Development of a Geospatial Approach for Assessing Groundwater Connectivity for Land Planning Activities

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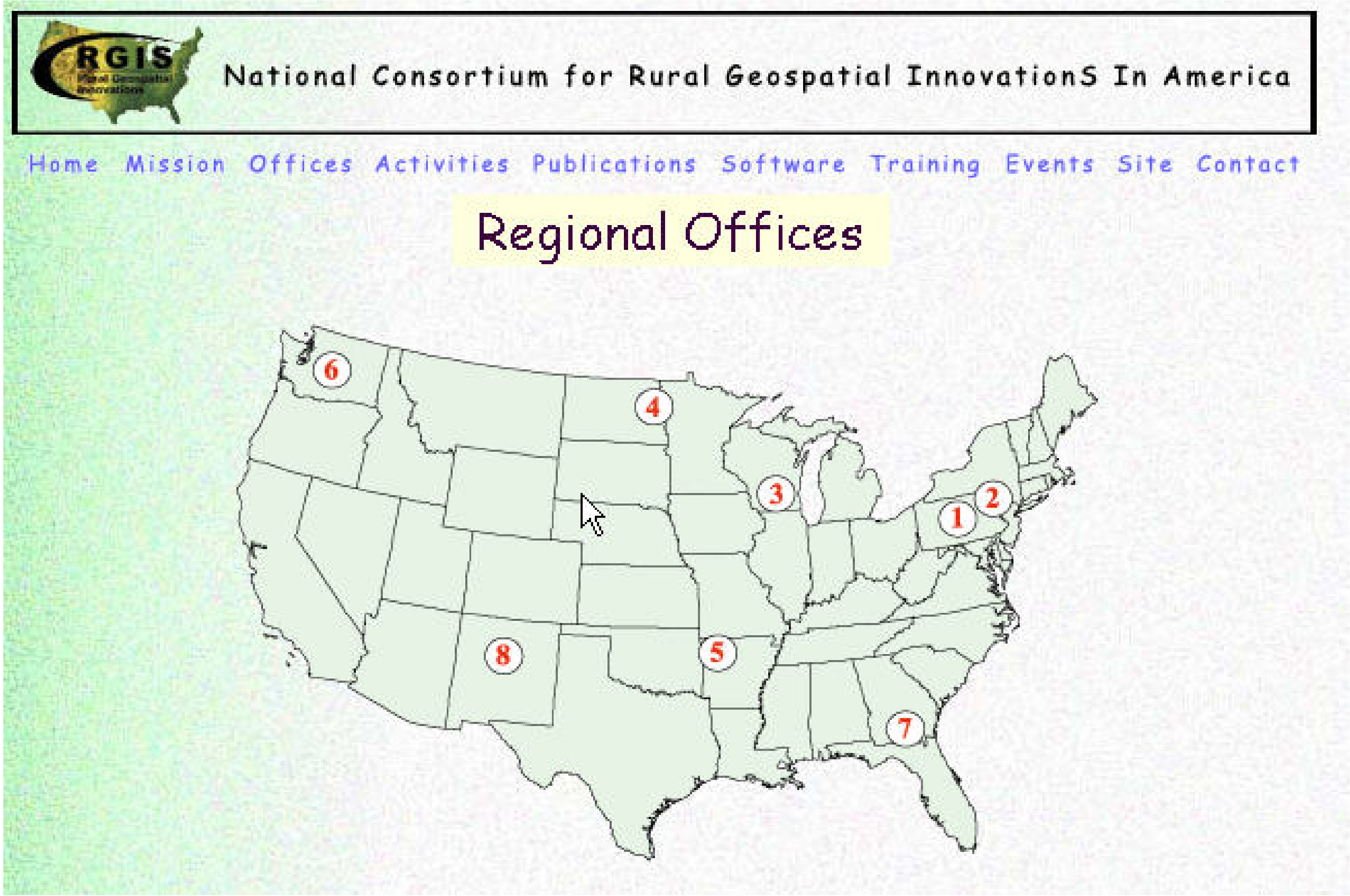


Understanding groundwater connectivity dynamics is important for:

- Effective forward-planning for both conservation and sustainable development;
- Gaining improved understanding of groundwater inputs that maintain critical wetland habitats and summertime in-stream flows (Bradley, 1996);
- Implementing aspects of government legislation for improved water supply and habitat management (e.g. Washington Shoreline Management Program – delineation of ‘associated wetlands’).

Project Goals

- Develop reliable method to enable governments to integrate groundwater considerations into their planning process.

- Method would provide the ability to:
  - Spatially delineate critical habitat and sources of groundwater recharge to floodplains and shorelines – i.e. *hydraulic connectivity*.
  - Track pollution sources and pathways that might potentially affect surface and groundwater supplies.

- Examine the utility of a groundwater model to provide rural communities with the necessary information.

Model Selection Criteria

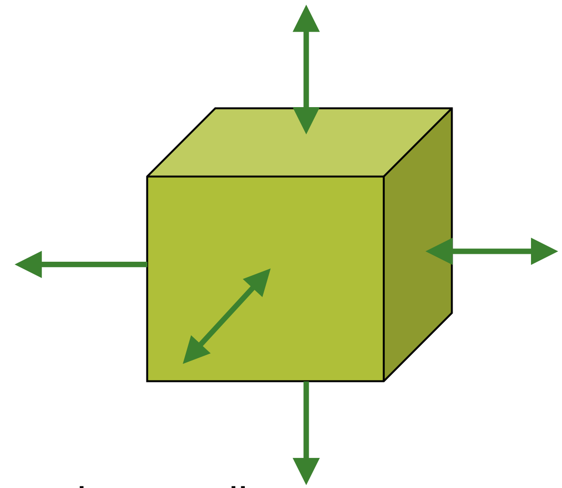
- Identify a groundwater modeling system that could:
  1. Characterize hydraulic connectivity between wetlands and river systems;
  2. Publicly available versions of the model online;
  3. User documentation available;
  4. Model development could be achieved using freely available government and geospatial datasets.

Numerical Groundwater Model: MODFLOW

- Publicly available, finite-difference computer model;
- Can be used to generated 1-D, 2-D, and 3-D hydrogeologic models;
- *Can generate hypothetical models* – uncalibrated, idealized representations of the groundwater flow regime;
- Can generate calibrated models where output is compared to observed data;

MODFLOW: Conservation of Fluid Mass

- Each grid cell represents an elemental control volume of saturated , porous media:



Mass flow in – mass flow out = change in mass storage

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}$$

Where:

K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, that are assumed to be parallel to the major axes of hydraulic conductivity (L/T);

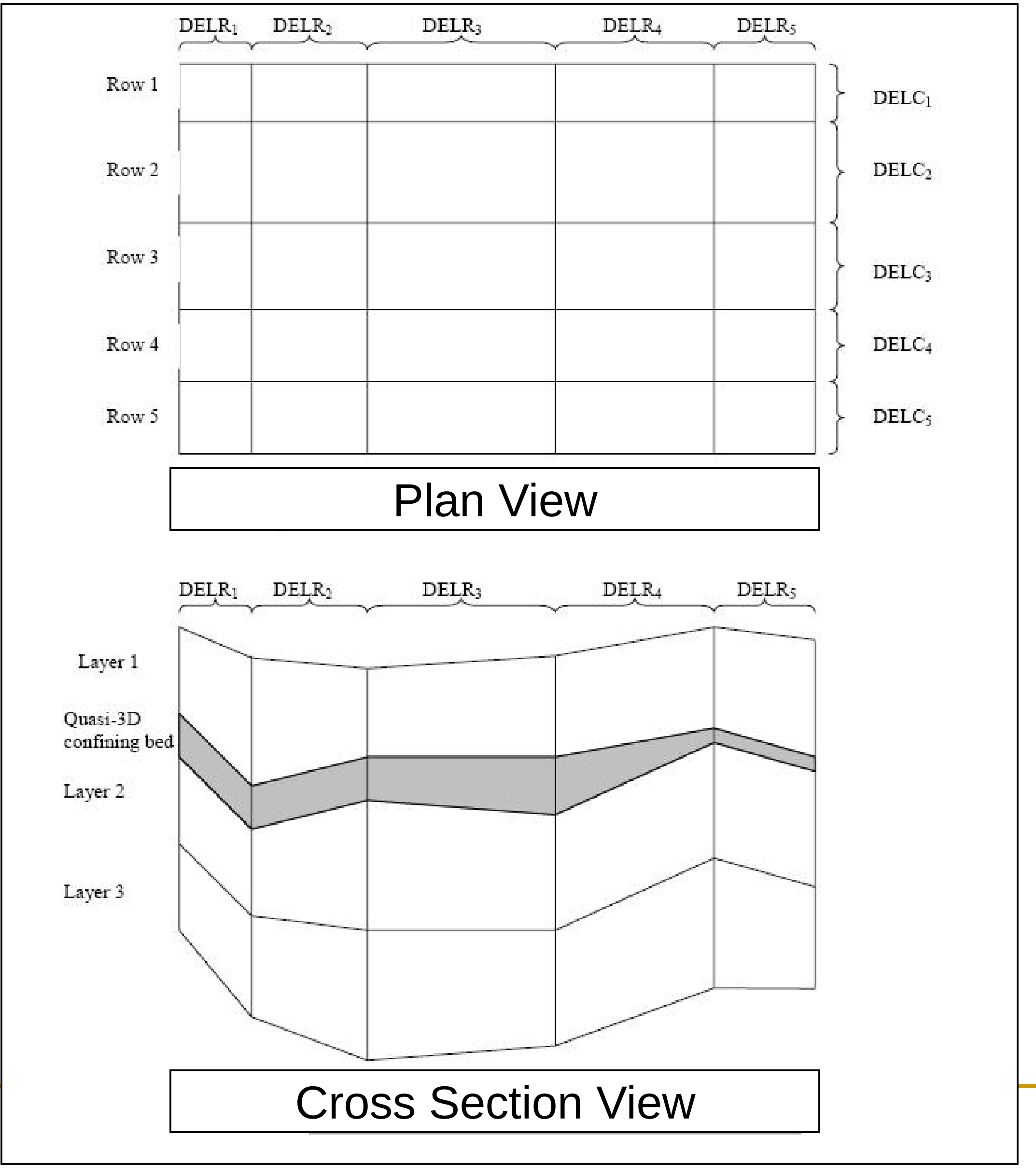
h is the potentiometric head (L);

W is a volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow in (t^{-1});

S_s is the specific storage of the porous material (L^{-1}); and

t is time (*t*)

MODFLOW Grid Analysis



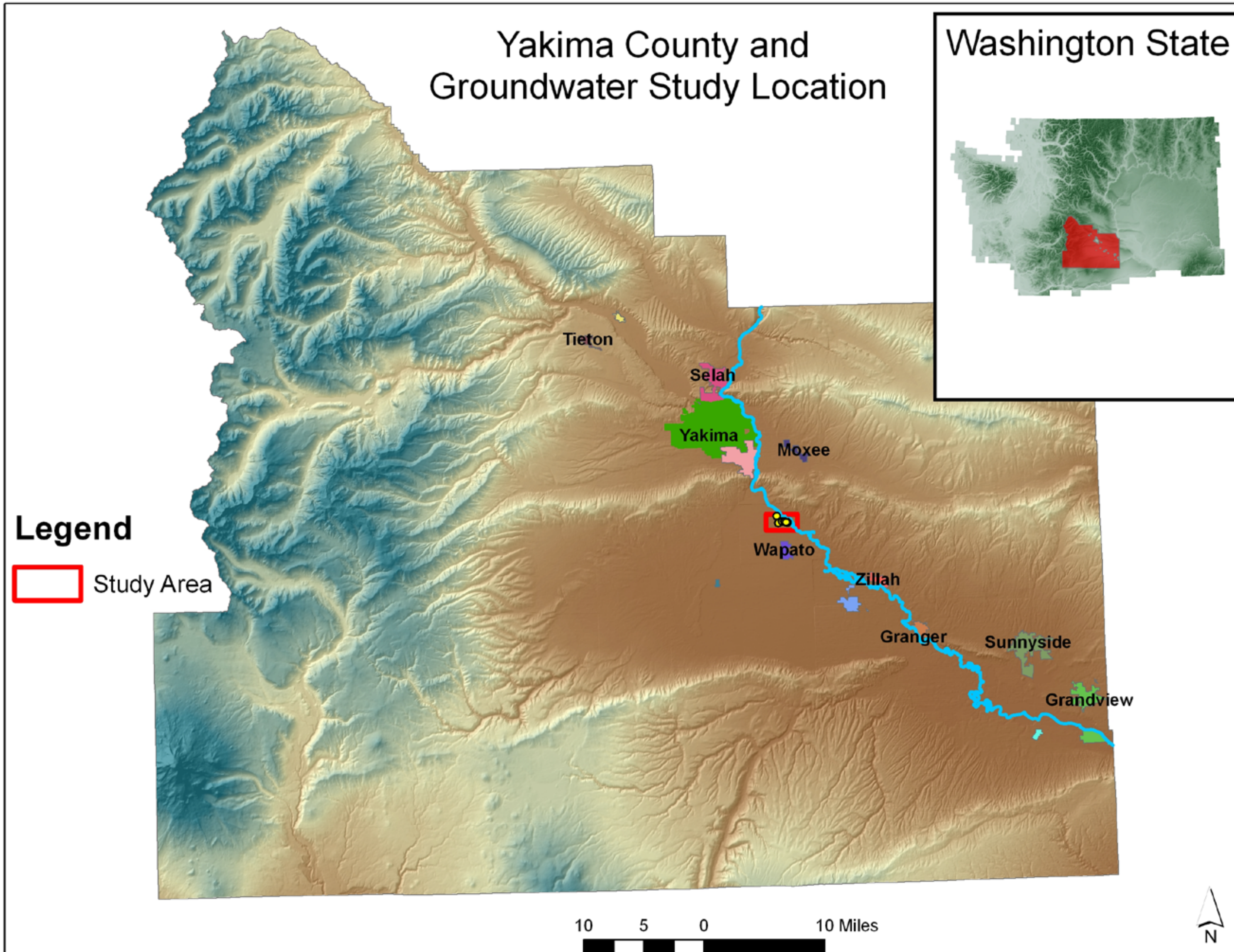
Data Requirements & Assumptions

- Geologic Stratigraphy (Government Reports; Well logs)
- Conductivity:
  - Hydraulic Conductivity (Kx, Ky, Kz): Government studies; Literature-based estimates.
- Effective Porosity (Eff. Por):
  - Government studies; literature-based estimates.
- Initial Heads:
  - STATSGO (State Soil Survey) water table elevation averages; field measurements; existing government reports.
- Steady State or Transient State Assumption
- Model Boundary Conditions – Constant Head, River Boundaries, Drains, Walls, Transient Recharge, ET

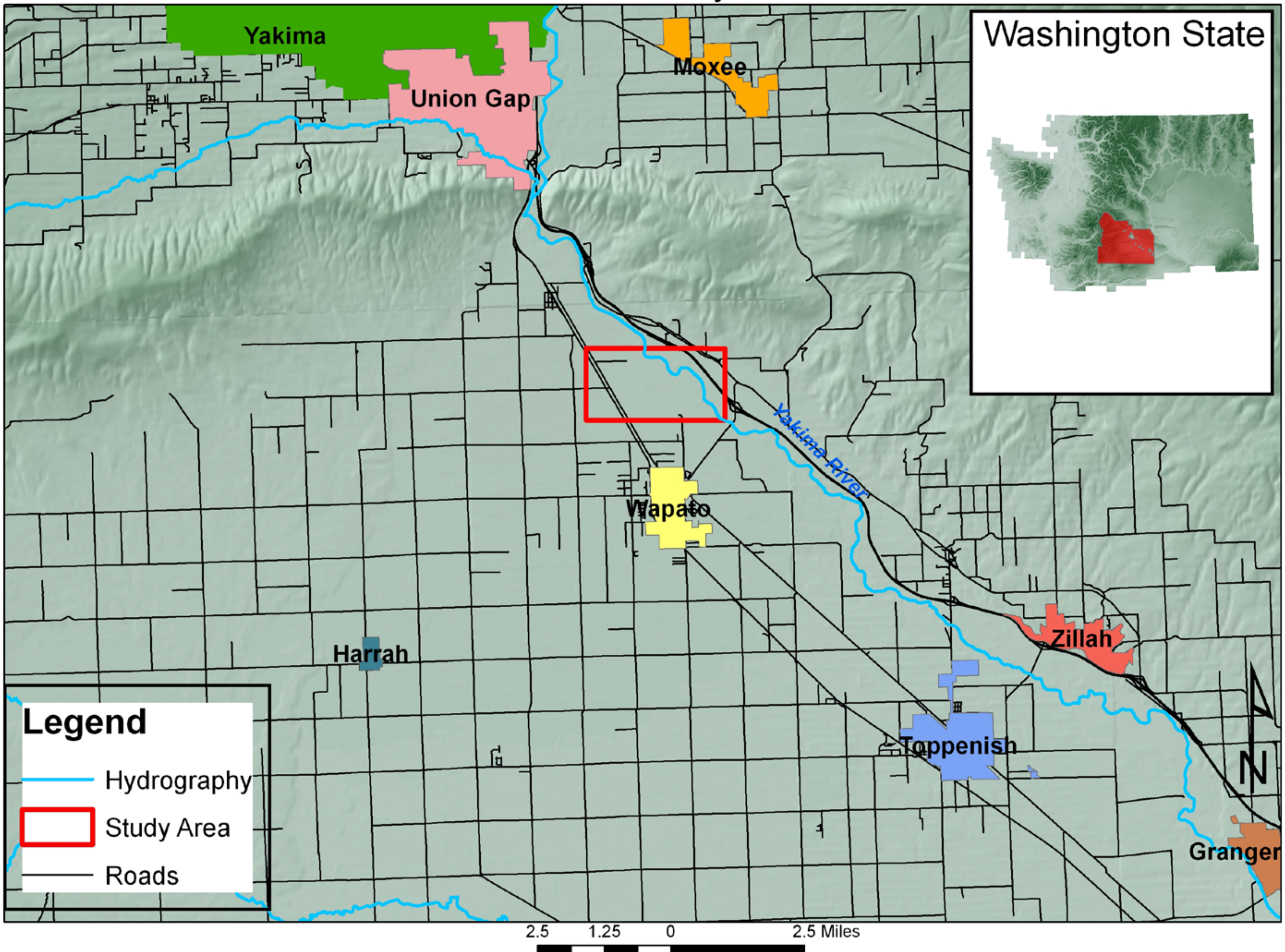
Case Studies:

Yakima River, Wapato, Washington

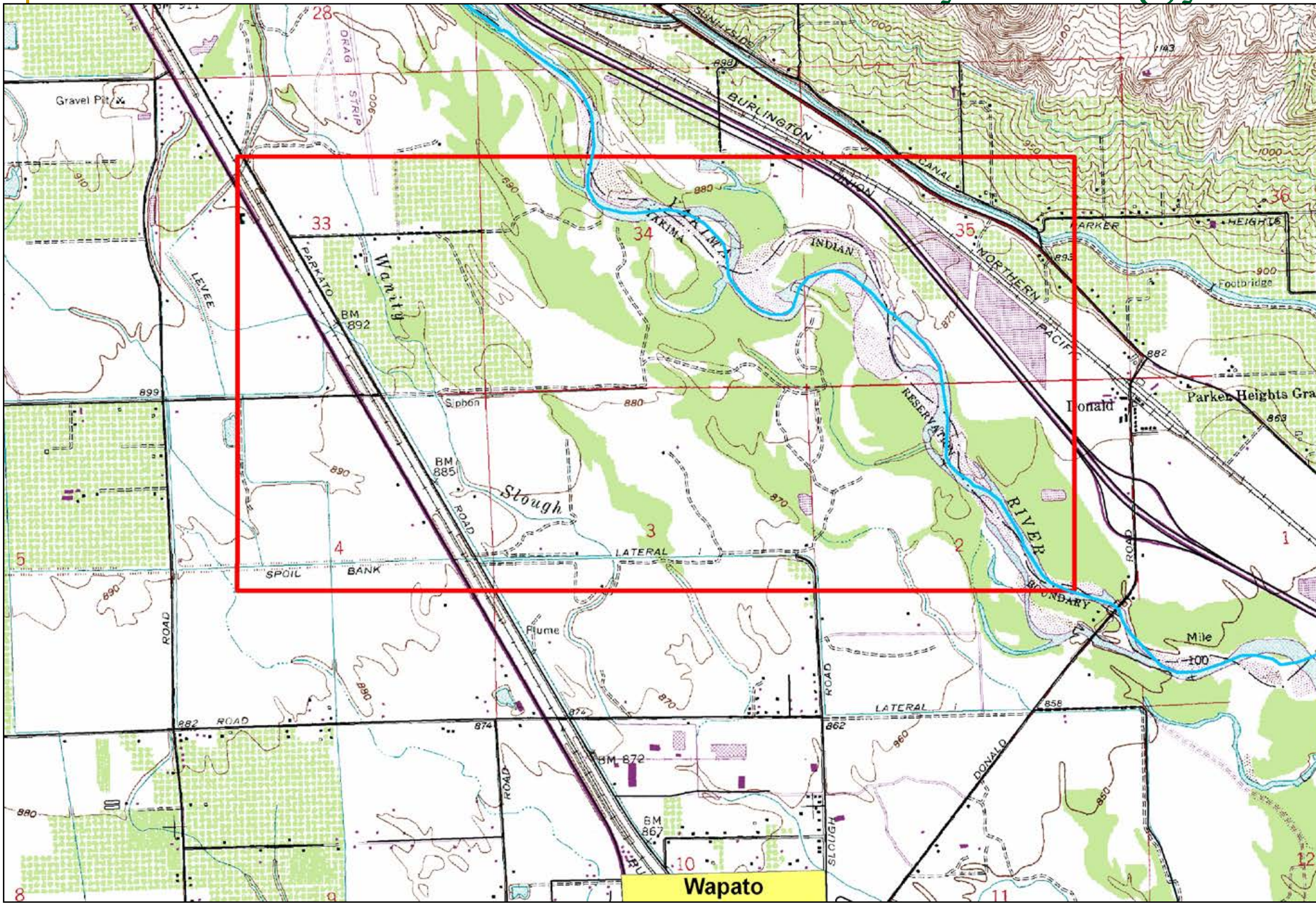
Nisqually River, Yelm, Washington


Yakima County and
Groundwater Study Location
Washington State
Legend
Study Area
Tieton
Selah
Yakima
Moxee
Wapato
Zillah
Granger
Sunnyside
Grandview
10
5
0
10 Miles
N

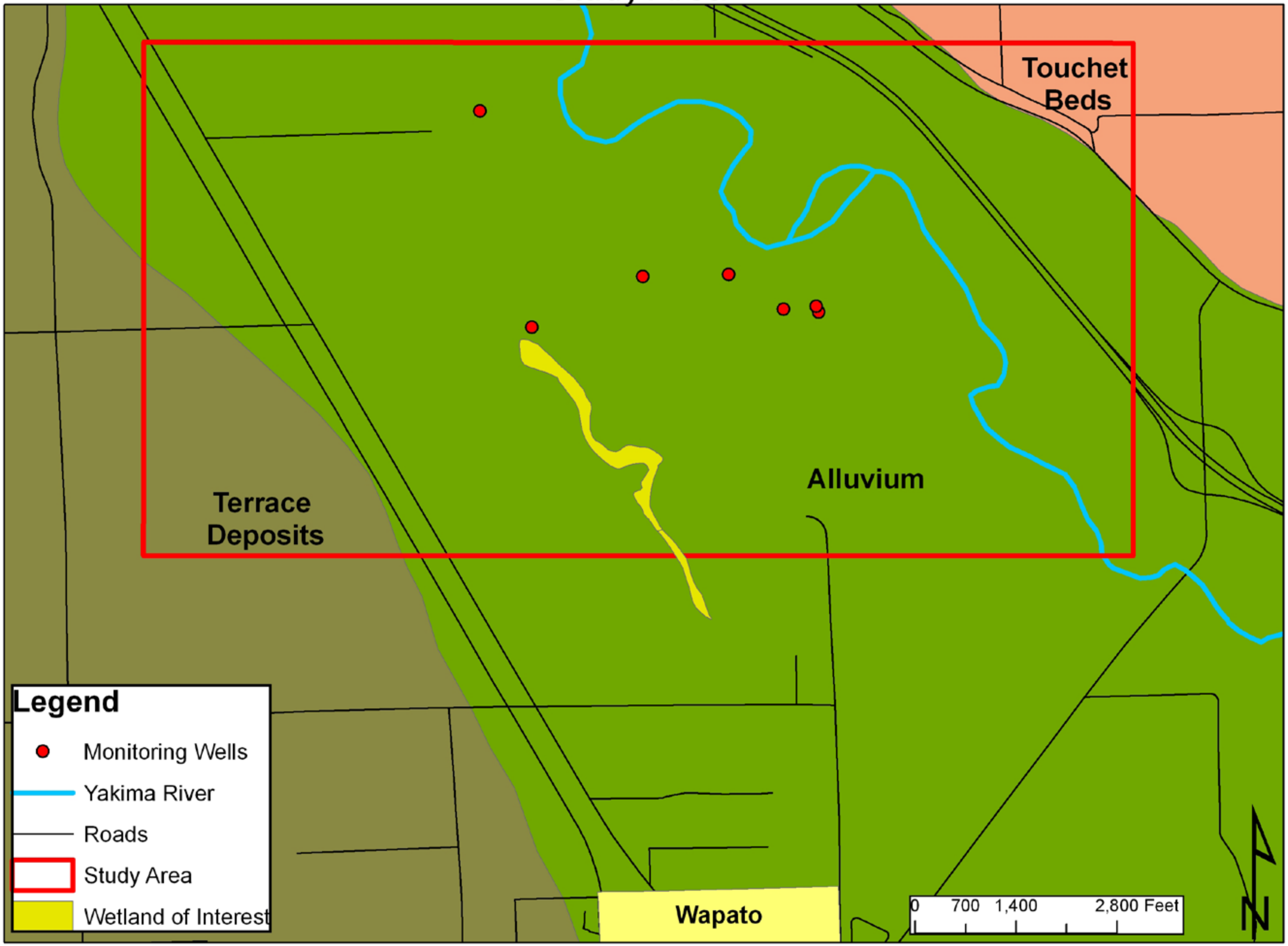
Yakima County and Groundwater Study Location



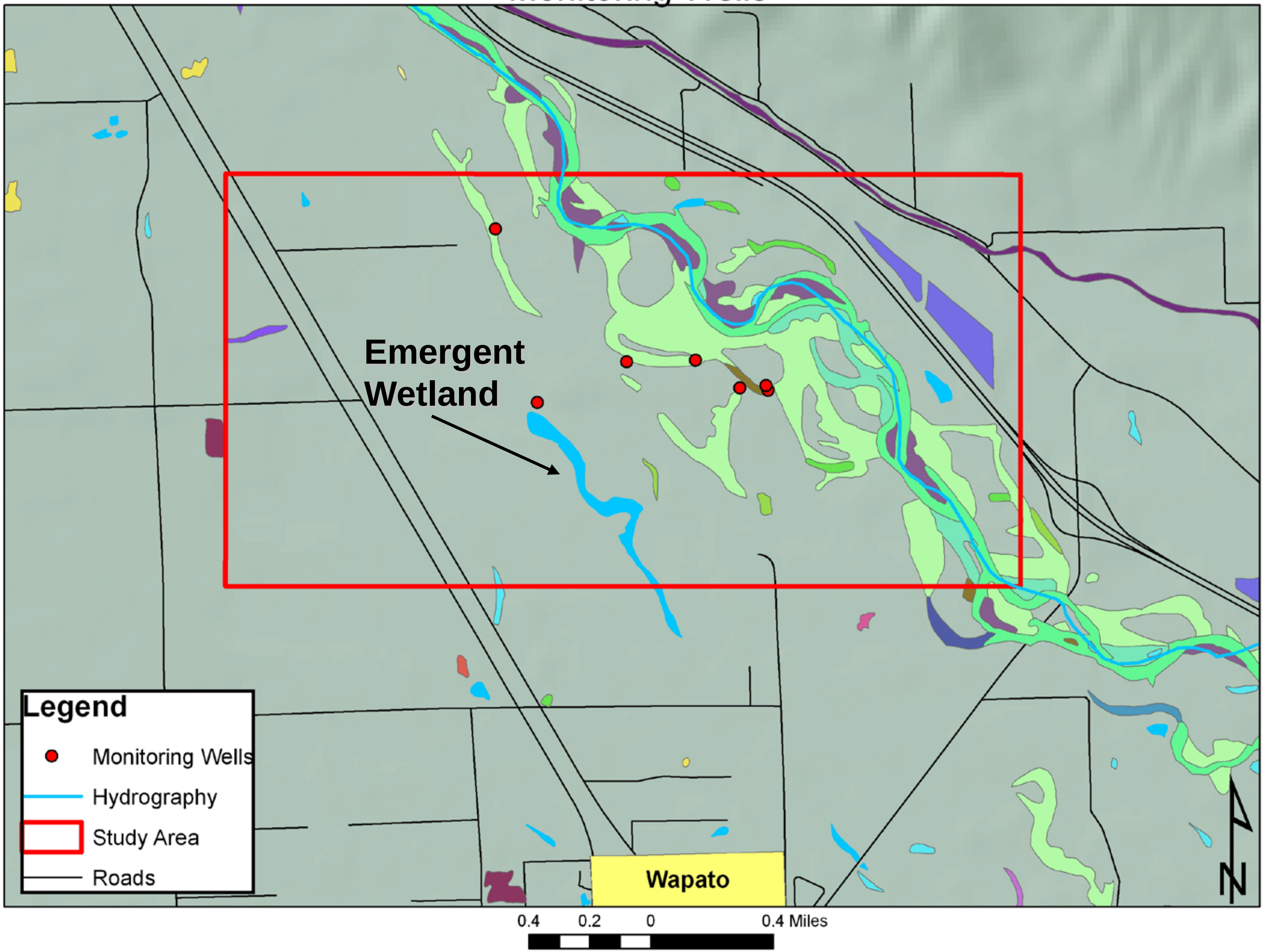
Site Location and Surface Hydrology



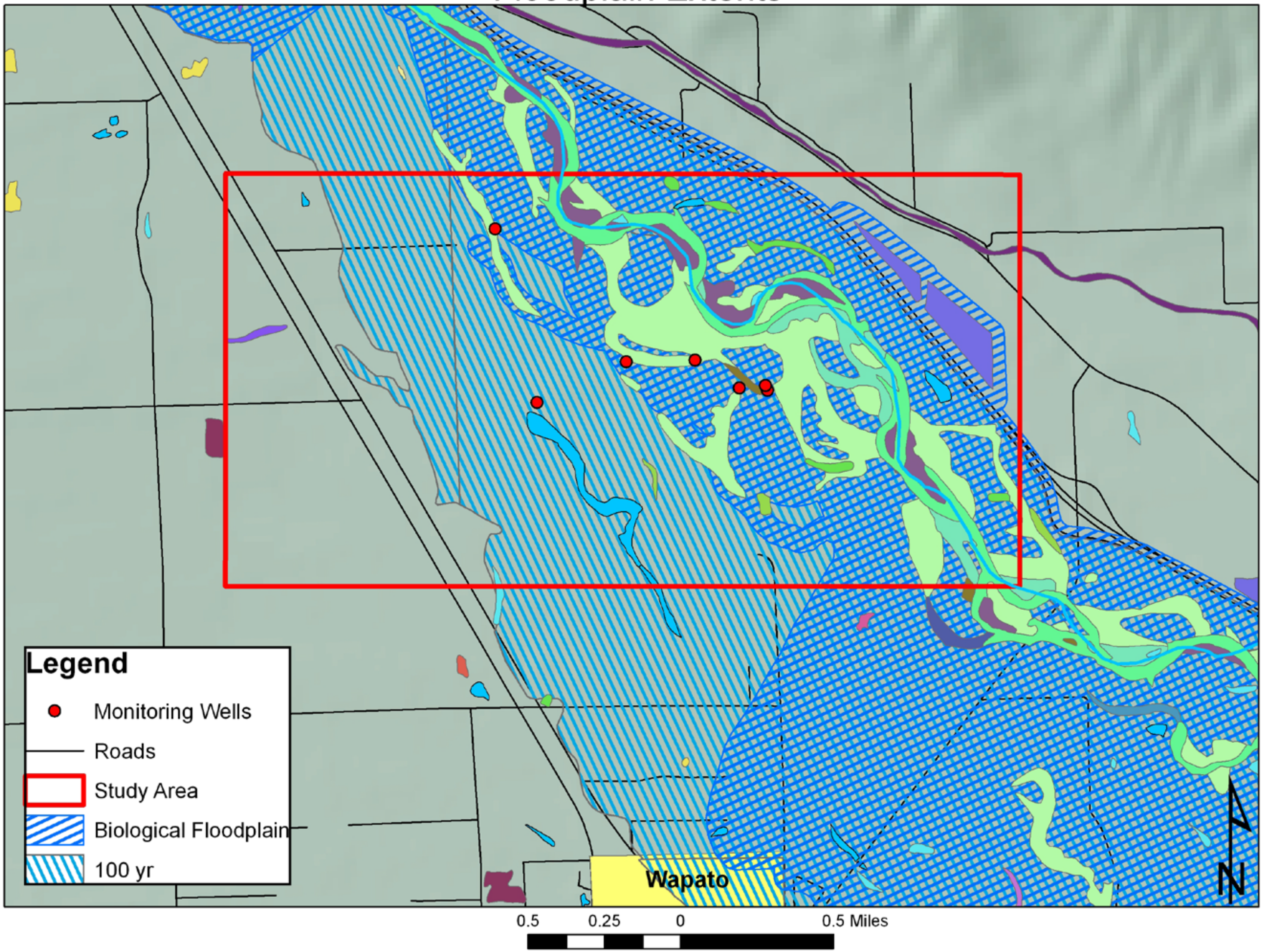
Geologic Deposits Within Study Area



NWI Wetland Locations and Groundwater Monitoring Wells



NWI Wetland Locations and Floodplain Extents



Data Collection and Model Development

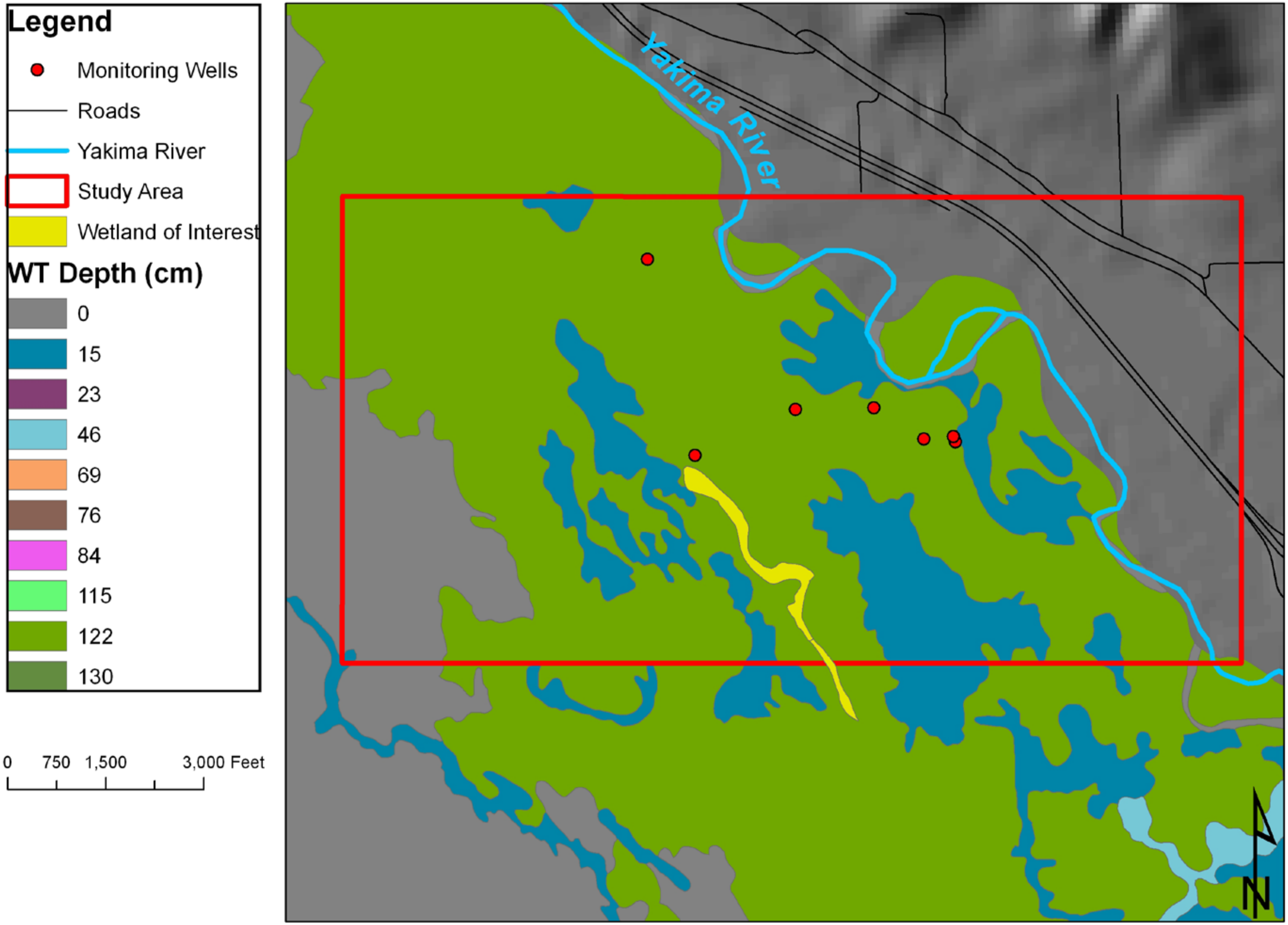
Hydrogeologic Setting:

- Stratigraphy – Used well logs for the area, downloaded from WADOE website; generally first 50 feet consisted on sand, gravel, and cobbles.
- Corresponded with USGS geologic studies:
  - Young alluvium, unconfined aquifer ranging from 50 – 500 ft thick;
  - Unconsolidated stream deposits of silt, sand, and gravel with cobbles throughout;
  - Interaction of surface water with groundwater occurs within a few tens of feet of land surface (Skrivan, 1987).

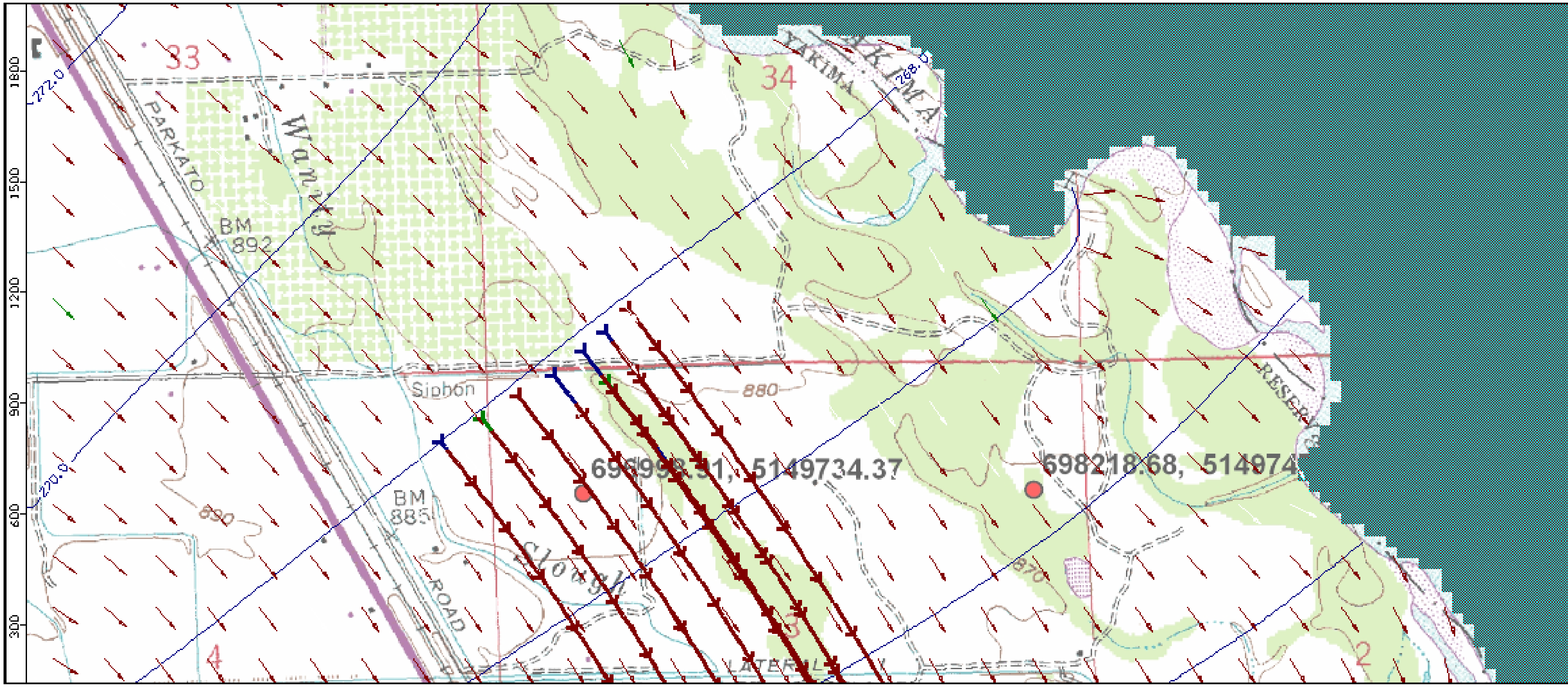
Data Collection and Model Development

- Hydraulic Conductivity values (K_x, K_y, K_z) obtained from literature (Prych, 1983)
- Effective Porosity: 15% (Wagner, 1995)
- Storage: Specific Yield = Porosity (Waterloo Hydrologeologic, 2005)
- Water Table Elevations:
  - STATSGO depth to water table estimates used for Constant Heads – Subtracted from DEM surface elevation.
  - Initial Heads - Field data used to interpolate head elevations for study area (Snyder, 2001).

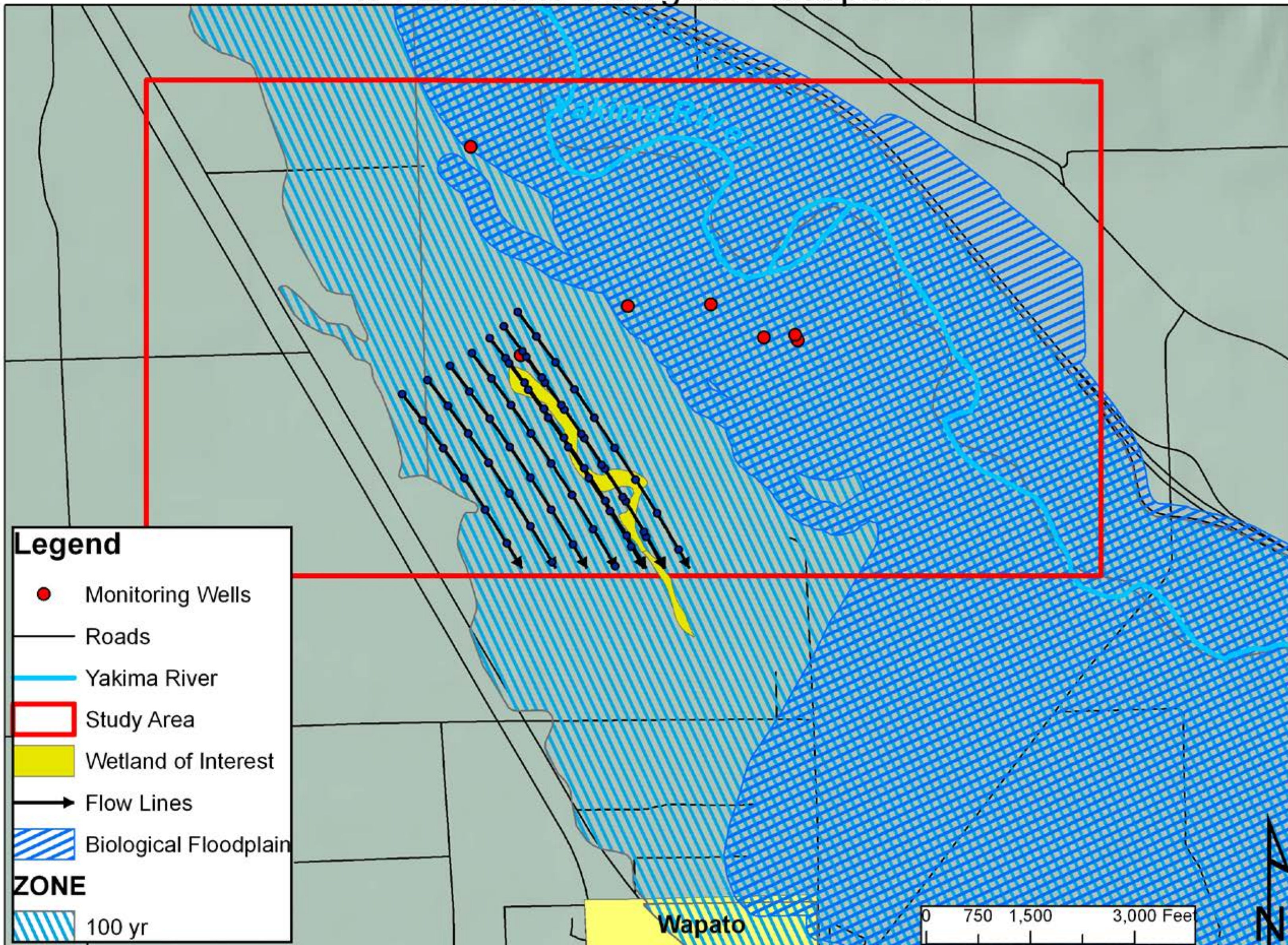
Depth to Water Table Gased on STATSGO Soils Data



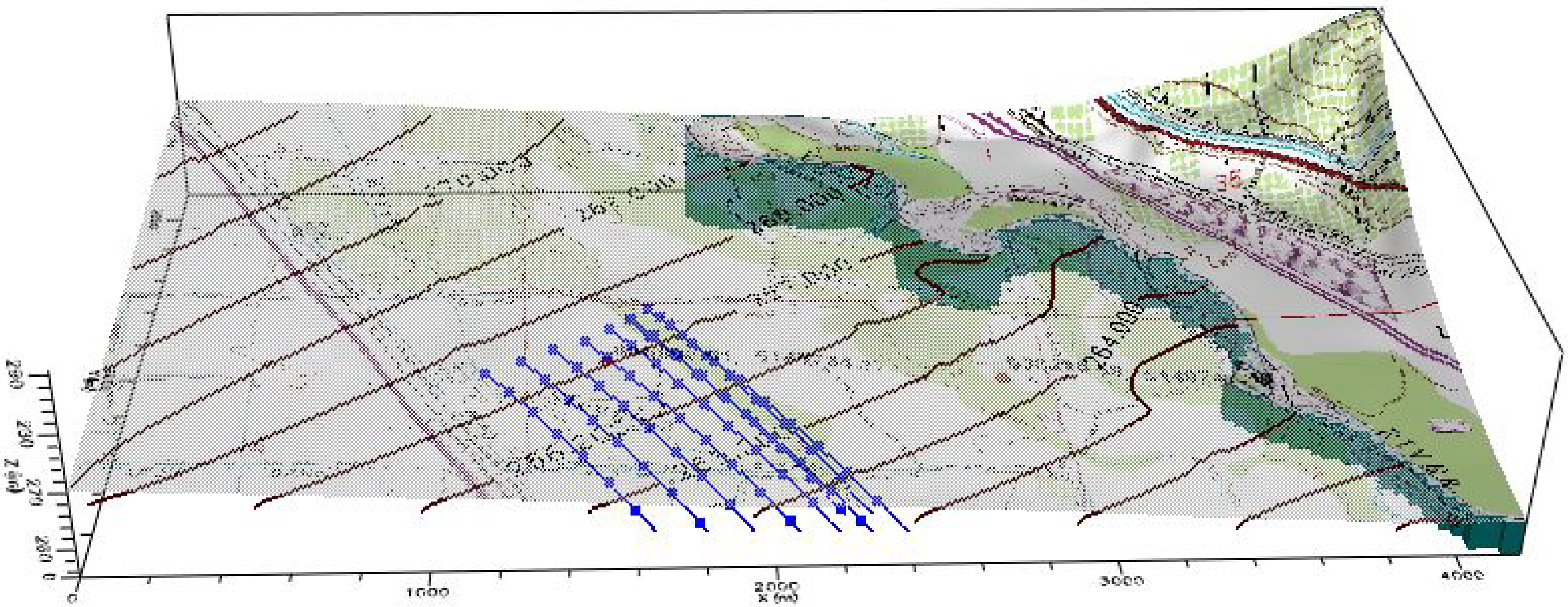
2-Dimensional Perspective of Groundwater Flow Direction within Unconfined Aquifer



Groundwater Flowlines in Relation to FEMA and Biological Floodplains



3-Dimensional Perspective of Predicted Flow Paths



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Limitations

- Vadose zone interactions not captured – however can be modeled with MODFLOW-SURFACT program – more data required!
- Constant head assumption – more realistic to implement a transient model that incorporates *precipitation* and *ET* – need more data to accomplish this as well!
- Conceptual model – not calibrated.

Strength of modeling approach:

- Identification of hydraulic connectivity between wetlands and biological floodplains – Provides an *initial scoping tool* – model can be extended if results warrant a more in depth investigation.
- ‘Associated Wetlands’ delineation based on SMP legislation.
- Contamination plume analysis (direction of travel, rate of travel, ID water bodies at risk).
- Land use decision support – Identify potential risks to groundwater, wetland, and river environments based on ‘what if?’ scenarios.
- Entire approach utilized freely available data and model (MODFLOW) – model can be expanded as data becomes available.

Thank you!

Questions?

Acknowledgements

- USDA-CSREES – funding support
- Central Washington University – Hardware and software support.

References

Bradley, C. (1996). Transient modelling of water-table variation floodplain wetland, Narborough Bog, Leicestershire. *Journal of Hydrology 185*, pp. 87-114.

Prych, E. A. (1983). Numerical simulation of ground-water flow in lower Satus Creek Basin, Yakima Indian Reservation. Water-Resources Investigations 82-4065. U.S. Geological Survey: Tacoma, WA.

Skrivan, J. A. (1987). Ground-water hydrology of the Toppenish Creek Basin, Yakima Indian Reservation, Washington. Water-Resources Investigations 82-4010. U.S. Geological Survey: Tacoma, WA.

Wagner, R. J. (1995). Areal extent of petroleum-related compounds from a gasoline and diesel-fuel leak in ground water at a site in Yakima, Washington, 1984-1989. Water-Resources Investigations 92-4017. U.S. Geological Survey:Tacoma, WA.

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Groundwater Modeling

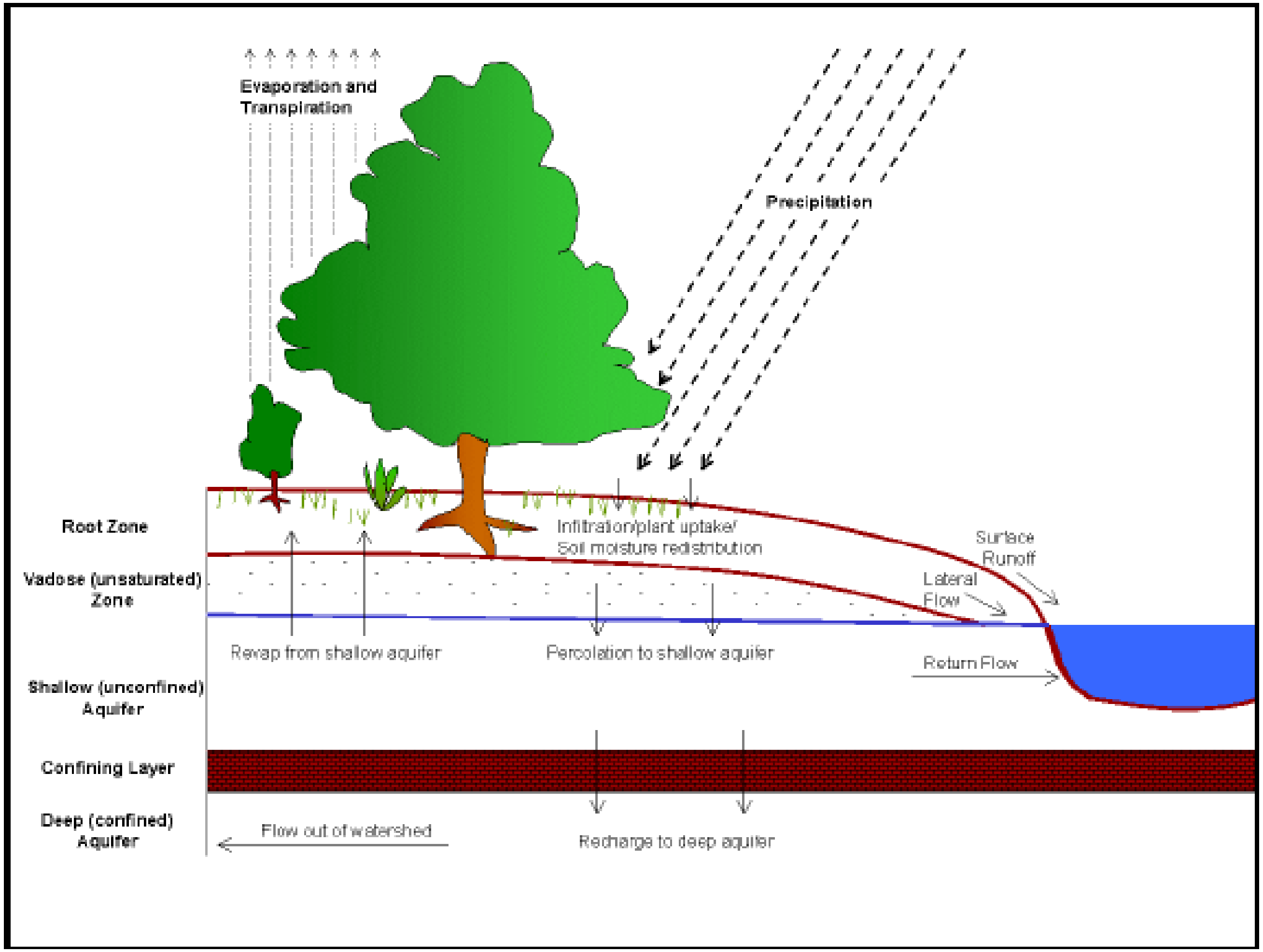
- Groundwater modeling can play an important role within a hydrogeologic study

- It involves developing tools (i.e. models) to represent the processes that occur in the groundwater environment so that system behavior predictions can be made.

- For example:
  - Regional or local groundwater flow direction
  - Groundwater – surface water interactions
  - Contaminant plume concentrations at specific points

- The more representative the modeling tool is of reality, the more reliable the predictions

System processes



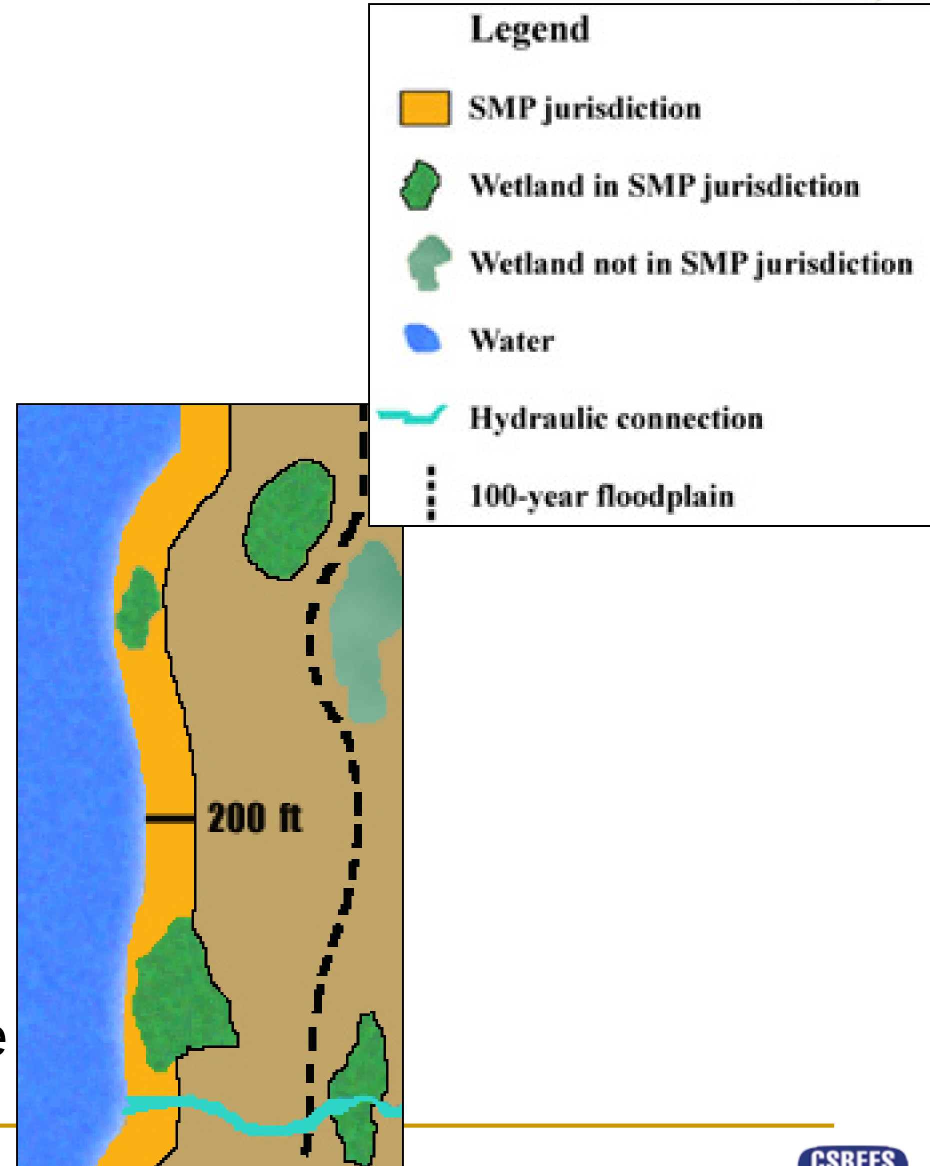
Mathematical equations are used to characterize each of the processes

Policy case study: Shorelands and Associated Wetlands

- The land areas and wetlands bordering the shorelines of the state that are under jurisdiction of the Shoreline Management Act are called "**shorelands**."
- The Act defines a minimum geographic area and also provides local government options to include a greater area within its master program.

Considering all the factors

- A wetland's hydrology does not have to be in a defined channel to be considered associated.
- Hydraulic continuity clues include undrained hydric soils continuous with the waterbody, and sheet flow from the site during or following precipitation events.
- In some cases wetlands *outside* the 100-year floodplain *may* be associated if they are hydraulically connected with shoreline waters through surface or subsurface flows.



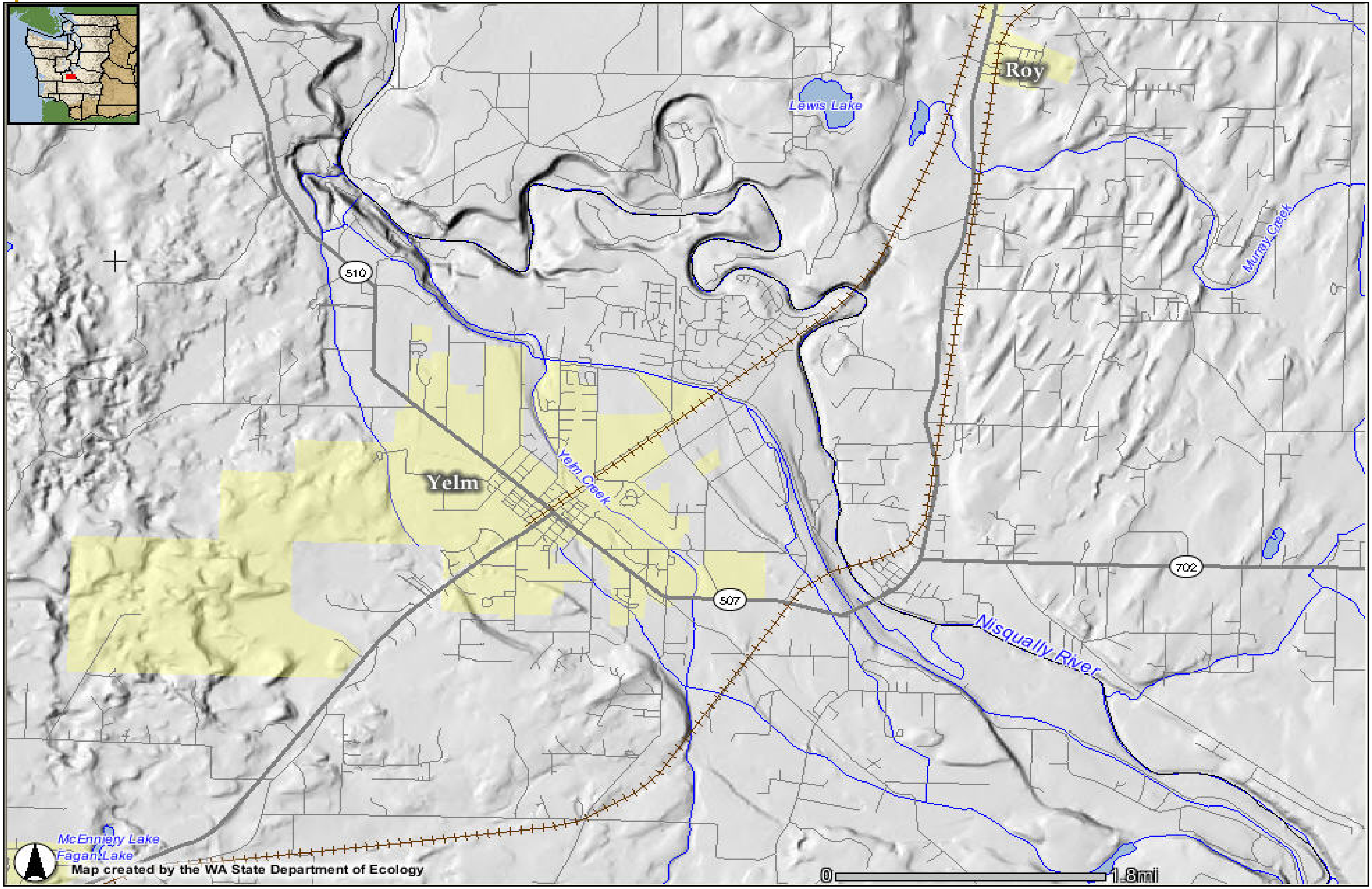
‘Grey Areas’

- Establishment of Shoreline Management Program jurisdictions for Lakes and Streams is somewhat straight forward (e.g. Ortho photos, GIS data, DOQs, Floodplain maps all provide visual data that can aid assessment)
- However, ‘Associated wetlands’ may be difficult in some cases – Subsurface connectivity?
- Which wetlands should be classified as ‘associated’ and therefore included?

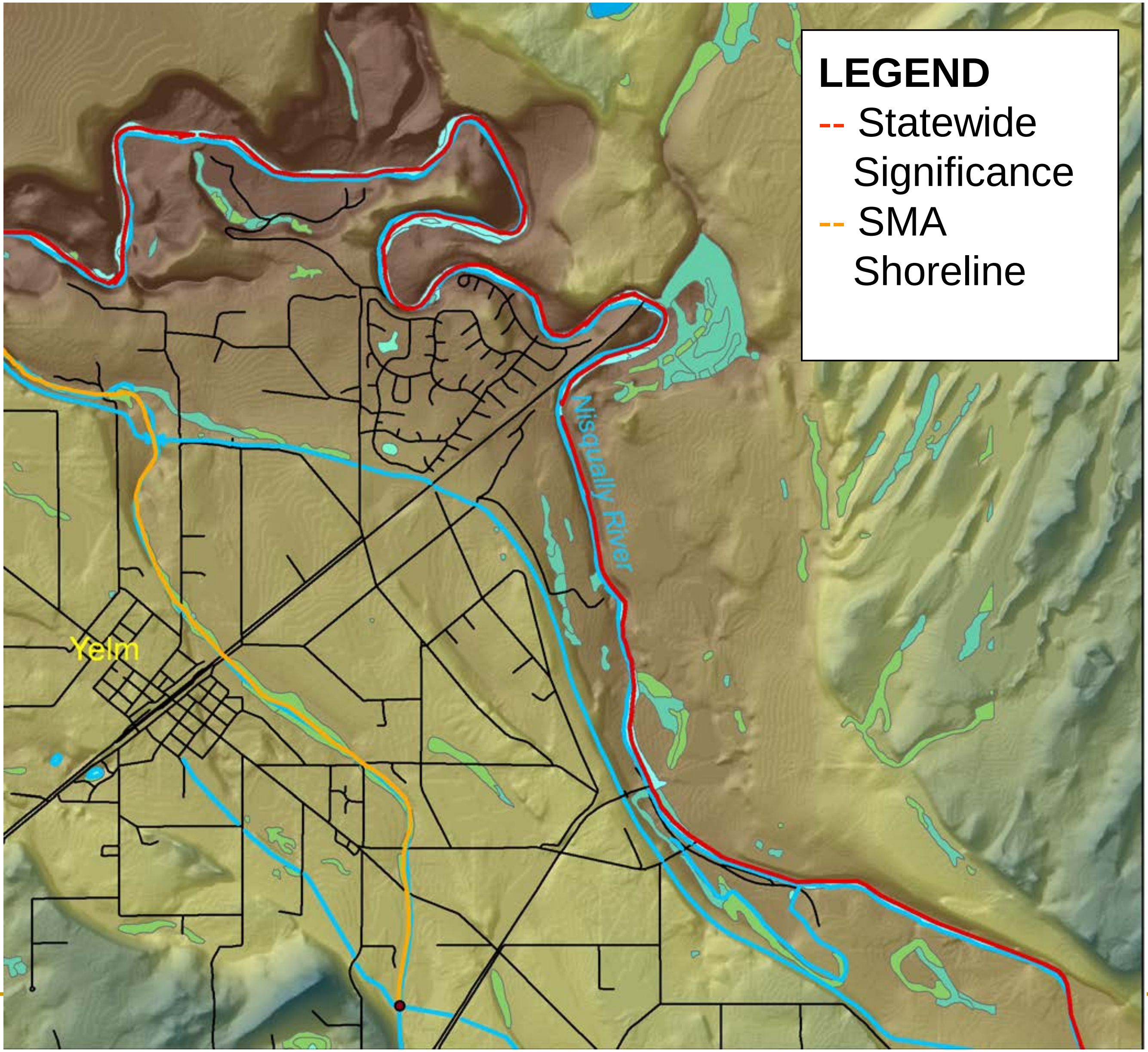
Associated Wetland assessment using MODFLOW

- Case study approach: SMP applicaiton
  - Yelm, Washington (East side of Cascade Mtns.)
  - Apply MODFLOW to develop an uncalibrated groundwater model that could provide additional information to determine hydraulic connectivity of questionable ‘associated wetlands’.

Case Study 1: Yelm, Thurston County, WA



Designated SMA Streams



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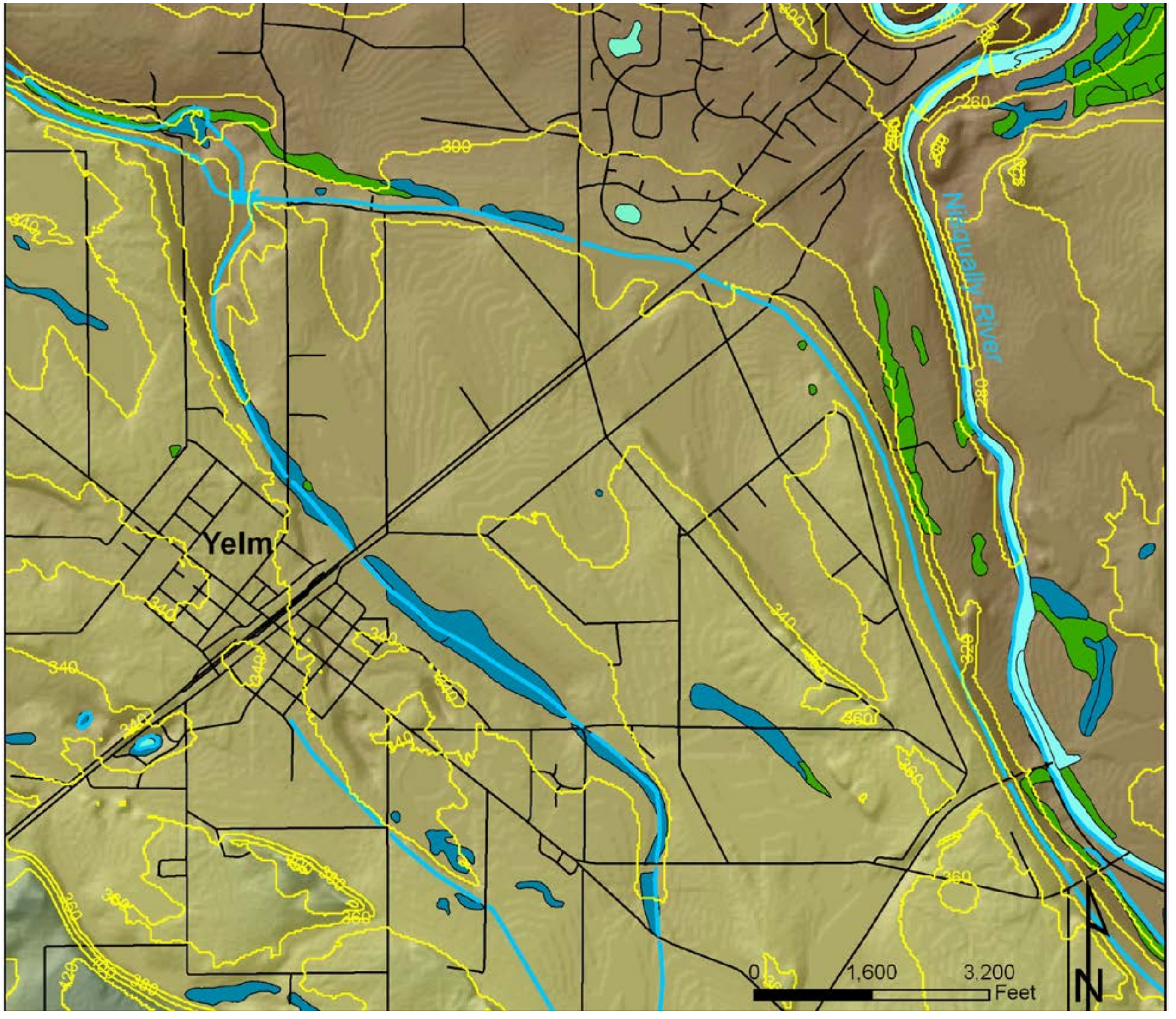
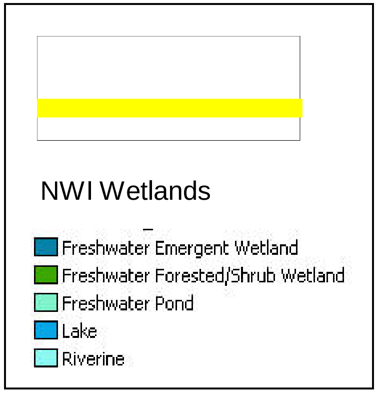
Area of Interest and Local Wetlands





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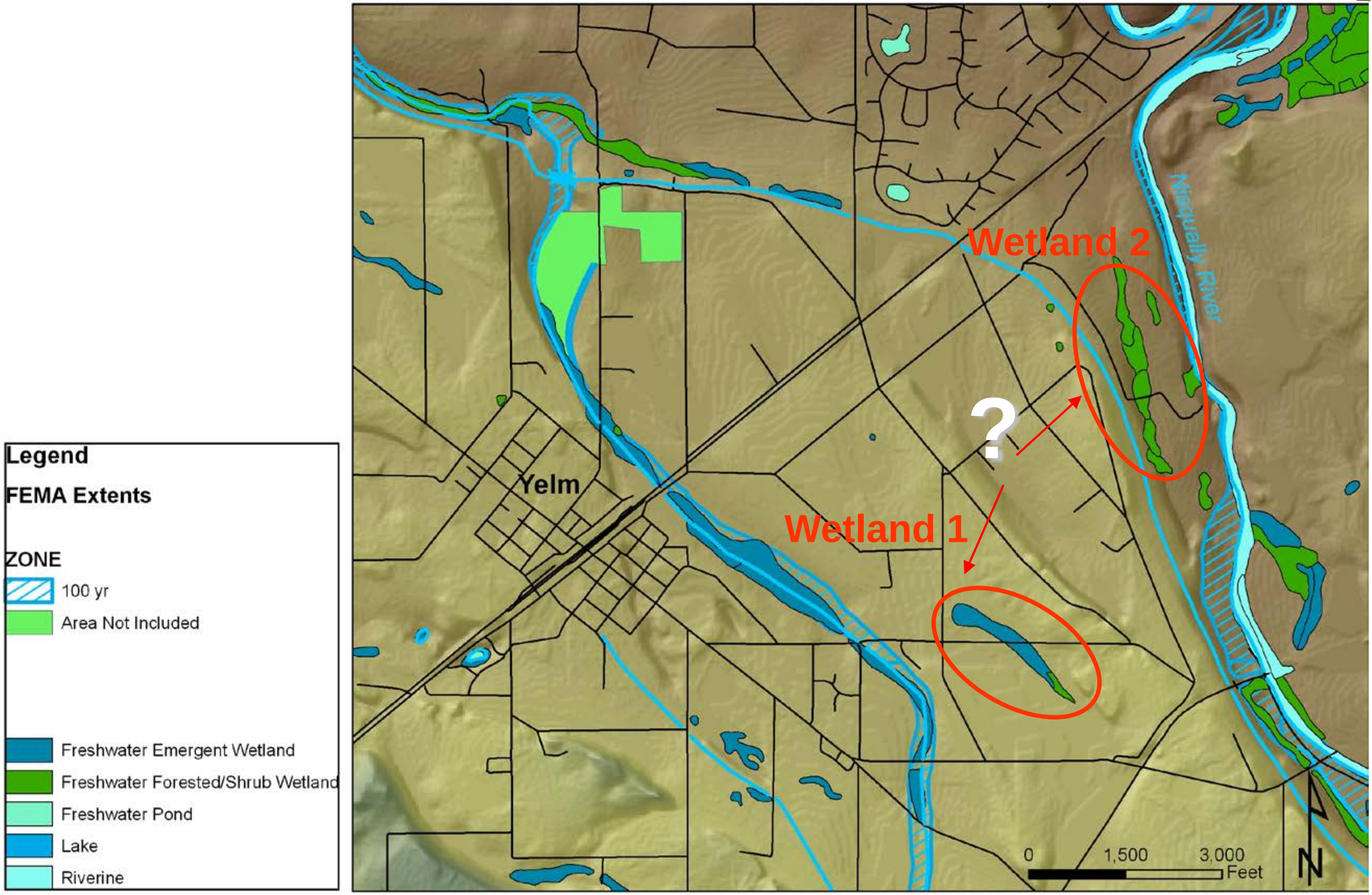
FEMA extents and NWI Wetlands



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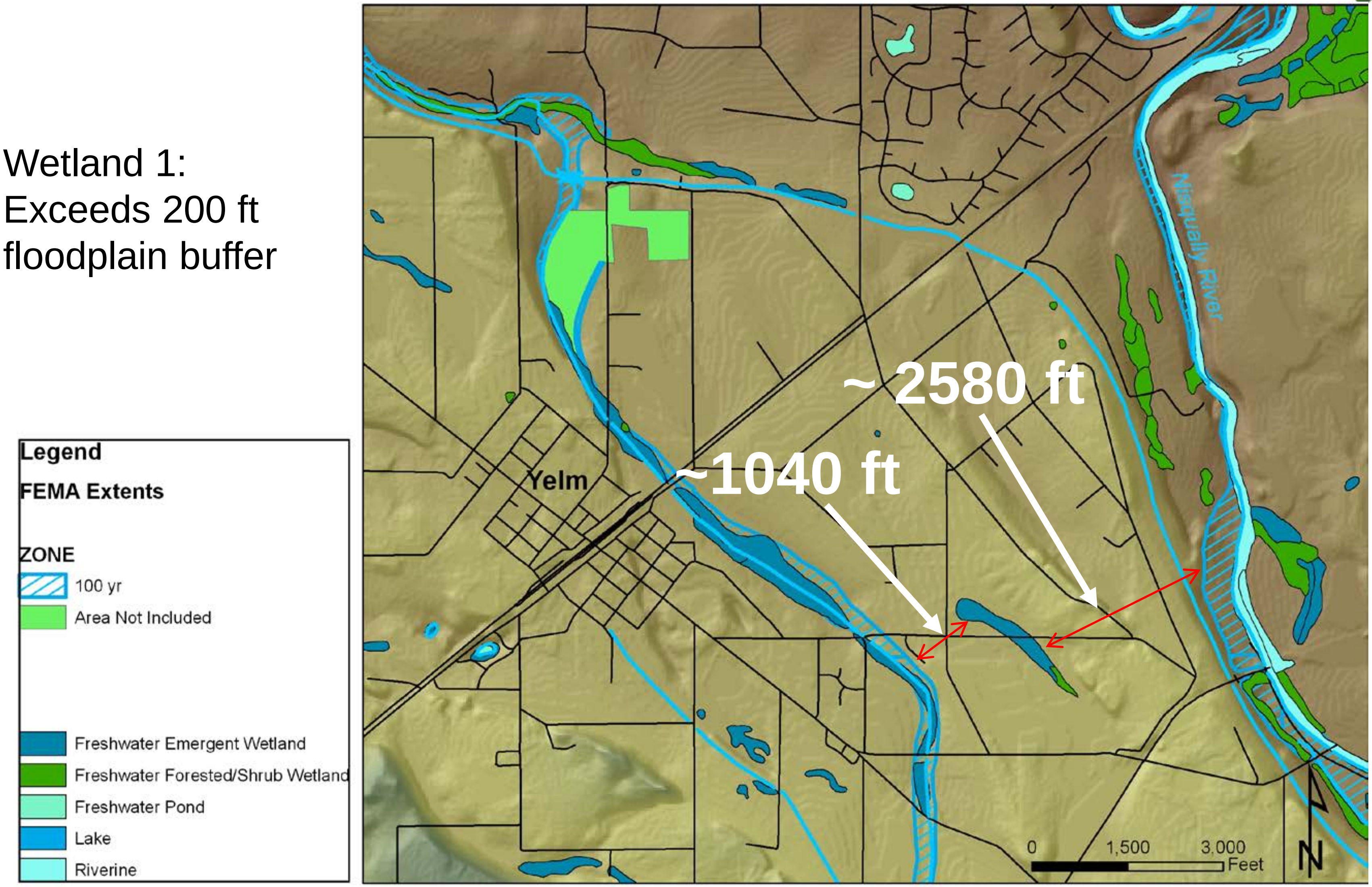
FEMA extents and NWI Wetlands

Wetland 1:
Exceeds 200 ft floodplain buffer



Are these 'Associated Wetland'?

- Is it outside the 100 yr FEMA floodplain? Yes!
- Is it outside 200 ft buffer of the FEMA floodplain? Yes!
- Is it connected by surface hydrology? Does not appear to be.
- Is it hydraulically connected by subsurface flow? Difficult to assess based on this data…
- Groundwater Modeling could provide needed information!

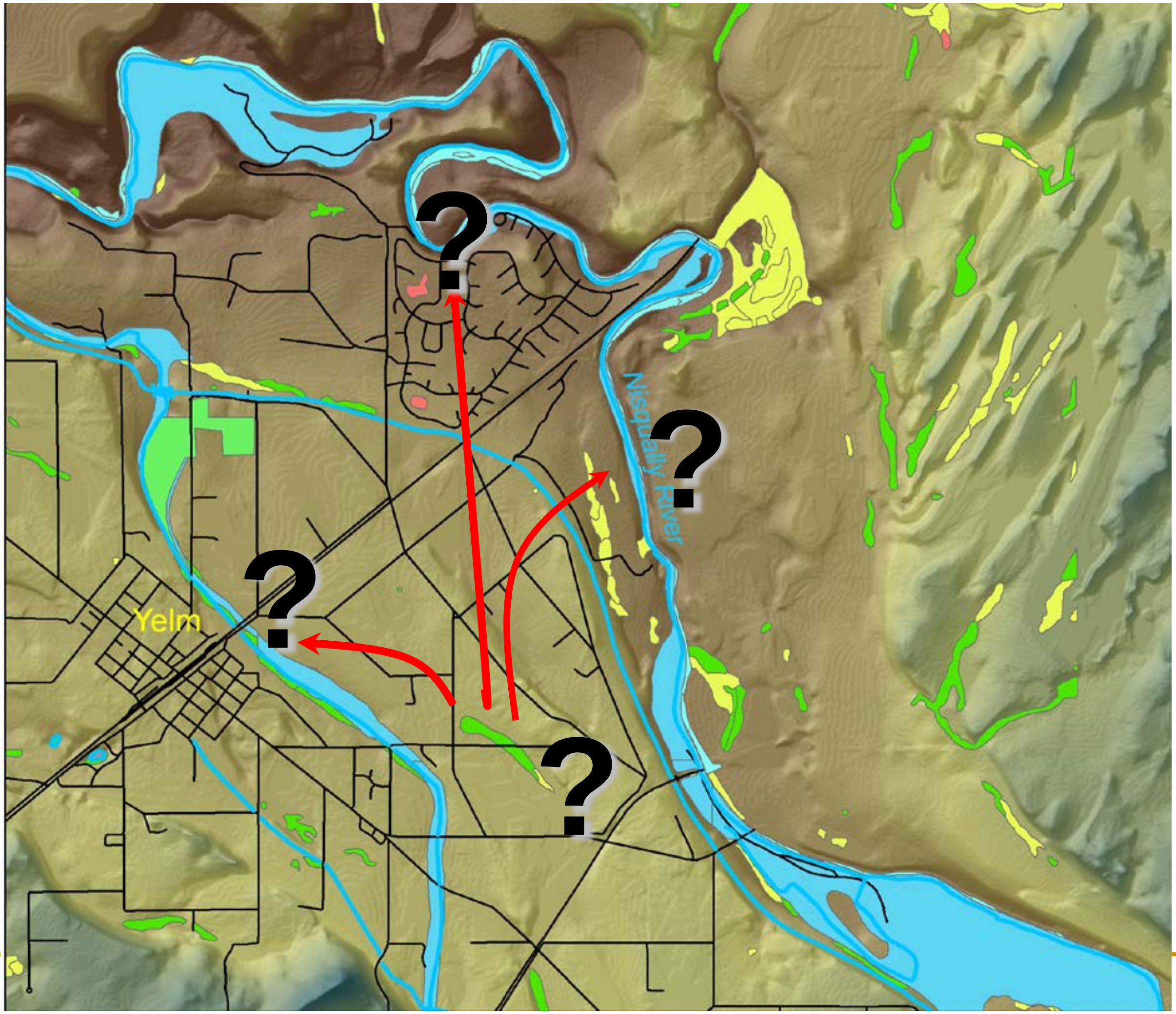
MODFLOW

- Apply MODFLOW to discern if there are subsurface hydraulic connections with Nisqually River or Yelm Creek, or neither.

- Modeling Steps
  - Define objectives
  - Collect data
  - Build a conceptual model
    - It is suitable? If yes, then…
  - Design model grid
  - Assign model parameters

Modeling Objectives

- To assess subsurface flow direction of groundwater between wetland of interest and nearby SMA streams.



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Data Collection

- Local geologic stratigraphy
- Local groundwater elevations
- Hydrogeologic Parameters
  - Hydraulic Conductivity of geologic units;
  - Specific Storage (Ss) / Specific Yield (Sy)
  - Total Porosity / Effective Porosity
- Model boundaries
- GIS data (Digital elevation model; hydrology, NWI wetlands; STATSGO/SSURGO soils data)
- Background imagery (optional) – Digital Raster Graphics (DRGs)

Public Data Resources

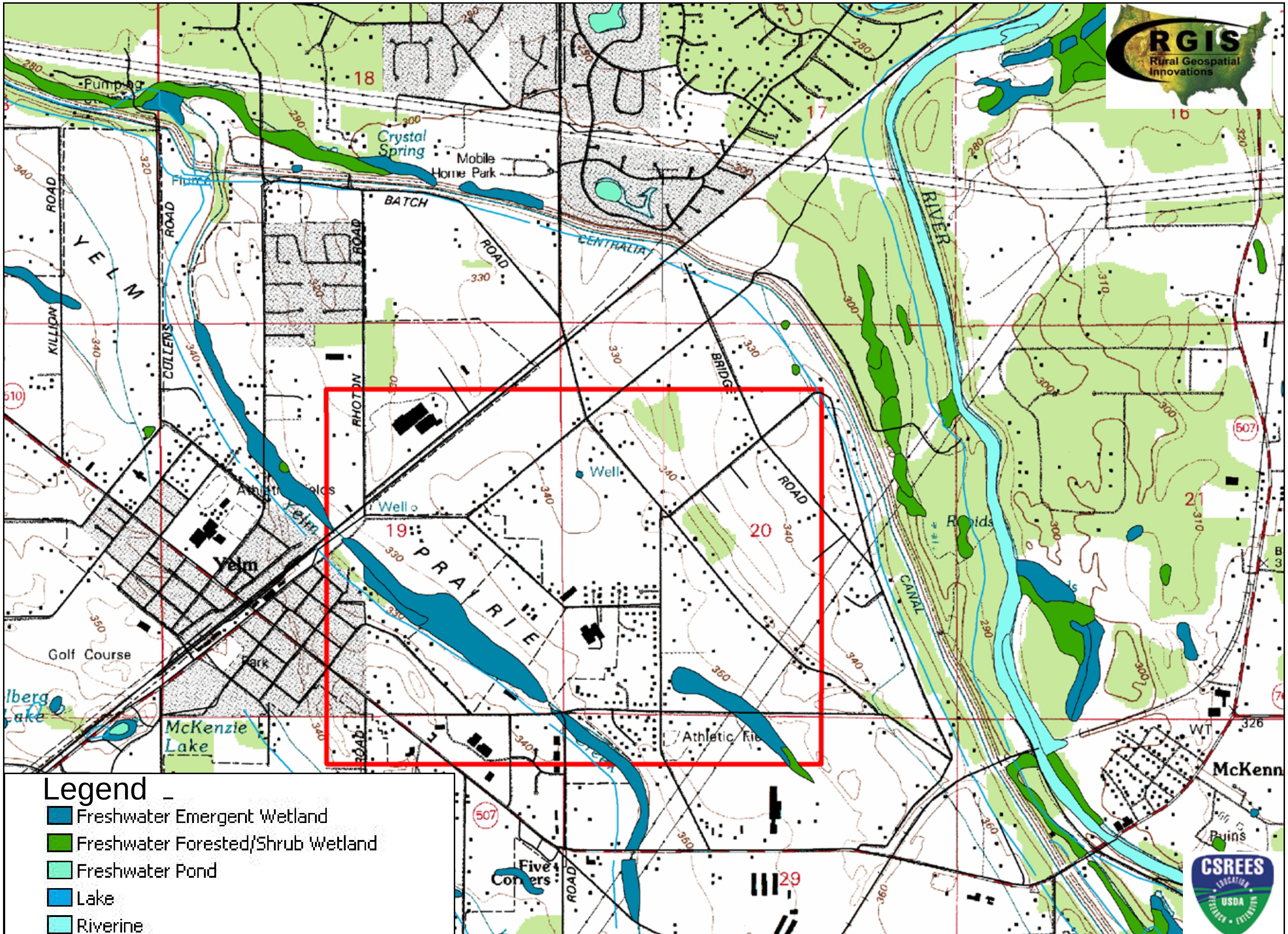
- Existing USGS reports for selected area;
- Other existing government studies (e.g. WA Departments of Ecology, Transportation, Natural Resources, etc.);
- Well Logs – local soil/geologic stratigraphy;
- Soil Surveys (e.g. STATSGO, SSURGO);
- Elevation data (e.g. USGS DEM (10m, 30m);
- The above resources often have data pertaining to:
  - Soil/Geologic Stratigraphy; Aquifers (confined/unconfined)
  - groundwater elevations;
  - hydrogeologic parameters (e.g. hydraulic conductivity, Storage, Porosity)

Define Conceptual Model Boundaries

- Need to look for natural hydrologic boundaries that constrain the flow system.

- These can include:
  - Geologic divides (e.g. rock outcropping)
  - Surface water divides (e.g. rivers, lakes, ocean, watershed divides)
  - Groundwater divides (e.g. aquitards)
  - No divides (e.g. locate area of interest, extend boundaries beyond this area)

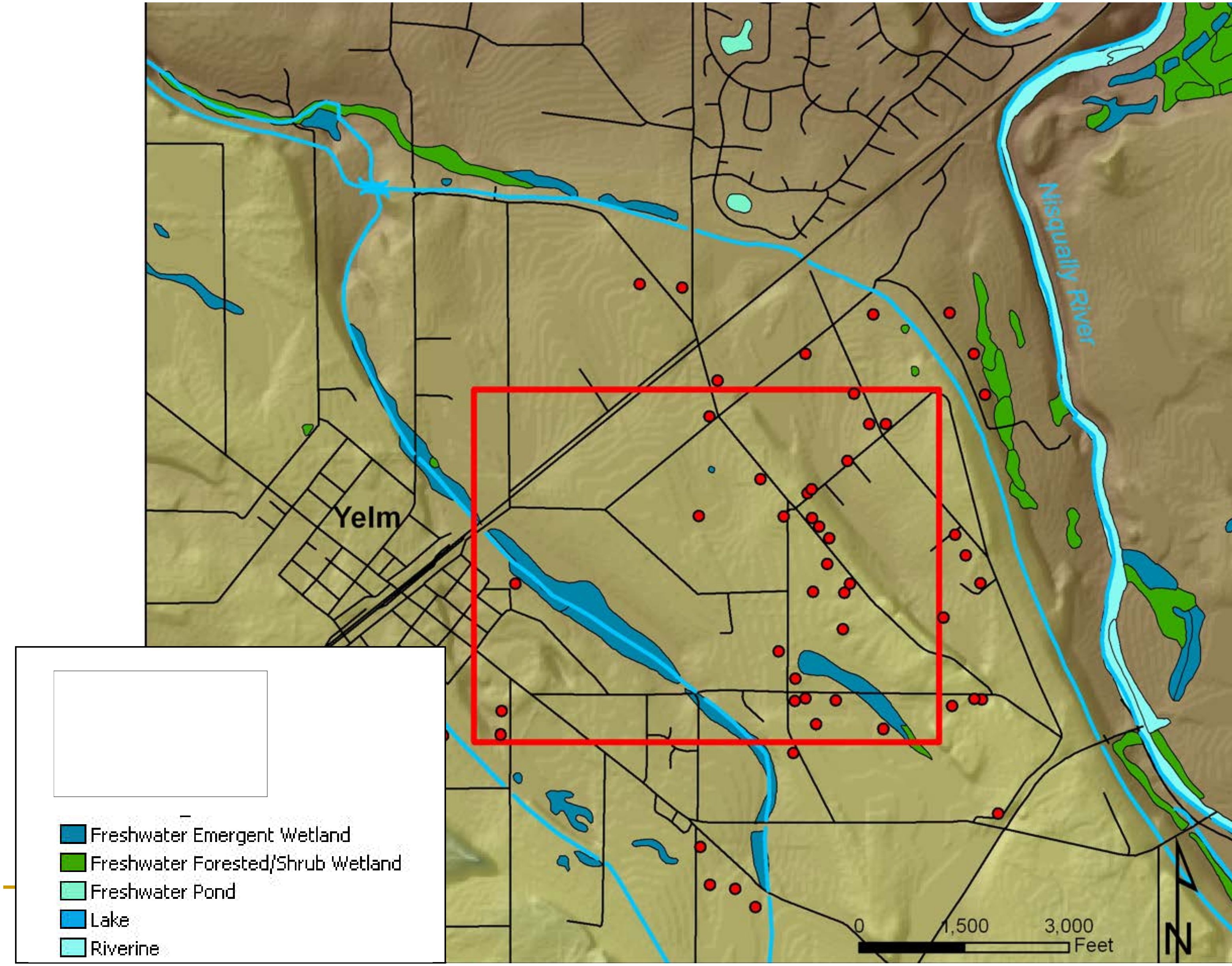
Area of Interest - Yelm



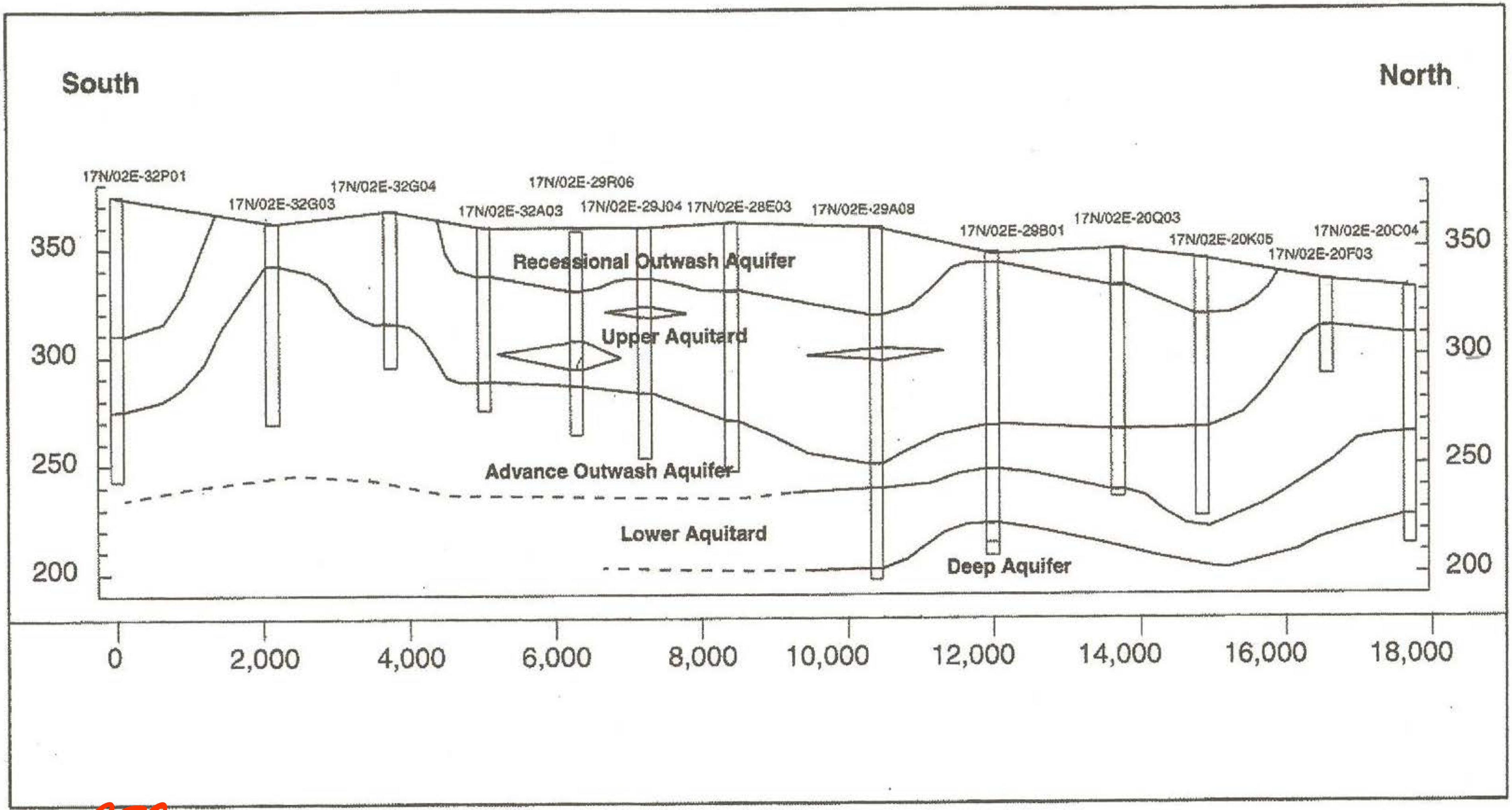
Geologic Stratigraphy

- Well Logs
  - (Washington State Department of Ecology)
- Yelm groundwater study
  - Washington State Department of Ecology Groundwater Study (Denis Erickson, 1998)
- Regional Geologic Studies
  - (USGS Report: Drost, Dion, & Jones, 1998)
- These resources are useful because they often include measurements of Hydraulic Conductivity (K), Storage values (Ss,Sy), and Porosity.

Well Locations



Hydrogeologic Cross-Section



Source: Erickson, 1998

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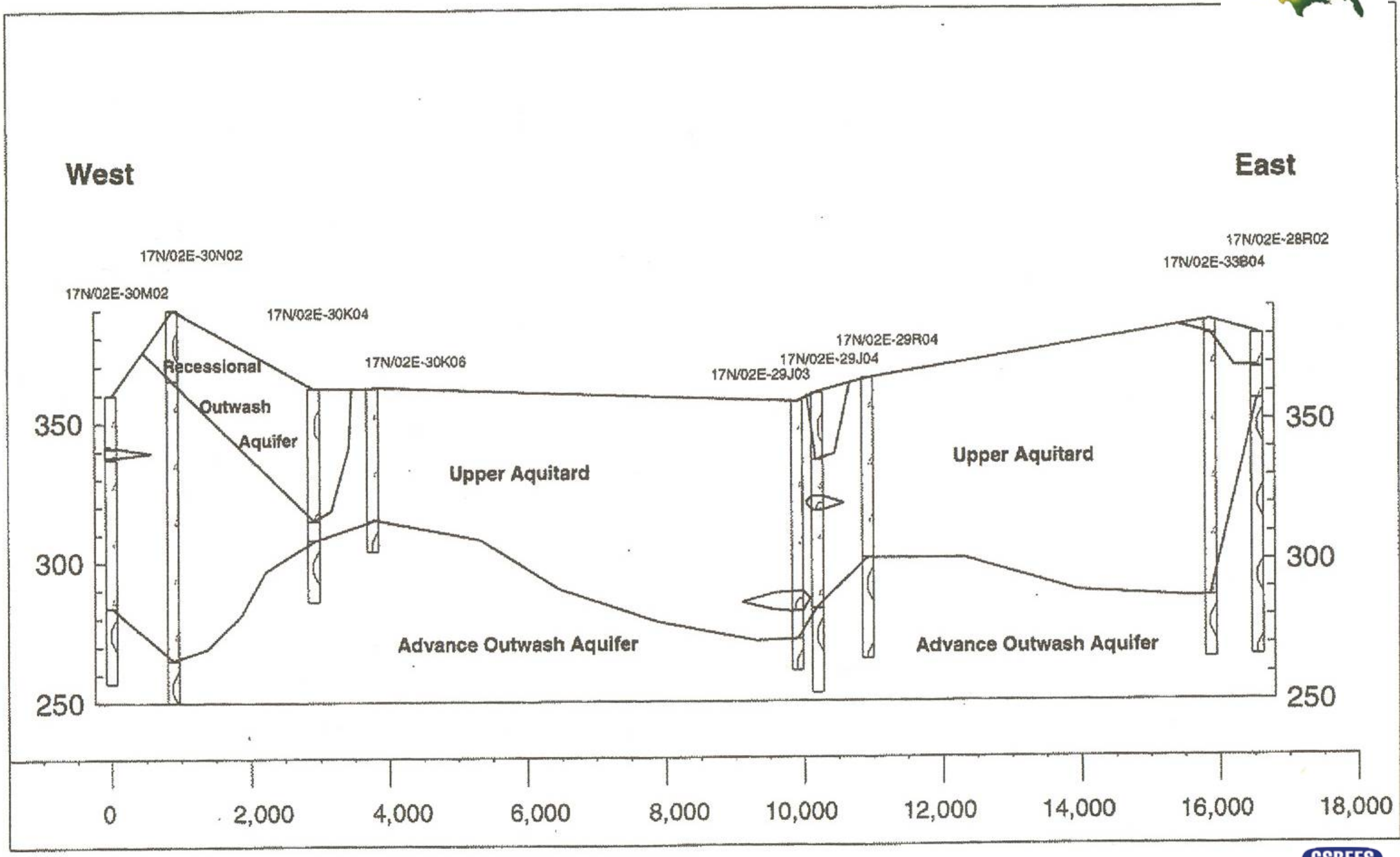
Hydrogeologic Cross-Section



Source: Erickson, 1998

Hydrogeologic Interpretation: Aquifers

- Recessional outwash considered as an unconfined aquifer
- Vashon till layer considered as an aquitard
- Advance outward considered a confined aquifer

Geologic Unit Representation within the model

- Model surface elevations can be imported using USGS DEM data
- Till layer developed from well log point data.
  - A point elevation shapefile can be used to interpolate an elevation grid representative of the till layer
    - spot elevation were attained for the till layer via well logs
- Recessional outwash and Till layers assigned hydrogeologic parameters based on literature (Drost, Dion, & Jones, 1998; Erickson, 1998)

Model Construction

- Model analysis grid was created with a cell resolution of 10m, 1.5 km by 2.0 km
- Point elevation file was imported to represent surface elevations – these were at a cell resolution of 30m, and interpolated to 10m (import tool can only handle approx. <8000 records)

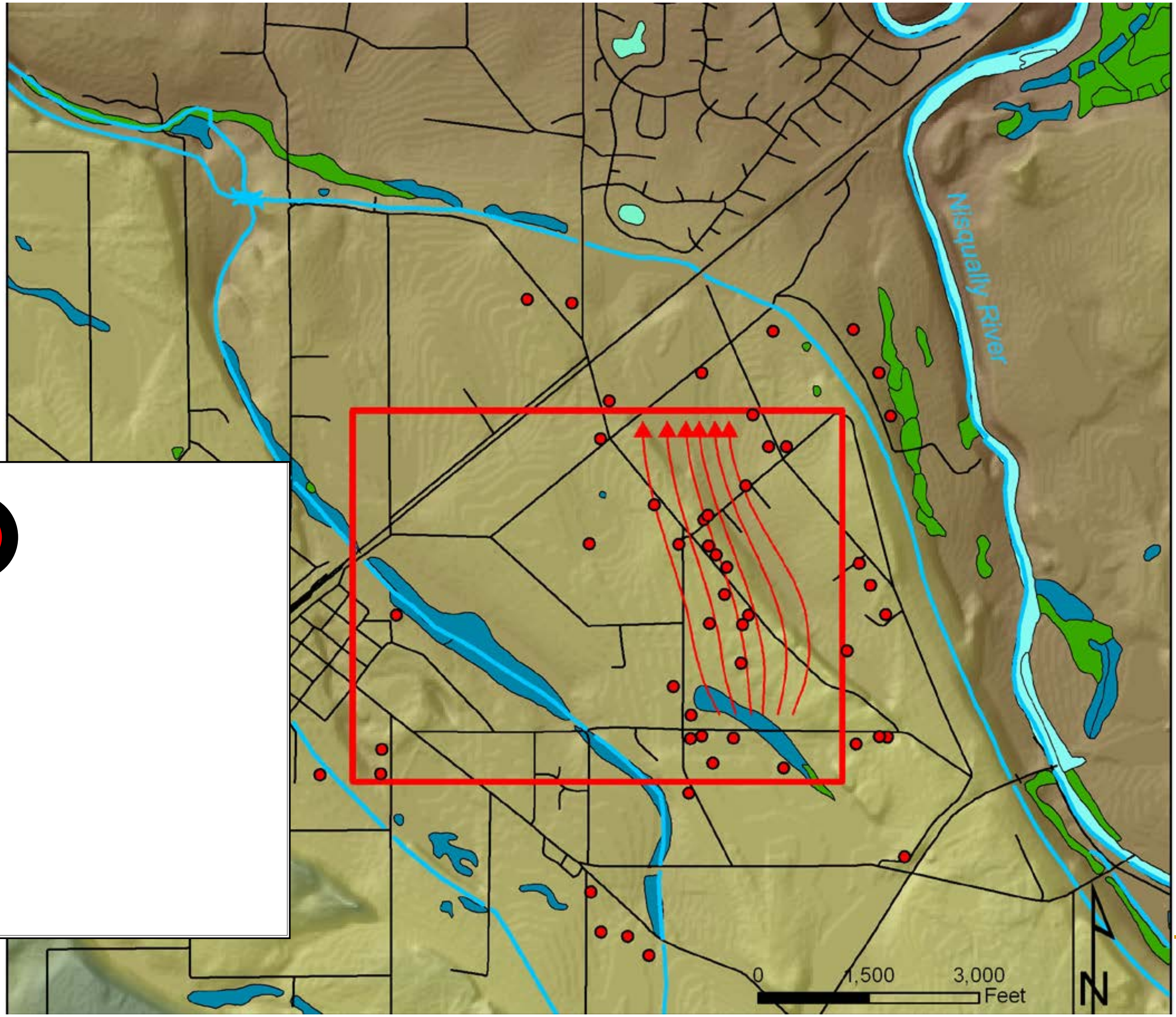
Water Table Elevations

- Initial heads were attained from:
  - Well monitoring reports (Erickson, 1998)
  - STATSGO/SSURGO data – provides a crude estimation of depth to water.
- Till elevation values were estimated from well log data and interpolated to generate an estimated elevation grid for the till layer
- Till - treated as an confining unit.

Boundary Conditions & Assumptions

- Constant heads were assigned to all sides of the model based on water table elevations
- This allows for the generation of a hypothetical scenario to deduce which direction groundwater will travel within the unconfined aquifer.
- Tracking particles were placed within the boundaries of the wetland to determine which direction groundwater would flow
- Steady State conditions assumed

Results:
Projected Groundwater Flow Paths



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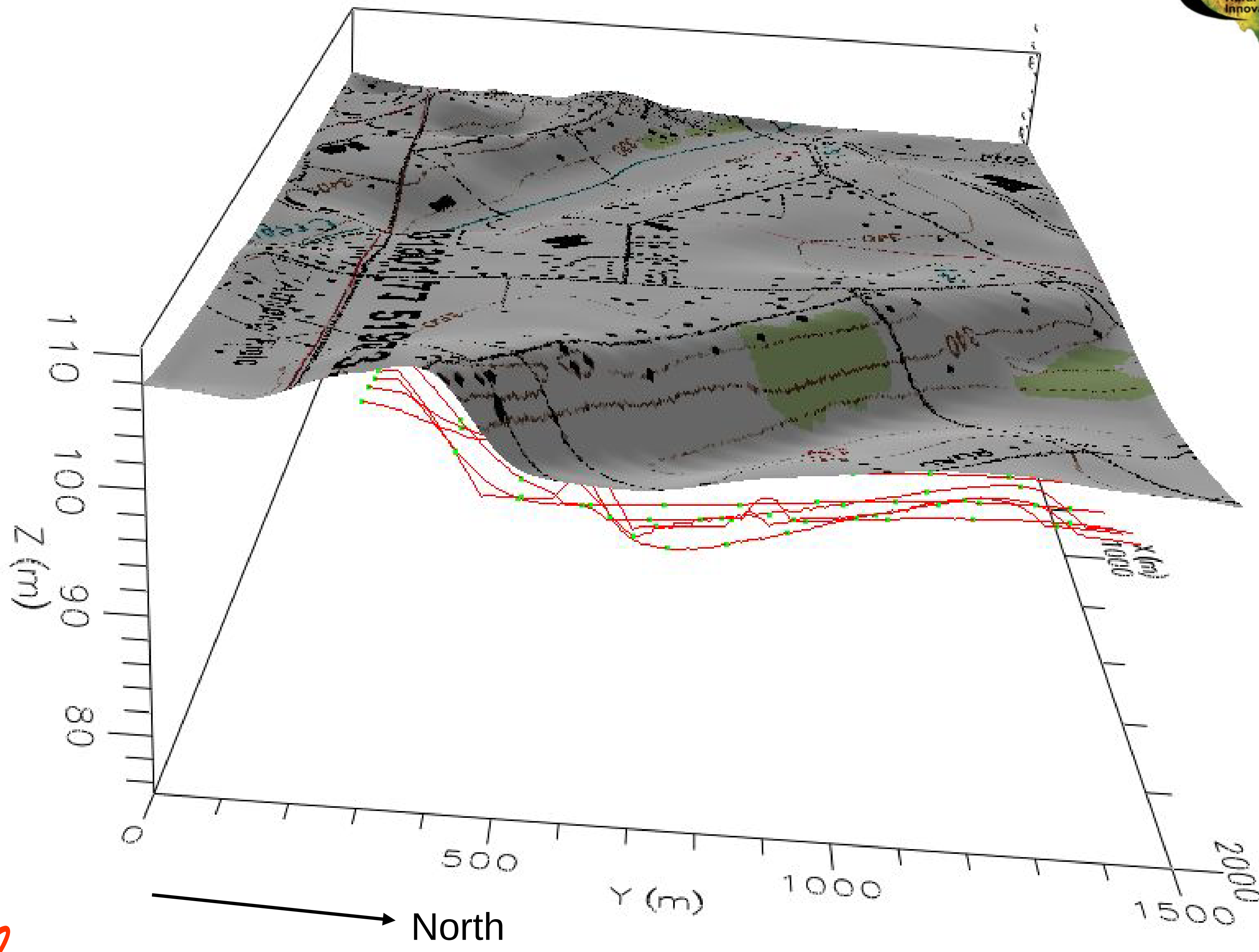
Pathline Direction



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Conclusions

- Wetland in question appears to be hydraulically connected to Nisqually river.
- Subsurface flow appears to flow north to the Nisqually River.
- These results are supported by observations provided by Erickson (1998).
- Wetland probably should be incorporated within the SMP of Thurston County.

Strengths & Limitations of Approach

Limitations:

- Assumes steady state; not completely reflective of actual conditions.
- Constant heads assumed; not likely in reality.
- Calibration not completed; accuracy is uncertain.

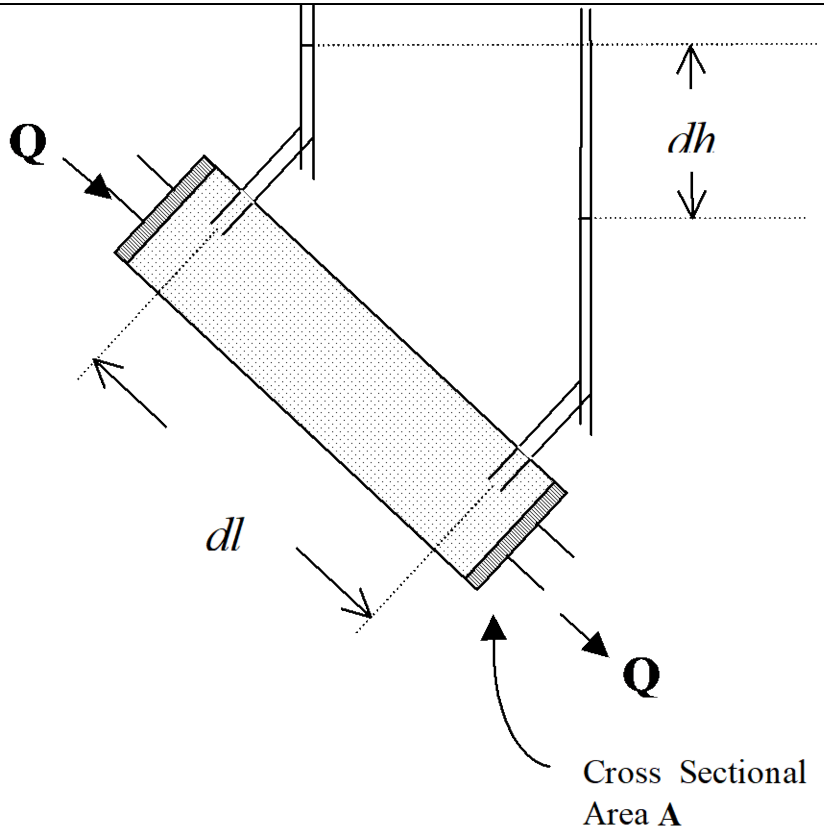
Strengths:

- However, approach provides a general impression of likely direction of flow within the unconfined aquifer system.
- Utilizes readily available model and data resources.
- Provides added information to support decisions regarding the inclusion of potential ‘associated wetlands’.

Darcy's Flow Equation

Conservation of Fluid mass

$$v = \frac{Q}{A} = \frac{-k\rho g}{\mu}\frac{dh}{dl}$$



v:	specific discharge
Q:	volumetric flow
A:	area
k:	specific permeability
g:	gravitational acceleration
ρ:	density
μ:	viscosity
dh/dl:	hydraulic gradient

Regional Stratigraphy

Table. 1. Lithologic and hydrologic characteristics of geohydrologic units in northern Thurston County

System	Series	Geologic unit		Geohydrologic unit, in this report[1]	Typical thickness (feet)	Lithologic characteristics	Hydrologic characteristics
Quaternary	Holocene		Alluvium	Qvr Qvrm	10-50	Alluvial and deltaic sand and gravel along major water courses. Moderately to well-sorted glacial sand and gravel, including kettled end moraine	An aquifer where saturated. Ground-water is mostly unconfined. Perched conditions occur locally.
Quaternary	Pleistocene	Vashon Drift	Recessional outwash and end moraine				
Quaternary	Pleistocene	Vashon Drift	Till	Qvt[2]	20-60	Unsorted sand, gravel, and boulders in a matrix of silt and clay.	Confining bed, but can yield usable amounts of water. Some thin lenses of clean sand and gravel.
Quaternary	Pleistocene	Vashon Drift	Advance outwash	Qva	15-35	Poorly to moderately well-sorted, well-rounded gravel in a matrix of sand with some sand lenses.	Ground water mostly confined. Used extensively for public supplies near Tumwater.
Quaternary	Pleistocene	Kitsap Formation		Qf[3]	15-70	Predominantly clay and silt, with some layers of sand and gravel. Minor amounts of peat and wood.	Confining bed, but in places yields usable amounts of water.
Quaternary	Pleistocene	Salmon Springs(?) Drift (Noble and Wallace, 1966) / Deposits of "penultimate" glaciation (Lea, 1984)		Qc	15-50	Coarse sand and gravel, deeply stained with red or brown iron oxides.	Water is confined. Used extensively for industrial purposes near Tumwater.
Quaternary / Tertiary	Pleistocene / Miocene and Eocene	Unconsolidated and undifferentiated deposits		TQu	Not known	Various layers of clay, silt, sand, and gravel of both glacial and nonglacial origin.	Contains both aquifers and confining beds. Water probably confined.
Tertiary	Miocene and Eocene	Bedrock		Tb	Not known	Sedimentary rocks consisting of claystone, siltstone, sandstone, and minor beds of coal. Igneous bodies of andesite and basalt.	Poorly permeable base of unconsolidated sediments. Locally an aquifer, but generally unreliable. Water contained in fractures and joints. Well yields relatively small. Numerous abandoned wells.

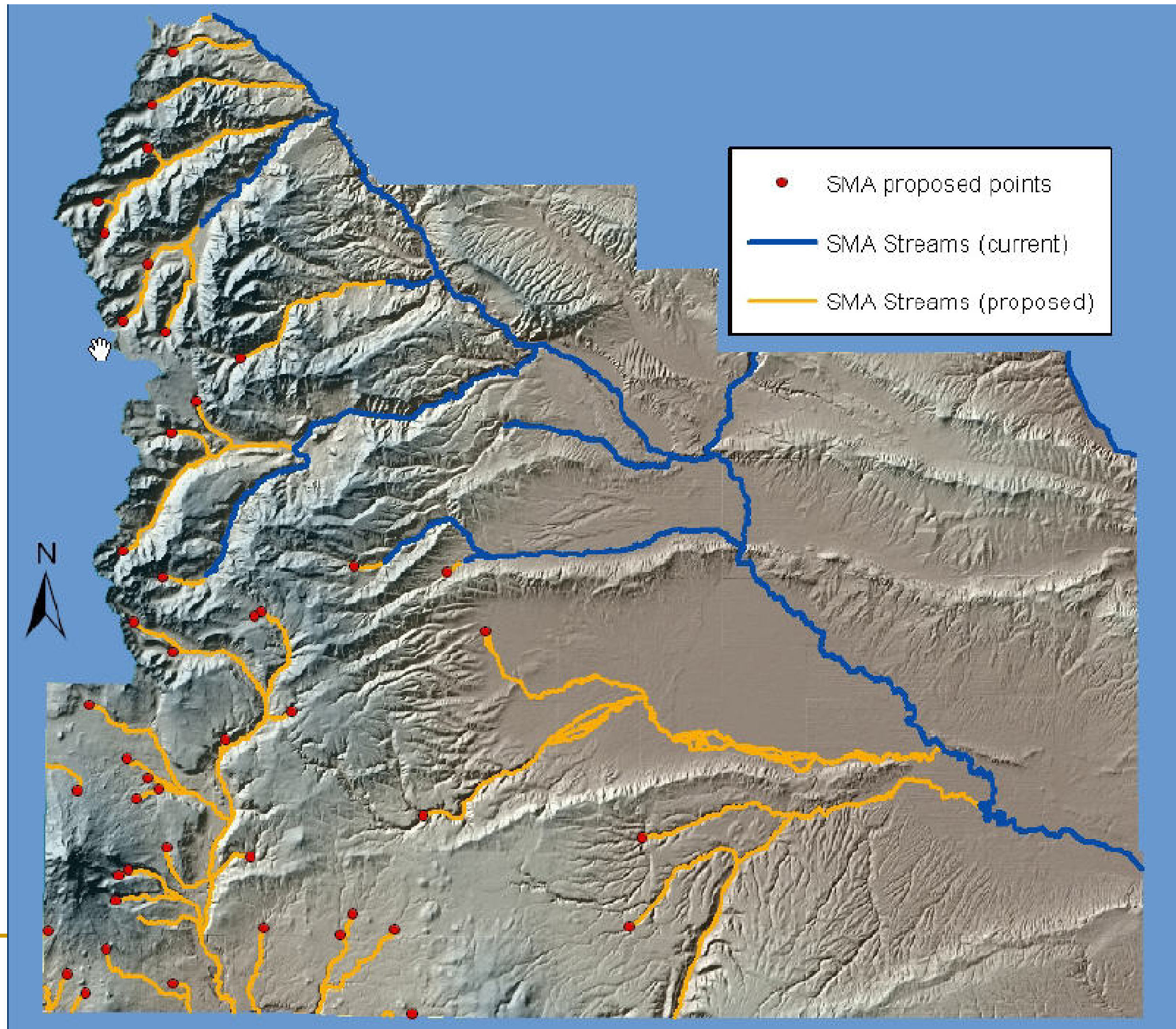
[1]The identification of geohydrologic units in this report is a "best estimate" based on drillers' logs and existing surficial geology maps.

[2]Includes "late Vashon lake deposits" (Washington State Department of Ecology, 1980). May include till of "penultimate" glaciation (Lea, 1984).

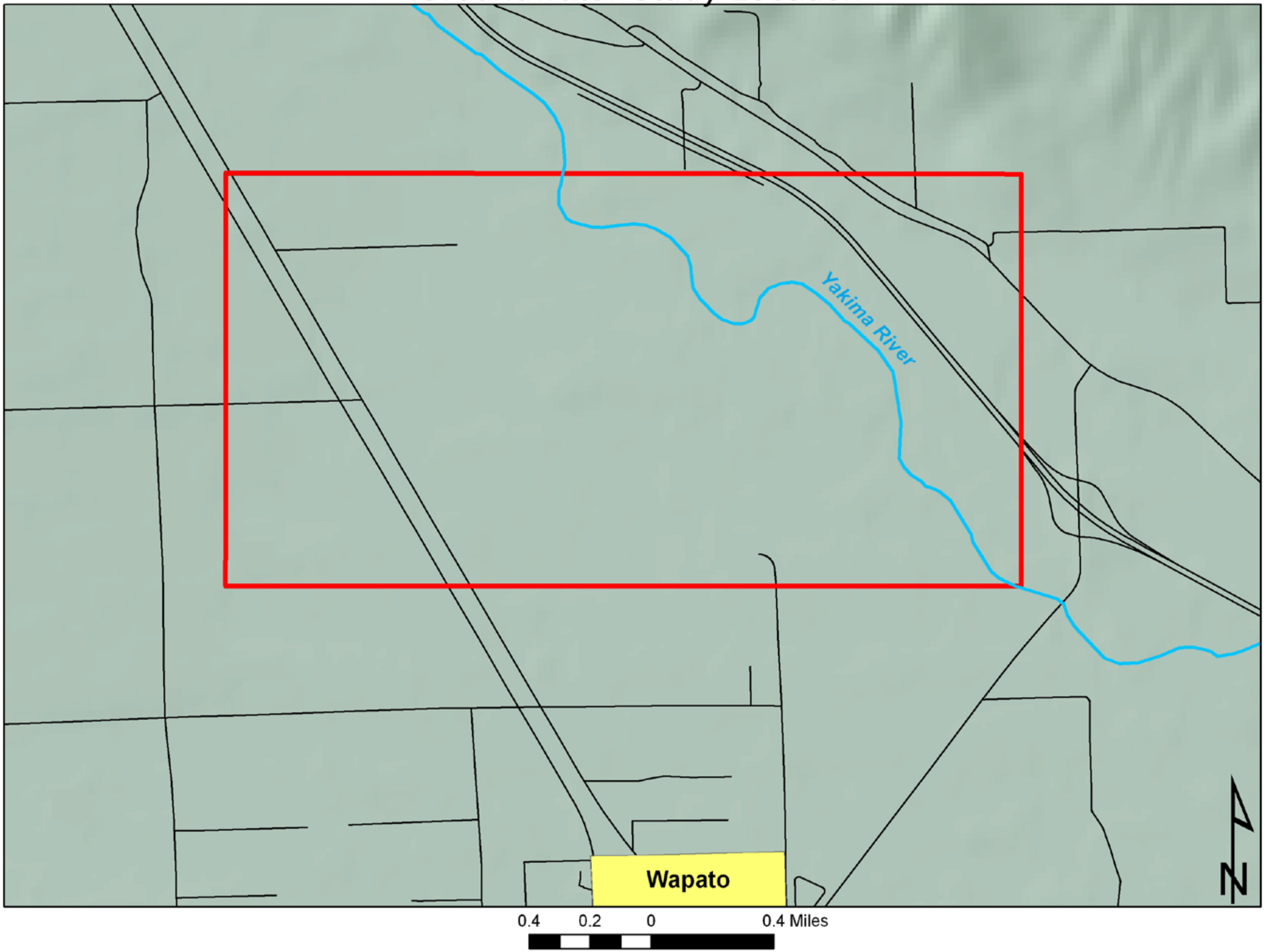
[3]Includes alluvium younger than Kitsap Formation in Nisqually River delta. May include some Vashon till (where multiple tills are present). May include till of "penultimate" glaciation (Lea, 1984).

Source: Drost, Dion, & Jones, 1998

SMP Example: Yakima County– Current & Proposed Streams



Yakima County and Groundwater Study Location



Determination of Wetland Hydraulic Connectivity…Why?

1. Application of State policies (e.g. Shoreline Management Act – Delineation of ‘associated wetlands’)

2. Groundwater Contamination and Plume Analysis

3. Wetland Ecosystem Analysis
   - Wetland hyperheic studies – Which wetlands are connected with which floodplain systems?

Why model?

- Resource managers may be required to develop management plans.
- Often need to assess possible impacts of these plans, however existing studies for specific sites are not available.
- Modeling provides an opportunity to assess impacts of resource management plans before their implementation.

Numerical Groundwater Model

- Incorporates physical features of the natural system as mathematical expressions:
  - Geology – hydraulic properties and stratigraphy
  - Sources – boundary conditions
  - Observations – calibration and validation to assess model accuracy

- Study area is divided into grid cells, where each cell can have different parameters.

- However, all properties within each cell are assumed to be homogeneous.