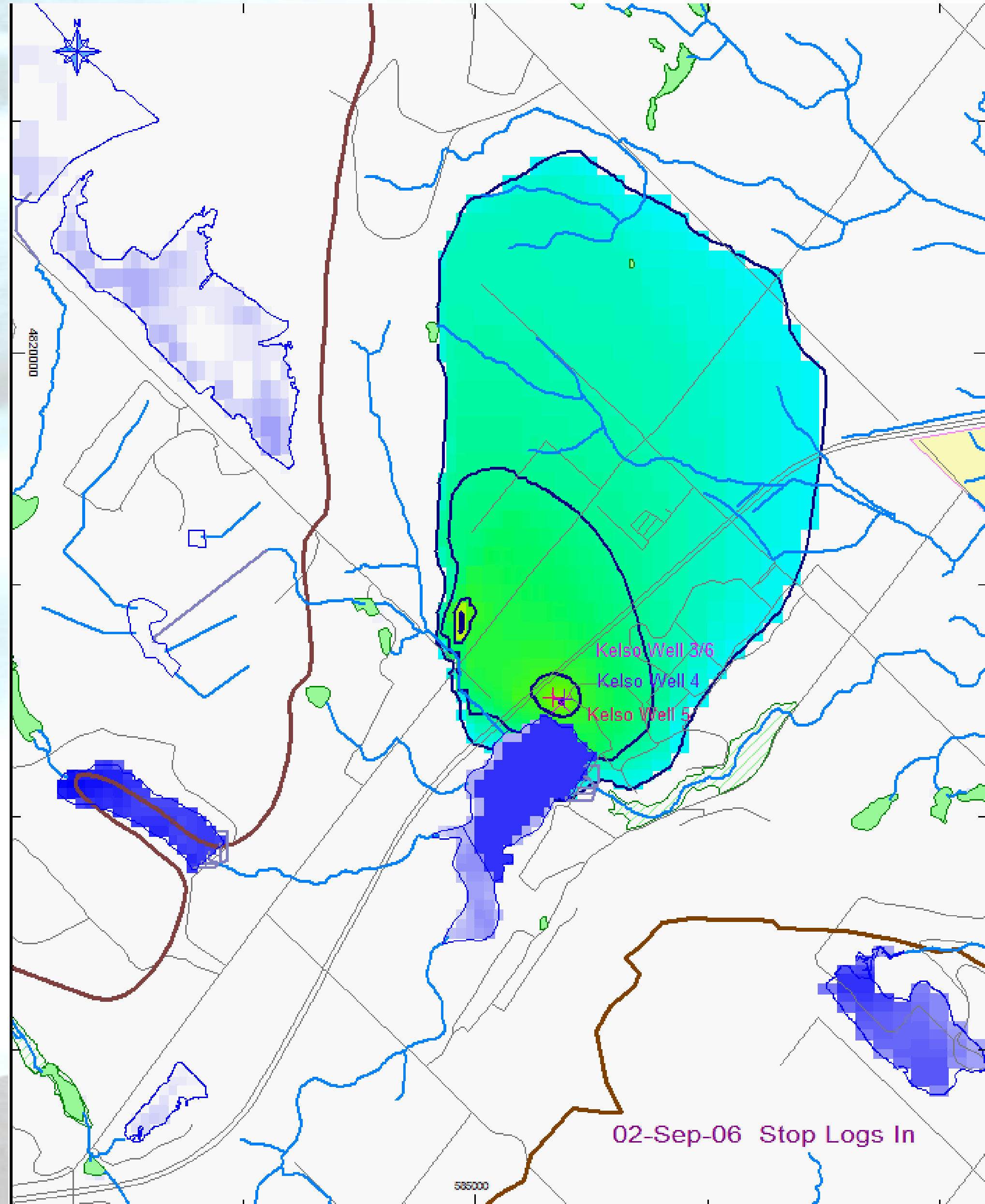
- White-blue gradation indicates total streamflow



Earthfx Incorporated

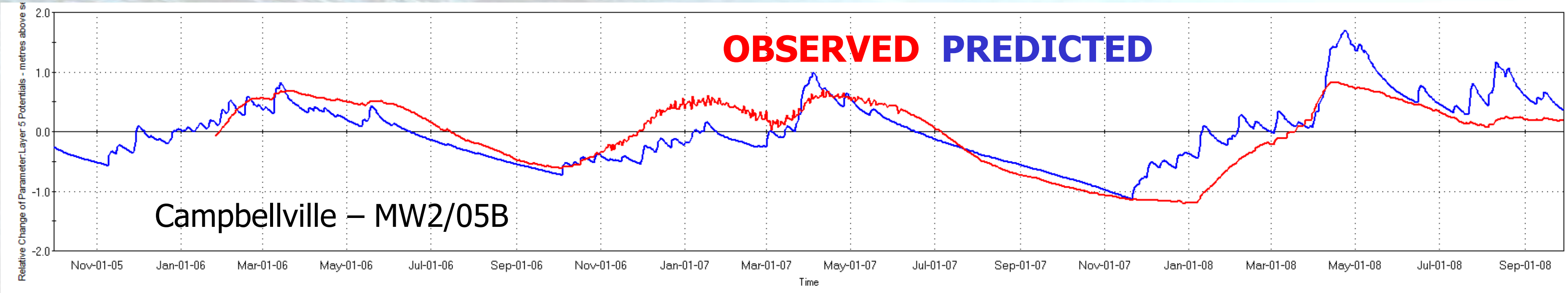
Transient Wellfield Drawdowns

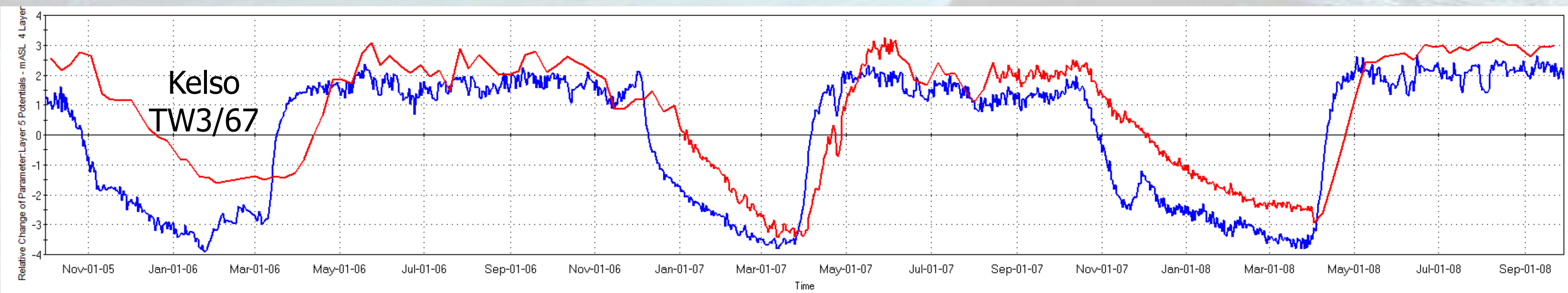
- Drawdown response varies with reservoir leakage

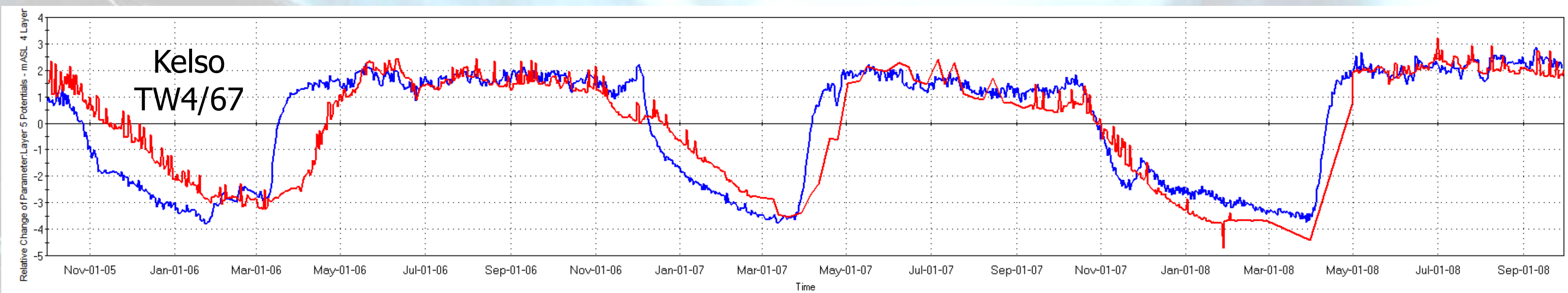


Earthfx Incorporated

Simulated Heads in Wellfield Monitors

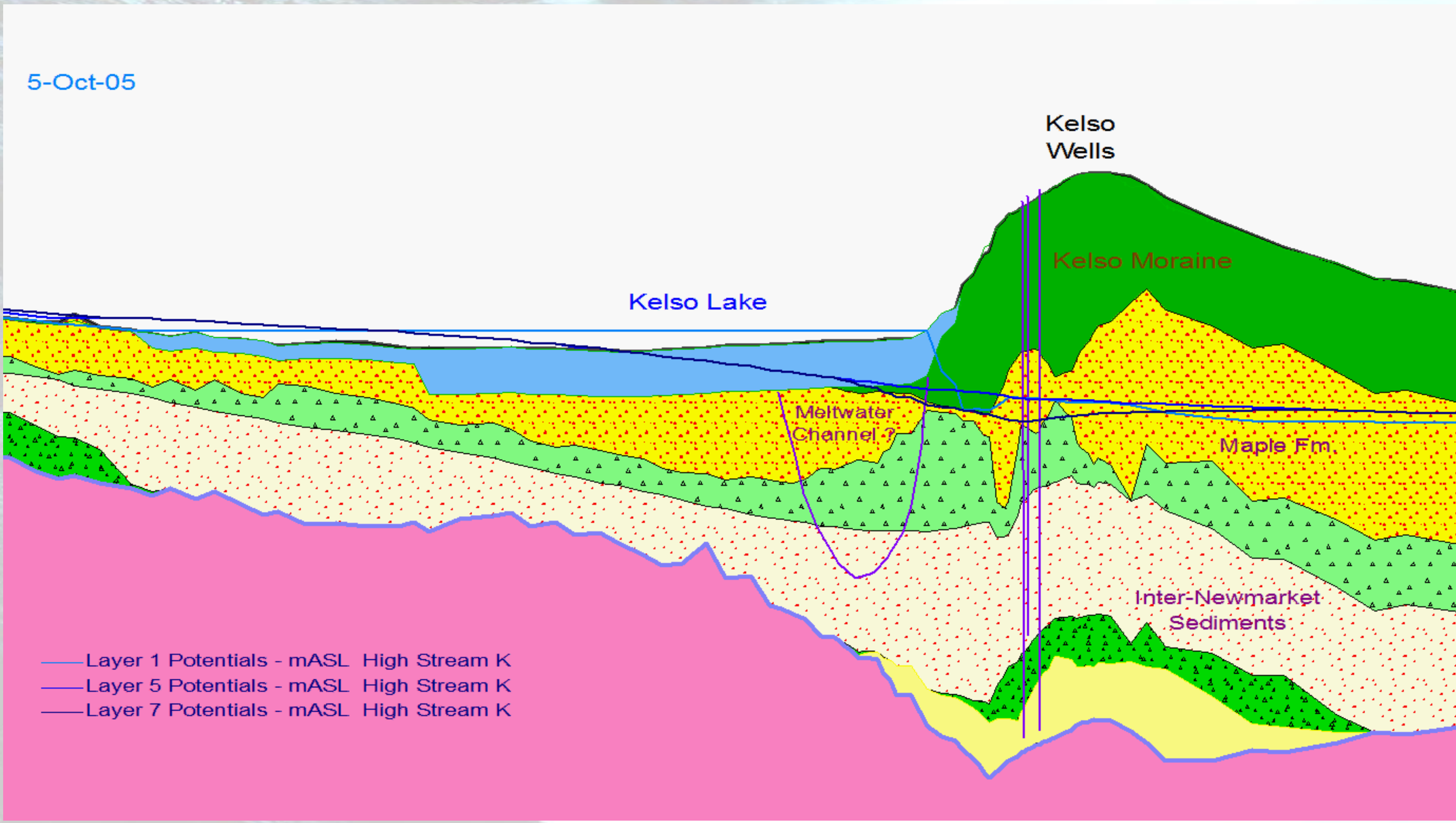






Earthfx Incorporated

Kelso wells out of phase with normal seasonal response.
Shows influence of high leakage from lake at summer stage



Cross section through wellfield and reservoir

Earthfx Incorporated

Conclusions: GSFLOW

- GSFLOW: An integrated model based on two powerful and mature SW and GW models
  - MODFLOW, but adapted to handle shallow wet/dry problems
  - PRMS, but cell based and fully distributed
  - Plus – support for different grid resolutions and channels
- Capable of representing the complex shallow flow system, plus real world stream and reservoir hydraulics
- Ideal for:
  - Analysis of cumulative impact of GW takings on SW features
  - Eco-hydrology, fisheries, drought and low-flow condition analysis
  - Problems involving pits, lakes and wetlands that incise one or more subsurface layers

Summary: New Conceptual Models

- New isotope analysis requires that we consider a significant portion of streamflow response as "event mobilized groundwater"
  - Overland runoff is not the dominant process
  - Old conceptual models of the unsaturated zone with predominantly vertical flow need to be discarded
- Modelling suggests that the key processes are:
  - Soil zone storage and cascading soil zone interflow
  - Aquifer/aquitard saturated interface flow
- Simulations suggest that runoff response in natural basins is highly variable and actually groundwater controlled

Conclusions

- Is it SW/GW or GW/SW?

- Answer: isotope analysis indicates:

  SW = fast GW!

Earthfx Incorporated

Thanks

- Jeff McDonnell, 2011 Birdsall-Dreiss Lecturer
- Conservation Halton

Earthfx Incorporated