Bench-scale water treatment testing of three next generation hollow-fiber (HF) nanofiltration (NF) membranes was conducted to characterize divalent ion rejection capabilities and investigate removal mechanisms. Existing mathematical models were investigated to describe solute transport using synthetic magnesium sulfate solutions including the size exclusion model, homogenous solution diffusion (HSD) model, dimensional analysis, and the HSD model incorporating film theory. Solute transport for two of the membranes were described by HSD theory and were predictive of their 90% divalent ion removal. A third membrane was more accurately modeled using size exclusion and was found to be predictive of its 40% divalent ion rejection. Feed ionic strength variation was shown to significantly impact rejection. In this work, semi-empirical models were developed to describe solute transport under varying feed ionic strength conditions. Bench-scale testing of aerated groundwater confirmed the HFNF membrane divalent ion rejection capabilities. Pilot testing of a commercially available HFNF membrane was shown to remove divalent ions and dissolved organic carbon (DOC) by 10% and 25%, respectively. Financial evaluations indicated that HFNF offered cost savings over traditional spiral-wound (SW) NF, $0.60/kgal versus $0.85/kgal operating costs, respectively. Traditional SWNF membranes produced superior water quality achieving 90% divalent ion removal and 96% DOC removal but required extensive pretreatment. When considering the costs of constructing a new 2 million gallon per day (permeate) HFNF process, conceptual cost comparisons revealed that HFNF technologies could reduce capital costs by approximately $1 million, and operating costs by $0.27/kgal for an 85% recovery plant.