<u>Ph.D. Thesis Title:</u> A Generalized Finite Volume Framework for Unified Multi-Region Hydraulic Modeling

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We have presented the development of a Finite Volume method-based unified multi-region hydraulic model. The developed model integrates the individual processes of surface overland flow, channel flow, and saturated-unsaturated subsurface flow through the imposition of appropriate boundary conditions or addition of source/sink terms at the interfaces of the flow regions. To address the inherent heterogeneity of the porous media at the micro-scale level, we have developed an algorithm for generating random hydraulic conductivity fields incorporating the concept of Representative Elementary Volume (REV) into the standard sequential Gaussian simulation technique. The proposed algorithm generates randomly distributed hydraulic conductivity fields for unstructured grid systems conditioned by in-situ measurements. We have developed a confined groundwater flow model which can simulate well-flow problems considering the effects of finite well radius, well-bore storage, well-bore skin, and partial well-penetration. We have proposed a Proper Orthogonal Decomposition (POD) based reduced-order framework for the confined groundwater flow model to optimize the computational expenses in terms of CPU time and usage incurred for complex problems. We have developed solvers for both pressure head-based and mixed forms of the modified Richards Equation for simulating saturated-unsaturated flow through heterogeneous porous media. The overland and channel flow processes are modeled by a simplified Zero-inertia (ZI) approximation of the Saint-Venant equations. The governing equations for subsurface, overland, and channel flow processes are linearized by applying the Picard iteration scheme with subsequent discretization using an implicit Finite Volume scheme. We have implemented a stabilized and adaptive time-stepping algorithm for smooth convergence and increased computational efficiency. The individual flow solvers and the coupled multi-region watershed flow solver have been developed utilizing the open-source Finite Volume-based computational fluid dynamics framework, OpenFOAM®. We have validated the individual flow models with various theoretical benchmark examples, laboratory experiments, and field-scale problems of increasing complexity from the literature. Grid-convergence study has been performed separately for each flow solver. The watershed model is validated by the results of some standard surface-subsurface flow models for several benchmark problems. The numerical results

presented in this Thesis show good accuracy of both the individual flow models and the integrated watershed model, thereby ensuring their potential applicability for modeling various hydrological flow problems.