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Abstract—Hydrology intersects many other disciplines. Success in water supply management, energy reservoir development, agriculture, and climate research all depend on models of soil processes. For example, climate change research recognizes that transfer of mass and energy between atmosphere and soil cannot be ignored. Recently, it has become clear that the cold arctic provides more feedback to the climate than previously thought because of its vast permafrost formations that are thawing. Application of numerical hydrologic models to such non-traditional environments requires enhancements of and additions to the soil processes included in more traditional situations. For example, mass and energy transport must consider phase changes between water and vapor and ice, rather than just water and vapor. Further, the usual assumption of a stationary soil matrix is no longer acceptable. A significant process in cold regions is the annual freezing and thawing that results in heaving and slumping of soils and movement of soil particles, leading to large asymmetries in ice distribution. Additionally, soil bacteria and plants are important elements in permafrost conversion. New models that couple hydrologic, thermal, chemical, microbial and vegetative processes are being created to try to estimate the impact of climate warming in the arctic.

Numerical models of coupled hydrologic processes in soils are advancing quickly in terms of resolution achieved and processes included, but better experimental verification is sorely needed for these models. Is it sufficient to experimentally test overlapping sets of submodules of a complex model or must the entire system be tested experimentally (and probably much more expensively) because of strong model nonlinearities? Further, multi-scale methods are urgently needed. Soils are heterogeneous on many scales. Complicating this are chemical and biological reactions in and on soils that occur on their own time and space scales, but are interrelated to hydrologic and climate scales. Can reliability in complex model predictions be assured if they can only practically be verified experimentally on one or two scales? Should such models only be used to generate a relative ranking of importance of process interactions, and not to make predictions? These sorts of questions are not new but may become more difficult to answer. Stochastic methods have seen much development, but are still challenged by this multiplicity of scales and processes. Other multi-scale approaches such as regular and singular perturbation methods and fractal representations may be useful. Another need is the ability to propagate uncertainties through models. Stochastic and statistical methods as well as deterministic approaches (e.g., use of adjoints, perturbation methods and interval analysis) are being developed, but need to be extended to multi-process situations. Interpretation of field data can frequently end up as an inverse problem, with all of the associated ill-posedness questions. It appears safe to say that hydrology is as challenging as any area of research today.