The examination committee will choose from the following questions to test your comfort with "core knowledge" needed to enter a PhD program in hydrology. The qualifier will last two hours and will cover at least six questions to be selected by the committee, of which approximately half will be from the "core knowledge area" (the COMMON POOL of questions – see below) and half from the student's "specialty area". Plan to have about five minutes to provide your initial answer, followed by 5-10 minutes of follow up questions based on your answer.

We suggest that a student will answer questions presented by a panel of three members of the water faculty, of which at least one member will be from the student's specialty area. The student's advisor may attend as an observer, but they may not ask questions, or prompt, or otherwise assist the student, and they will not have a vote in the final decision. The committee will meet at the end of the exam to determine whether the student has demonstrated sufficient familiarity with the material and ability to reason through questions and discussions. If the committee has concerns that the student may not be successful in the PhD based on the exam, then they will be given a specific set of tasks to complete and guidance on the committee's concerns so that they can prepare to retake the exam. Students who do not pass the first exam must schedule a re-examination no sooner than 3 months and no longer than 12 months from the date of the first exam. The re-examination will be administered by the same committee. The same pool of questions will be available, but the focus will be to determine whether the student has demonstrated enough growth to indicate that they are likely to be successful in the PhD program. The advisor will take an active role in the discussions for a reexamination and they will have a vote with the expectation that they have the best sense of the student's qualifications.

CONTENTS

THE COMMON POOL

Hydrologic system conceptualization and modeling:

1. **Generic Modeling (Role, Usage, Limitations):** Provide at least three examples to illustrate the role of models in science and engineering. Be prepared to discuss how models are used to understand systems, make projections, and support decisions. What are the limitations or common misuses of modeling.

2. **Generic Conceptual Modeling (Processes):** Draw a simple figure that describes the interactions among water fluxes (e.g. precipitation, runoff, infiltration, GW flow and typical flow paths through the subsurface). Be prepared to discuss how geologic maps, exploratory drilling, and meteorological, surface water and groundwater observations are used to form a site-specific conceptual hydrologic model from this general base figure.

3. **Generic Conceptual Modeling (Time Scales):** Produce a table that shows the fundamental time scales of groundwater, streamflow and atmospheric processes. Be prepared to explain why these processes have such different timescales and to discuss the implications of these differences for modeling each domain.

4. **Generic Conceptual Modeling (Hysteresis):** Provide a generic definition of hysteresis. Be prepared to sketch a graph that illustrates hysteresis for a process related to hydrology.

5. **Generic Conceptual Modeling (Mass Conservation):** Write a mass balance equation that applies at any scale and show how it can be applied to a watershed. Be prepared to discuss all typical inflows and outflows and to describe how each is typically measured or determined.

6. **Watershed Conceptualization (Components):** Provide an answer to the question, "What is a watershed?" Be prepared to discuss one is delineated, its components (hillslopes, networks, riparian areas), and how it can be used as a control volume.

7. **Watershed Conceptualization (Flow Paths):** Sketch typical flow paths through a watershed in cross section. Be prepared to explain how you could use this and what additional information you would need to estimate water residence times along each path.

8. **Groundwater System Conceptualization (Recharge):** Sketch a cross section through a watershed to illustrate and explain the concepts of mountain block and mountain front recharge. Be prepared to contrast the underlying hydrologic processes that contribute to

each and to sketch a plan view map to illustrate how mountain front recharge may impact equipotentials.

9. **Groundwater System Conceptualization (Hydrogeologic Structure):** Explain how geologic processes lead to anisotropy and heterogeneity. Be prepared to discuss basic statistical approaches to quantifying hydrogeologic structure.

10. **Groundwater System Modeling (Workflow):** Provide a schematic representation of a groundwater modeling workflow for use in decision support. Be prepared to discuss how this workflow can be manipulated to support different viewpoints. What is your ethical responsibility as a modeler in this process?

11. **Groundwater System Modeling (Approaches):** Describe the differences between analytical and numerical solutions to physics-based equations. Be prepared to discuss the differences between finite difference, finite element, and finite volume methods for numerically solving differential equations. Contrast these approaches with statistical models including machine learning. Offer an answer to the question, "What is a groundwater model?" Be prepared to contrast numerical, analytical, statistical, and machine learning approaches to groundwater modeling. For the numerical approaches, discuss the differences between finite difference, finite element, and finite volume methods. Provide at least two examples of how groundwater models are used in practice and comment on how the right modeling approach can be selected.

12. **Earth System Modeling (Conceptualization):** Provide a definition of Earth system models (ESMs)? Be prepared to discuss the major terrestrial hydrological processes that may feedback to climate, and must therefore be represented in an ESM.

13. **Land Memory (Conceptualization):** List the factors (or hydrological processes) that affect 'memory' time scales on/over land surfaces (bare land, urbanized land, agricultural land, forested land) as opposed to on/over water regions (e.g., lakes, oceans). Be prepared to discuss how these affect hydrometeorological processes (surface energy and water fluxes) and how might they may be represented in hydrological and/or Earth System models. How does the memory relate to "persistency" of land water storage (snow, soil water, groundwater ...) and to the time scales of the impacts of land water on climate predictability? How long can the land 'memory' last compared to atmospheric 'memory' and ocean 'memory'. How is this relevant to seasonal-to-seasonal (from 2 weeks to 2 years) climate prediction?

14. **Plant-Water-Atmosphere Interactions (Conceptualization):** Draw a simple diagram that describes how water moves from the soil to the atmosphere through a plant. Be prepared to discuss the following. Identify the main "resistances" that will affect the transportation of water through the soil/plant/atmosphere continuum. What is plant stomatal resistance?

How does it relate to potential evaporation (PE)? What is the relationship between stomatal resistance and water vapor pressure deficit (VPD). Discuss how to scale transpiration from a single leaf to an entire ecosystem.

<u>Hydrometeorological variables and measurement:</u>

15. **Hydrologic Fluxes:** Discuss how precipitation, runoff, infiltration, evaporation, transpiration, and recharge processes (and their fluxes) are related. Be prepared to discuss how each is typically measured or inferred.

16. **System Drivers:** What is the general set of meteorological variables needed to run a land surface hydrology model? Be prepared to discuss how the energy and mass fluxes are driven by these variables and identify energy fluxes that constitute available energy for land-atmosphere energy exchange. How are mass and energy conserved with this set?

17. **Precipitation:** Describe three methods of measuring precipitation, including at least two from: in situ (rain gauge) , ground radar, or satellite precipitation. Be prepared to describe the instruments used and the basic procedure for measurement. What are the strengths and weaknesses of each method? What are the optimal uses of each method in hydrology?

18. **Satellite-based Remote Sensing:** Provide a definition of remote sensing. Be prepared to discuss why remote sensing is important for studying the Earth. How can satellites help study hydrology and atmospheric science? Which components of the water cycle are "observable" by satellites? Explain why and give examples. What are "Geostationary satellites" and what makes them different from other types of satellites?

<u>Flow through porous media:</u>

19. **Soil Hydraulic Properties:** Be prepared to define the following properties, including units, and describe how they can be measured or inferred in the laboratory and/or field: porosity; permeability; hydraulic conductivity; specific storage; specific yield, transmissivity, storativity, diffusivity. In particular, differentiate aspects of these properties that rely on fluid vs. porous medium properties. Discuss the scale at which these properties can be measured.

20. **Soil Hydraulic Properties (Volumetric Water Content):** Provide a definition of the volumetric water content. Be prepared to describe how it can be determined by oven drying and using at least one indirect situ method.
21. **Flow Through Porous Media (Elevation, Pressure, and Hydraulic Head):** Plot the elevation, pressure, and hydraulic head versus elevation for steady state 1D, vertical, saturated flow through a homogeneous medium given the Type I boundary condition values. Be prepared

to use the result to explain the meaning of steady state flow and to define the head formulation of energy potential. State any additional properties needed and show how to calculate the flow, flux, and average linear groundwater velocity.

22. **Flow Through Porous Media (Darcy's Law):** Write Darcy's Law, defining all terms and units. Explain why there is a negative sign included. Explain how it relates permeability, energy gradient, and flux or flow. Be prepared to explain any assumptions used in its development. Explain how it is included in the flow equation as an expression of water mass balance.

23. **Flow Through Porous Media (Unsaturated Flow Equation):** Write the mixed form of the unsaturated flow equation, defining all parameters with units. Be prepared to explain the assumptions needed to simplify the two-phase flow equation to the Richards' equation. Explain how pressure head is related to matric potential.

24. **Flow Through Porous Media (Capillarity):** Draw a vertical capillary tube with an air and water interface. Also draw the hydrostatic profile of water saturation in a homogeneous vadose zone above the water table. Be prepared to define what capillary pressure is and explain what it depends upon. Use the two images to explain the concept of air-entry pressure for a soil sample. Then explain how the soil water characteristic curve can be explained based on a bundle of capillary tubes.

25. **Flow Through Porous Media (Infiltration Dynamics):** Sketch plots of water content versus depth through time that illustrate how infiltration occurs into a previously drained medium in response to constant flux and constant head surface boundary conditions. Also sketch water content versus depth during drainage from a uniform initial pressure head in a homogeneous medium. Be prepared to identify differences between the two infiltration plots. Explain why the drainage plot shows nonlinear water content variations with depth.

26. **Pumping in a Confined Aquifer:** Sketch and describe drawdown versus horizontal distance through time for a confined aquifer. Be prepared to describe the impacts of changing T and S. Be able to explain why the extent of drawdown is different in an aquifer under confined conditions and the same aquifer under unconfined conditions after pumping at the same rate for the same time.

27. **Groundwater Level Monitoring:** Draw a schematic cross section of a monitoring well. Describe the process of installing a monitoring well. Contrast two different drilling methods, explaining where each would be more appropriate. Discuss the advantages and disadvantages of using a long-screened interval. Explain how a water level meter works. Identify and discuss four common sources of error in measuring water levels.

Water quality, chemistry and geochemistry:

28. **Groundwater Quality:** Provide two examples of common water quality issues in groundwater, including sources in the environment (and how we might fingerprint them). Choose solutes with different persistence. Be prepared to discuss why their persistence differs and describe a natural or anthropogenic strategies for remediation for each.

29. **Water Chemistry:** Describe how pH, temperature, DO, EC, and alkalinity are measured. Be prepared to discuss how they control the impacts of metals on surface water; how they impact biological activities in soil; and how they influence weathering reactions.

30. **Water Chemistry:** Define what is meant by a detection limit and a regulatory limit for chemical compounds in groundwater. Discuss how pH, temperature, DO, and EC impact water quality (for human health and aquatic organisms).

31. **Water Chemistry:** Draw an example of a plot used for end member mixing analysis. Be prepared to describe how environmental tracers can be applied to quantify sources of stream water using this plot. Discuss at least one limitation of this method.

32. **Water Chemistry:** Provide a basic definition of oxidation-reduction (Redox) reactions and identify which chemical parameters are used to measure redox zonation in waters. Be prepared to discuss how they can alter water quality. Draw a picture of the common redox ladder (going from more oxic to reduced) in natural vs. contaminated (e. g., oil spill) groundwater environments.

33. **Isotopes and 'Dating' of Water:** Draw a picture of how stable water isotope values change through the water cycle. Be prepared to discuss what physio-chemical processes are responsible for isotope fractionation. Describe the principles of radiocarbon dating of water, including writing the radioactive decay equation, and calculating the applicable age range. What are common processes in the subsurface that may impact radiocarbon 'ages'?

34. **Advection and Dispersion of a Solute Plume:** Write the advection dispersion equation. Also draw a typical breakthrough curve and the concentration versus distance at a given time for transport of a pulse release through a 1D column. Finally, sketch the 3D evolution of a contaminant/solute plume through time. Be prepared to provide units and expected values for each parameter and describe how they can be measured or inferred in the laboratory and/or field. Explain diffusion conceptually. Describe the physical mechanisms that combine to produce dispersion at multiple scales. Explain the impacts of each parameter on the shape of the breakthrough curve. Explain the general shape of the solute plume in 3D.

35. **Geochemical Carbon Sequestration:** Discuss the major processes that contribute to natural geochemical carbon sequestration. Be prepared to list and discuss three main human activities that affect natural geochemical carbon sequestration.

36. **Climate Change & Geochemical Processes:** Give at least three examples of how climate change can alter geochemical processes in the hydrological cycle. Be prepared to the potential effects on water resources. Include how risk analysis can be included in hydrologic practice in the face of risks caused by climate change.

37. **Climate Change and Geochemical Cycling:** What is the “turnover time” in the context of geochemical cycling? Explain how changing climate (e.g., changes in temperature and patterns of precipitation) can affect the turnover time of a geochemical cycle? Provide an example to illustrate how climate change can affect geochemical cycling via physical, chemical, and biological processes.

<u>System modeling and inference:</u>

38. **Inference (Model Adequacy):** Provide an answer to the question, “*How can you decide if your model is good?*” Be prepared to discuss the roles of model performance, metrics, and benchmarking.

39. **Inference (Model Structural Error):** Discuss why model structural error can be harder to identify and quantify than errors in parameter values for a given model structure. Be prepared to discuss possible approaches to identify model structural error.

40. **Inference (Hypothesis Testing):** Provide a clear and simple explanation of the statistical basis for hypothesis testing. Be prepared to explain what it means to maximize the likelihood associated with a model hypothesis.

41. **Inference (Identifiability, Uncertainty & Risk):** Be able to provide short definitions of any of the following: sensitivity, identifiability, uncertainty, vagueness and risk. Be prepared to explain the causes and components of predictive uncertainty.

42. **Inference (Interrogating a System):** Explain how to interrogate and investigate the functional (behavioral) nature of a dynamical environmental system. Be prepared to discuss the differences between observability, conditional observability, identifiability, and conditional identifiability of a system.

43. **Inference (Statistical Treatment of Uncertainty):** Write out Bayes Law. Be prepared to define all terms and give an example of the application of Bayes Law. Discuss how hydrologic observations are used to construct a model and estimate parameter values in the context of Bayes' Law.

Water policy and societal issues:

44. **Water Policy & Societal Issues:** List five pressing challenges facing the world with respect to water sustainability in the next 20 years. Be prepared to discuss the most promising solutions. Be as specific as you can in your answers.

45. **Climate Change and Water Resources/Ecosystem Management:** Produce a schematic figure that explains the concept of water use efficiency for an agricultural ecosystem. Be prepared to use the diagram to present two ecosystem management practices that can increase plant water use efficiency. Discuss how an increase in atmospheric CO2 concentration and warming may each affect water use efficiency of a C3 crop.

SPECIALTY - GROUNDWATER AND VADOSE ZONE HYDROLOGY

1. **Pore Scale Concepts**: Draw a schematic representation of the water distribution in a porous medium at partial saturation. Be prepared to use this as a basis to explain the dependence of water content on water pressure and of hydraulic conductivity on water content.

2. **Pedotransfer Functions**: Define the term ‘pedotransfer function’ and cite at least one example. Be prepared to explain the limitations of, for instance, inferring K from sand, silt, and clay fractions.

3. **Upscaling**: Draw a 1D system undergoing parallel and another experiencing series flow through a system. Be prepared to use your drawing to explain how to calculate the equivalent hydraulic conductivity. Explain why these concepts help to explain the anisotropy of natural geologic systems. Relate the concept of effective K to the concept of upscaling of parameters from the sample to column to field scales.

4. **Measurement methods - characteristic curves**: Describe two experimental set ups to use paired measurements of water content and pressure head at a single depth through time can to define $\theta(\psi)$. One should be steady state, the other transient. Be prepared to describe two ways that water content can be measured, contrasting the advantages and disadvantages of the two approaches.

5. **Measurement methods - suction**: Sketch a tensiometer, labeling the parts. Be prepared to explain the operating principles of a tensiometer, including discussion of the necessary hydraulic characteristics of the porous cup.

6. **Measurement methods – Ksat in the field**: Be prepared to sketch a ring infiltrometer, borehole permeameter, and disc infiltrometer. Briefly describe each method and discuss its advantages and limitations.

7. **Measurement methods – Ksat in the lab**: Sketch the laboratory setup for a constant head and for a falling head test. Be prepared to develop the equation for the analysis of a falling head test. Explain when a constant or falling head test is preferred.

8. **Measurement methods – surface-groundwater exchange**: Sketch the setup used to measure GW-SW flux. Be prepared to describe the observations needed and calculations used. Discuss how this value can be used to determine streambed hydraulic conductivity.

9. **Transient flow - saturated**: Sketch two transient head profiles for flow through a homogeneous, steady-state, 1D, saturated system given an initial steady state flow condition, a constant Type I bottom boundary condition and initial and final top boundary conditions of Type I or II. Be prepared to discuss all aspects of your profiles with respect to how transient flow occurs in a porous medium. Explain the physical mechanisms of storage for a saturated medium. Use the results to discuss how the diffusivity controls the rate that transient conditions propagate through a flow system.

10. **Response of a confined aquifer to pumping**: Draw a schematic representation of the conditions for which the Theis equation applies. Sketch the head distribution with distance from a the well at one time for three aquifers: one with properties S and T, another with S/2 and T, and a third with S and T/2. Be prepared to use the results to explain the meaning of 'potentiometric surface' and confined aquifer. Explain how the parameter values affect the shapes of the curves. Explain superposition, show an example of its use for a Theis solution to represent a model boundary. Show another example of its use to represent recovery after pumping ceases. Show the drawdown versus distance at the end of pumping and for some later time. Explain why drawdown continues to increase after pumping stops at some distance from the well.

11. **Particle tracking**: Sketch a water table elevation map in plan view and add on particle track from one boundary across the domain to another boundary. Be prepared to explain how particle tracks are calculated. Explain the difference between a quantitative flownet and a potentiometric surface map with particle tracks.

12. **Solute transport**: Draw a schematic diagram of the movement of a solute front through a capillary tube. Be prepared to use this to explain the concept of mechanical dispersion (i.e., Taylor-Aris dispersion). Use the insights from Taylor-Aris dispersion to defend the use of advection-dispersion equation for modeling solute transport in groundwater aquifers. Then critique the use of the ADE for representing dispersion.

13. **Numerical solution of the groundwater flow and transport equations:** Describe the general concept for solving groundwater flow and transport equations numerically. Be prepared to identify and discuss at least two considerations that one must consider when choosing either a commercial software package or an open-source code to solve groundwater flow and transport. How would you conduct a parameter sensitivity analysis for a model of flow or transport?

14. **Soil Water Characteristics**: Sketch representative $\theta(\psi)$ and $K(\theta)$ curves and for two standard soil types (e.g. sand, loam). Be prepared to write the van Genuchten Model and identify all terms, with units. Show how one of these curves can be used to predict the change in water stored in a 1D vertical column between two hydrostatic conditions with different water table depths. Relate the result to the specific yield. Use the result to discuss why flooding is more rapid in areas with shallow water tables. Use the $K(\theta)$ curve to explain why unsaturated flow is nonlinear and why this adds considerable computational demand. Compare the van Genuchten and Brooks-Corey soil water characteristic (SWC) curves, explaining conditions for which each is preferred. Explain what is meant by hysteresis for unsaturated flow and show how it would impact one of the curves that you have drawn.

15. **Soil Water Characteristics**: Sketch a figure that illustrates the bundle of capillary tubes models. Be prepared to use this figure to explain why the relative permeability of a soil varies with soil water pressure.

16. **Richards' Equation**: Write one form of the Richards' Equation. Be prepared to define all terms, including units. Explain the assumptions and the line of reasoning to derive the Richards' equation from the two-phase flow equations. Does the Richards' equation assume that air is not moving? Why or why not? Write a second form of the Richards' Equation and explain when it would be preferred over the first.

17. **Transient flow - unsaturated**: Sketch the advance of a wetting front in 1D in response to steady state infiltration into a previously drained medium. Be prepared to use the plot to explain how the water content versus time will evolve at a series of depths. Be able to sketch the progression of the wetted bulb beneath a point infiltration source in 2D, cross section, and discuss how the soil type affects the shape of the wetted area.

18. **Response of an unconfined aquifer to pumping**: Sketch the drawdown versus time response of an unconfined pumping test. Explain what leads to delayed drainage and how this contributes to the classic ‘s-shape’ of the response curve.

19. **Response of an unconfined aquifer to pumping**: Sketch a potentiometric surface that shows the impacts of pumping. Be prepared to explain how the zone of influence and the zone of capture are determined and how each can be used.

20. **Stream Capture**: Write a mass balance for a simple watershed including a stream. Be prepared to use your drawing to explain the concept of stream capture. Give at least two examples of how a pumping well can capture water from a stream; for one of these, the captured water should never reach the well.

21. **Numerical Solution of Richards’ Equation**: Write Richards’ Equation. Be prepared to describe how nonlinearity complicates numerical solution of this equation. How does the Celia et al (1990) paper solve the mass conservation issue of numerical solutions of the Richards’ equation?

22. **Focused topic - mine dewatering**: Sketch a diagram that explains to a lay person why some mines need to be dewatered and how a pumping well is used to achieve this. Be prepared to explain to a non-expert audience why mine dewatering may have hydrologic impacts far from the mine and why these effects may last longer than the mining operations.

23. **Focused topic - subsidence**: Explain briefly how pumping from a confined aquifer causes subsidence. Be prepared to produce an illustrative figure to show where within an aquifer/aquitard sequence compaction is most likely to occur and explain why. Explain what controls whether the effects are reversible.

24. **Focused topic - localized recharge**: Use a plan view map to illustrate and explain how localized recharge (e.g. irrigation, managed aquifer recharge) may impact an equipotential map. Be prepared to discuss why most of the precipitation that falls in Tucson does not become recharge.

25. **<u>Focused topic – seawater intrusion</u>**: Draw a sketch showing the expected salt/freshwater boundary at the shore with no pumping including flow lines in the fresh water region. Be prepared to explain the shape of the interface. Discuss the impact of near shore pumping of fresh water on the salt/fresh interface.

26. **<u>Focused topic – salinization</u>**: Draw a figure with arrows that show water flux in the shallow subsurface and near surface atmospheric boundary layer. Be prepared to use the figure to explain how salt accumulates during deficit irrigation based on water and salt mass balances. Identify and explain likely depths of accumulation.

SPECIALTY - SURFACE WATER AND HYDROMETEOROLOGY

1. **Naturalized Flow:** Rivers like the Colorado have many dams to regulate water flow and produce hydropower or provide water for users even outside of the basin. Gaging stations downstream do not measure the natural flow through these rivers. For hydrological analysis purposes we need naturalized flow. Describe how one can calculate the naturalized flow. How is such a dataset determined?

2. **Intensity-Duration-Frequency curve:** What is an Intensity-Duration-Frequency (IDF) curve (for a point) and what is an areal IDF (for a catchment) of precipitation records (Design Storm)?

3. **Flood Frequency Analysis:** What is the main principle of flood frequency analysis. Discuss how to estimate the 100-year flood event with only 50 years of daily flow data.

4. **Curve Number Method:** Discuss broadly the principal idea of CN. Can you relate this method of estimating stormflow from rainfall data to the infiltration capacity of the soils in a catchment?

5. **Unit Hydrograph:** Discuss the pros and cons of the use of UH in routing stormflow through a catchment to produce the stormflow hydrograph.

6. **Evapotranspiration Estimation:** Discuss three ways to estimate daily ET with routinely measured hydrometeorological data (T, RH, u)

7. **Plants:** Discuss different ecological strategies that plants use to reduce the water use during the growing season. How do plants adapt to survive in humid vs arid environments? Are the different ecological strategies typically included in hydrological models? If not, what type of relationship is used in these models to estimate water use by plants?

8. **Eddy Covariance:** What is eddy covariance? Discuss how EC can be used to measure energy and mass (e.g., water vapor and CO_2) fluxes from the land surface to the atmosphere.

9. **Aerodynamic Resistance and Eddy Diffusivity:** What is aerodynamic resistance? Discuss its relationship with the eddy diffusivity.

10. **Stomatal Resistance:** Discuss the concept of stomatal resistance in the Penman-Monteith equation. What environmental variable influence the stomatal resistance of plants and how?

11. **Snow Water Equivalent:** What is snow water equivalent (SWE)? How can you measure the SWE of a snowpack?

12. **Snow Accumulation:** Discuss the mass and energy balance of a snowpack. What measurements are required to model the evolution of the snowpack during the accumulation (winter) season? What differences are there between snow accumulation in the Rocky Mountains vs the NE of the USA?

13. **Snow Melt:** Develop a simple model to calculate the melt rate of snow when isothermal at 0C. Given a snow-disappearance date for a small headwater basin, along with meteorological data, how might you determine the peak snowpack by back-calculating the total amount of melt that could have occurred?

14. **Hydrologic Fluxes as Functions of Latitude:** Draw a transect along the 110-degree west longitude roughly from Hermosillo up to the arctic circle. Assuming the transect does not cross any major water bodies, draw figures of the major dominant fluxes (P, ET, Q) as functions of latitude. For several locations along the transect also draw a seasonal cycle for these terms.

15. **Classes of Hydrologic Models:** Discuss the broad classes of hydrologic models? What are their strengths and weaknesses?

16. **Atmospheric Inversion:** What is atmospheric inversion? Why is there an inversion layer on the top of the atmospheric boundary layer during clear sky (convective boundary layer)?

17. **Black Body Radiation:** Discuss the concept of a black body. What is a grey body? What are the characteristics of a grey body with respect to radiation?

18. **Effects of the Atmosphere:** Why is our Sky blue? Do you think the sky as seen from the Moon's is also blue?

19. **Oceanic Influences:** What are the major oceanic Influences (sea surface temperature patterns) on the hydroclimate of a river basin?

20. **Utility of Land-Surface Water-Energy Balance Modeling:** Provide 5 examples of questions or practical issues that can be solved by a land-surface model. For each of your examples provide an alternate simple approach that might get you most of the way to a reasonable answer.

21. **3-Cell General Circulation:** What is the 3-cell general circulation? How does it control global climate (e.g., by controlling the distribution over land of desert and tropical forest)?

22. **Bias-correction and Downscaling:** What are bias-correction and downscaling? Why are the needed? How do they differ? How are they connected?

23. **Satellite Missions:** What are the principal methods by which the GPM, GRACE, SMAP, and SWOT satellite missions operate? What are their spatial and temporal resolutions and methods of operation?

24. **Active versus Passive Remote Sensing:** Explain the difference between Active and Passive sensors in remote sensing?

25. **Electromagnetic Radiation:** How is electromagnetic radiation related to remote sensing? Does the sun emit electromagnetic radiation? How about the Earth? What makes them different?

26. **Remote Measurement of Surface Soil Moisture:** Assume you want to design a sensor to measure surface soil moisture from space. What important factors should be considered to design a successful sensor that can provide useful information at all times?

27. **Global Warming:** Name at least 3 major greenhouse gasses. Why do they warm the planet? Explain based on the physical principle behind it.

SPECIALTY - HYDROCHEMISTRY AND WATER QUALITY

1. **Anthropogenic Age Tracers:** Explain the principles of using anthropogenic age tracers (e.g., tritium) to detect modern recharge. What are some of the uncertainties inherent in these dating approaches?
2. **Solutes:** Explain the difference between activities and concentrations of solutes.
3. **Mineral Solubility Reactions:** Explain the difference between Keq and saturation indices for mineral solubility reactions.
4. **Carbonate Systems:** Describe the carbonate system in natural waters. For example, explain how carbon dioxide from the atmosphere and root respiration drives carbonate mineral weathering. What is the dominant carbonate species at near-neutral pH? Why is carbonate mineral weathering such an important process in controlling the chemistry of natural waters? How does the presence of carbonates buffer the pH? What happens to carbonate equilibria when CO_2 degasses from water?
5. **Controls On Weathering:** Describe the difference between equilibrium and kinetic controls on weathering and what factors contribute to each control.
6. **Redox Reactions:** The degradation of organic matter in wetland or subsurface ecosystems involves complex geochemical processes primarily driven by microbial activity under varying redox conditions. Describe the following processes and discuss their required redox, hydrological condition, and resultant products.
7. **Role Of Clay Minerals:** Explain the role of clay minerals in the environment on influencing water major ion and trace metal chemistry.
8. **Remediation:** Explain how different behaviors (e.g., partitioning between water, vapor, soil phases) of common organic contaminants alter remediation strategies.
9. **Primary and Secondary Minerals:** Describe the weathering of primary minerals into secondary minerals and how this process contributes to the initial development of soil.
10. **Precipitation and Dissolution of Carbonate Minerals:** Describe the chemical reaction of Precipitation and dissolution of carbonate minerals. Discuss how these two geochemical processes regulate river water chemistry.
11. **Role of Geochemistry in the Hydrological Cycle:** Discuss and list at least five geochemical indicators that can be used to trace the interaction between surface water and groundwater.
12. **Adsorption-Desorption Equilibrium Dynamics of Minerals:** Write the Langmuir isotherm equation to describe the dynamic balance between the adsorption of solutes onto the surface of minerals and their release back into the surrounding medium. Use

the adsorption and desorption equilibrium equation to discuss how periodic soil drying-rewetting events affect the adsorption-desorption equilibrium dynamics of minerals.

13. **Riverine Carbon Flux:** Describe the processes that control the flux of inorganic and organic carbon in river systems.
14. **Role of Geochemical Processes in Trace Metals Pollution:** Explain how geochemical processes control the distribution and mobility of trace metals in river environments.
15. **Phosphorus Biogeochemical Cycling in Lacustrine Environments:** Describe the main process that inputs and outputs Phosphorus from a lake ecosystem. Discuss how each of these processes impacts water quality.
16. **Nitrate Biogeochemical Cycling in Groundwater:** Describe major sources of nitrate contamination and processes that can naturally remove nitrate in the subsurface? What environmental conditions are most favorable for natural nitrate removal?

SPECIALTY - MODELING AND SYSTEMS

1. **Hierarchy of modeling concepts:** What steps are taken during the development of a model? How do assumptions at one level of the model development process propagate and possibly inform mis-application of pre-developed models?

2. **Use cases for computational models:** Models can be used for multiple purposes, including historic reconstruction, forecasting, scenario analysis, or engineering for control. Compare and contrast the assumptions and goals for several of these use cases.

3. **Model performance measures:** There are many reasons to be interested in how well a model performs some particular task. Different tasks may be evaluated using different measures. Name at least two measures often used to evaluate models and what purposes you might find them applicable for. Additionally, consider when a particular measure may be inappropriate for evaluating a prediction.

4. **Regularization:** Explain the overall purpose of introducing regularization into a modeling workflow. Give an example of a regularization and what its purpose is. How do regularizations encode our preferences for a particular modeling task.

5. **Inference:** Describe the different kinds of inference (inductive, deductive, etc), and how they are applied in modeling. Possibly relate this back to the “Hierarchy of model concepts/development”.

6. **Metrics:** Objective functions are often used as a criteria to judge whether a model is fit for a specific purpose. Name several common objective functions/performance metrics, and some applications where they would be appropriate or inappropriate.

7. **Hypothesis Testing**: Explain what the statistical basis for hypothesis testing is. Explain what it means to maximize the likelihood associated with a model hypothesis. What are type I and type II errors?

8. **Over and underdetermined systems:** What is the difference between an *over-determined system* and *under-determined system*. What are problems associated with modeling such systems? Name an example of each of these types of systems in the context of hydrology.

9. **Data decomposition/representation:** Data can be decomposed into particular representations by choosing a particular basis. Some examples of this include the Fourier transform and Singular Value Decomposition. Choose a particular example, and describe how it is used to extract information from the data and explain what types of problems it can be used to solve/understand.

10. **Parameter estimation/calibration:** Explain the difference between "Manual-Expert" and "Automated" approaches to parameter estimation. Give an example of how/why each method may be preferred. For automatic calibration (also referred to as numerical optimization), describe a general workflow for implementing this.

11. **Sensitivity/uncertainty analysis:** Explain the difference between sensitivity and uncertainty. What are the major causes of uncertainty in modeling? How does sensitivity analysis relate to parameter estimation/calibration?

12. **Ensembles and Uncertainty**: How might you use ensemble simulations to address model uncertainty? Explain how you would design an ensemble and how you would incorporate the ensemble results into the answers your report to your client/audience?

13. **Coordinates, Dimensions, and Units**: Discuss the concepts of coordinates, dimensions, and units in data representation. How do these relate to the overall modeling process?

14. **Solutions of Differential Equations**: What is the difference between analytical and numerical solutions to differential equations? What are the strengths and weaknesses of each approach?

15. **Numerical methods for differential equations:** Describe the differences between finite difference, finite element, and finite volume methods for numerically solving differential equations. Additionally, what is the difference between implicit and explicit methods?

16. **Numerical methods:** Why do digital computers use finite-precision numerical representations? Describe the IEEE 754 floating point number representation. What are some tradeoffs between using high and low precision for computation and storage?

17. **Computer Architecture:** Describe the von Neumann architecture that computers generally use. What is the memory latency hierarchy, and how might it affect how you would approach your data storage/transfer strategy for a simulation versus data analysis problem?

18. **Parallel processing & scaling:** Describe the overall idea of parallel computing. What does it mean for a task to be "embarrassingly parallel"**.** How does Amdahl's law describe speedup for non-embarrassingly parallel tasks? Compare and contrast the concepts of weak scaling and strong scaling in computational benchmarking.

19. **Data driven and physics based modeling:** What are the differences between machine learning models and physically based hydrology models (eg. MODFLOW)? What are the strengths and weaknesses of each? If the machine learning model gets good enough will we still need the physical model?

20. **Classification versus Regression**: Explain how the modeling tasks of Classification and Regression are different. What objective functions are appropriate for each task?

21. **Over and underfitting:** Define the terms underfitting and overfitting. What are the consequences of each when applying a model to new data? How might you tell if your model is overfit or underfit?

22. **Bias variance tradeoff:** What is the bias-variance tradeoff? How does it relate to the mean-squared error metric? What is the relation to accuracy and precision? How can the bias-variance tradeoff be used to understand model complexity?

23. **Nonstationarity & Extreme events:** We believe many processes are in a nonstationary regime under climate change - what does this mean? How might this impact our ability to predict extreme events? Describe some standard distributions for modeling extreme events and comment on how robust they may be to parameter perturbations?

24. **Bias-correction and Downscaling**: What are bias-correction and downscaling? Why are they needed? How do they differ? How are they connected?

25. **Spatial interpolation:** Name a method for spatial interpolation. How does it work? What are its limitations and drawbacks?

26. **Data assimilation:** What is data assimilation and how does it work from a general perspective? Name an example of a data assimilation method used in hydrology and describe what types of problems it is useful for.