Environment and Natural Resources Trust Fund

2026 Request for Proposal

General Information

Proposal ID: 2026-382

Proposal Title: Determining Fracture Characteristics for Karst Groundwater Flow Modeling

Project Manager Information

Name: Qizhi He

Organization: U of MN - College of Science and Engineering

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Project Basic Information

Project Summary: We use new software to identify and investigate geometric and hydraulic properties of fractured aquifers needed for accurately modeling flow and pollutant transport. This development involves artificial intelligence/machine learning.

ENRTF Funds Requested: $581,000

Proposed Project Completion: June 30, 2029

LCCMR Funding Category: Water (B)

Project Location

What is the best scale for describing where your work will take place?

Statewide

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

During the Project and In the Future

Narrative

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

Groundwater in fractured rock formations is a vital resource for Minnesota's drinking water, agriculture, and industry. In southeastern Minnesota, including the Twin Cities, groundwater flow is largely controlled by fractures in limestone bedrock (karst landscapes), forming a complex and unpredictable flow system. These aquifers supply over half the drinking water for 3 million residents but are highly vulnerable to contamination from nitrate and other pollutants. Accurately modeling groundwater movement in fractured aquifers is crucial for effective resource management and contamination mitigation. However, existing groundwater models often rely on simplified assumptions about fracture networks, limiting their ability to simulate fracture flow and pollution spread. A major challenge is identifying fracture characteristics, including geometry (location, thickness, and orientation) and hydraulic properties (e.g., hydraulic conductivity), from limited field measurements. This identification process is an inverse problem, and it becomes particularly intractable when modeling large fracture networks due to computational constraints and data scarcity. To address this gap, this project proposes to develop new software to identify complex fracture characteristics and improve groundwater flow predictions. This project will also complement the LCCMR-funded project (ID: 2025-110) by enhancing fracture characterization, supporting the development of a computational model for contaminant transport in karst aquifers.

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

This project will develop and validate a machine learning (ML)-powered computational model to enhance fracture properties characterization and groundwater flow modeling in Minnesota's fractured aquifers. The model integrates a cutting-edge ML technique, Physics-Informed Neural Networks (PINNs), with the Analytic Element Method (AEM), a highly efficient analytical approach (by PI Strack) for modeling flow in fractured impermeable rock. Compared to traditional numerical models, AEM significantly reduces simulation cost by orders of magnitude while maintaining physical accuracy in fracture network simulations. First, we will implement the AEM-based fracture flow model and demonstrate its efficiency in simulating groundwater flow in complex fracture networks. Next, we will extend the model to solve the inverse problem—determining fracture geometry and hydraulic properties—by incorporating PINNs. This ML-based approach will process numerous simulations of varying properties, iteratively updating fracture characteristics for more robust and accurate identification. Finally, the developed model will be validated using benchmark tests and real-world data from Minnesota's Platteville Formation. Through comparative analysis with field data, we will demonstrate that the ML powered AEM effectively resolves previously intractable fracture characterization challenges. Additionally, we will test its application in improving groundwater flow modeling and advancing the understanding of fracture and flow properties.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

This project will develop machine learning-powered AEM software to characterize complex fracture properties in aquifers using field data, aiming to enhance groundwater flow and contaminant transport modeling. By enabling accurate fracture network reconstructions, it will assist state agencies, researchers, and practitioners in developing more effective groundwater management and pollution mitigation strategies. It will strengthen subsurface transport modeling for applications such as mineral carbon storage. The project will produce an open-source, user-friendly groundwater tool available for download on GitHub, ensuring broad accessibility. It will also advance AI/ML for Environmental Science education by integrating results into the University of Minnesota's curriculum.

Activities and Milestones

Activity 1: Development of efficient simulation method for modeling groundwater flow in discrete fracture networks

Activity Budget: $186,448

Activity Description:
This activity aims to develop a computationally efficient simulation model using the Analytic Element Method (AEM) for simulating groundwater flow in fractured aquifers. Building upon the recently developed AEM-based fracture flow model published in the Journal of Hydrology (Fall 2024), this work will enhance AEM's ability to simulate complex fracture networks with greater accuracy and computational efficiency. Groundwater flow in fractured rock consists of two key components: flow within individual fractures and flow between connected fractures. The fracture intersections play a crucial role in a discrete fracture network (DFN) as they dictate how water moves through the system. Contaminant spreading at these intersections is significantly larger compared to other dispersion mechanisms, making their accurate representation essential for groundwater modeling. This activity will reformulate AEM to simulate flow through fracture intersections, ensuring realistic flow representation. Additionally, conventional numerical models, e.g., USGS's MODFLOW hydrologic model, will be used to design and analyze synthetic benchmark examples to validate AEM's accuracy and efficiency. Further enhancements will focus on optimizing AEM for speed and parallel processing, enabling large-scale simulations and laying the foundation for machine learning-based inverse modeling in Activity 2, ultimately improving fracture characterization and contaminant transport predictions in Minnesota's fractured aquifers.

Activity Milestones:

Description	Approximate Completion Date
Reformulate AEM to simulate flow in fractured aquifers with complex fracture intersections	December 31, 2026
Use conventional numerical models to design and analyze synthetic benchmark examples	May 31, 2027
Validate 3D AEM models using benchmark examples and evaluate their accuracy and computational efficiency	December 31, 2027

Activity 2: Development of machine learning powered simulator for characterizing fracture and hydraulic properties in fractured aquifers

Activity Budget: $212,924

Activity Description:
This activity addresses the challenging inverse problem of identifying fracture geometries and hydraulic properties in fractured aquifers. We will develop a novel simulation tool using cutting-edge machine learning (ML) techniques for scalable network characterization and flow prediction. Initially, we will extend a physics-informed neural network (PINN) subsurface flow model, previously developed by PI He, using the synthetic benchmark examples (Activity 1) to demonstrate feasibility and establish a baseline for the inverse modeling. This PINN model will be used to determine fracture characteristics from given flow data. Next, we will integrate PINN with the highly efficient AEM model verified in Activity 1 to enable rapid fracture characterization and accurate groundwater flow modeling in fractured aquifers. The key advantage of this ML powered AEM model is its ability to compactly parameterize individual fractures and precisely describe flow behaviors in complex connected fractures. It will infer the unknown fracture characteristics, including geometrical and hydraulic properties, by utilizing various field measurement data collected in Activity 3, such as hydraulic tomography, borehole pressure, and tracer tests. Finally, we will validate the ML-powered model using benchmark examples and assess its reliability and scalability as the number of fractures increases, ensuring its effectiveness for groundwater flow modeling.

Activity Milestones:

Description	Approximate Completion Date
Develop physics-informed machine learning model for determining fracture characteristics	September 30, 2027
Develop machine learning-powered AEM model for determining large-scale fracture characteristics	September 30, 2028
Validate models on benchmark examples and assess their reliability and efficiency in complex fractured aquifers	December 31, 2028

Activity 3: Integrate field data, validate, and implement machine learning-powered simulator for fracture characterization and flow modeling in Platteville formation

Activity Budget: $181,628

Activity Description:
This activity focuses on validating and improving the machine learning-powered AEM model developed in Activities 1 and 2 using real-world hydrogeologic field data from Minnesota's fractured limestone aquifers, specifically the Platteville Formation in southeast Minnesota, which faces high contamination risks. By leveraging data from previous and ongoing Environmental Trust Fund projects, we will compile and integrate datasets for fracture properties characterization. This site is located on the UMN campus and necessary field experiments will be conducted to provide high-resolution data on fracture geometry, hydraulic conductivity, and groundwater flow patterns. Using the machine learning-powered AEM simulator, we will reconstruct realistic large-scale fracture networks and compare results with experimental measurements and conventional numerical models. The simulator will be refined to enhance groundwater flow and contaminant transport modeling, improving pollution migration predictions and risk assessment. By completing this project, we will gain a deeper understanding of fracture flow and contaminant transport in Minnesota's fractured and karst aquifers. All programming, synthetic examples, and field data will be publicly available on GitHub for broader accessibility. Additionally, research outcomes will be integrated into the UMN CEGE curriculum to advance AI applications in environmental science and groundwater modeling education.

Activity Milestones:

Description	Approximate Completion Date
Characterize fracture geometries and compile hydrogeologic field data of the Platteville formation	June 30, 2028
Use machine learning-powered simulator to identify fracture characteristics of the Platteville Formation	December 31, 2028
Validate machine learning-powered simulator with Platteville field data for improved groundwater flow and contaminant transport	March 31, 2029
Publication/dissemination, document codes in an open-access repository, and integrate findings into a teaching curriculum	June 30, 2029

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Otto Strack	University of Minnesota, College of Science and Engineering	Co-PI; Lead the development of the analytic element model and co-supervise graduate students in program implementation and numerical modeling of fractured aquifers	Yes
Peter Kang	University of Minnesota, College of Science and Engineering/ St. Anthony Falls Laboratory	Co-PI; Support model validation with field data and supervise a grad student for fracture characterization of Platteville formation	Yes

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?

The machine learning-powered software developed in this project for fracture system characterization and modeling will be open-source and shared with Minnesota agencies, stakeholders, and practitioners in groundwater management, contaminant mitigation, and geological engineering. Future development will focus on expanding model capabilities to simulate transport of multiple contaminants and incorporating additional field validation. Ongoing support will be pursued through federal (NSF, DOE, USGS) and state (MPCA) funding and industry partnerships. Collaborations with environmental and geotechnical organizations will ensure long-term adoption, while potential commercialization may provide sustainable funding for continued advancements in fractured aquifer modeling and groundwater protection.

Project Manager and Organization Qualifications

Project Manager Name: Qizhi He

Job Title: Assistant Professor

Provide description of the project manager's qualifications to manage the proposed project.

PI Qizhi He is an Assistant Professor in the Department of Civil, Environmental, and Geo-Engineering at UMN and an Affiliated Faculty with the CSE Data Science Initiative. He specializes in computational mechanics and machine learning applications in geosciences, with expertise in multiphysics modeling, inverse problems, and AI-enhanced numerical methods. His research integrates physics-informed machine learning with high-performance computing to improve flow and transport simulations in subsurface media, with applications in groundwater modeling, geohazard prediction, and environmental sustainability. Before joining UMN, Dr. He was a postdoctoral researcher at Pacific Northwest National Laboratory. He holds a Ph.D. in Structural Engineering and Computational Science and an M.A. in Applied Mathematics from UC San Diego. He serves on the editorial board of Computers and Geotechnics.

Co-PI Otto Strack is a Professor in the Department of Civil, Environmental, and Geo-Engineering at UMN, with over 50 years of experience in groundwater flow and transport modeling. A corresponding member of the Royal Netherlands Academy of Science, he has received multiple honors, including the Vreedenburgh Award and the M. King Hubbert Award from the National Groundwater Association. Dr. Strack pioneered the Analytic Element Method (AEM), a highly efficient numerical approach for regional-scale groundwater modeling. His expertise in AEM development will be central to this project.

Co-PI Peter Kang is an Associate Professor and Gibson Chair of Hydrogeology in the Department of Earth Sciences at UMN. His research focuses on groundwater flow and contaminant transport in fractured rock hydrogeology. Before UMN, he was a researcher at the Korea Institute of Science and Technology and a postdoctoral associate at MIT's Earth Resources Laboratory. He earned his M.Sc. and Ph.D. in Civil & Environmental Engineering from MIT. Dr. Kang established the Platteville Fractured Rock Hydrogeology Research Site at UMN, a key resource for validating the computational models developed

Organization: U of MN - College of Science and Engineering

Organization Description:
The University of Minnesota is one of the largest and most prestigious public research institutions in the United States, dedicated to advancing knowledge and innovation in science, engineering, and environmental sustainability. This project will be conducted within the College of Science and Engineering, specifically in the Department of Civil, Environmental, and Geo-Engineering (CEGE), which is among the nation's top-ranked programs. CEGE's mission is to addresses critical societal challenges related to water resources, infrastructure, and environmental protection through interdisciplinary research and education.

Part of this project will be supported by the St. Anthony Falls Laboratory (SAFL), a world-renowned research center specializing in environmental and geophysical fluid mechanics. SAFL provides cutting-edge laboratory and field capabilities for hydrogeological research. The project will leverage the computational resources of Dr. He's Intelligent Computational Mechanics Lab housed in the Civil Engineering Building. The lab is equipped with desktop workstations with NVIDIA GPUs for machine learning research and educational purposes. The project will also utilize the Minnesota Supercomputing Institute (MSI), a state-of-the-art facility supporting high-performance simulations and data analysis, ensuring efficient and scalable model development. These combined resources will facilitate the development and validation of innovative modeling tools for groundwater flow and transport in Minnesota's fractured aquifers.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineligible	% Benefits	# FTE	Classified Staff?	$ Amount
Personnel								
Qizhi He		Principal Investigator and project manager; Oversee all project activities and manage the project, supervise grad students to develop machine learning powered flow simulators for fracture characterization			36.6%	0.36		$68,615
Otto Strack		Co-Principal Investigator; Lead the development of the analytical element model and co-supervise graduate students in program implementation and numerical modeling of fractured aquifers			36.6%	0.51		$115,795
Peter Kang		Co-Principal Investigator; Assist in model validation with field data and supervise a grad student for fracture characterization of Platteville formation			36.6%	0.04		$8,571
2 Graduate Research Assistants (Benefits include 23.2% health + tuition)		One GRA will implement machine learning-powered flow simulators for fracture characterization; the other one will model flow and transport in fractured aquifers			43.7%	3		$352,109
1 Graduate Research Assistant (Benefits include 23.2% health + tuition)		Earth Science Graduate Student; Support aquifer characterization, compile field data, and numerical modeling of the Platteville formation			44.6%	0.5		$28,317
							Sub Total	**$573,407**
Contracts and Services								
							Sub Total	**-**
Equipment, Tools, and Supplies								

							Sub Total	**-**
Capital Expenditures								
							Sub Total	**-**
Acquisitions and Stewardship								
							Sub Total	**-**
Travel In Minnesota								
							Sub Total	**-**
Travel Outside Minnesota								
	Conference Registration Miles/ Meals/ Lodging	Two domestic conference trips for 1–2 participants	Present results of LCCMR-funded work, outreach, and demonstration of the new capabilities of the new Minnesota's machine learning powered ground water modeling software	X				$7,500
							Sub Total	**$7,500**
Printing and Publication								
	Printing	Posters	Present results of LCCMR-funded work in conferences and outreach					$93
							Sub Total	**$93**
Other Expenses								
							Sub Total	**-**
							Grand Total	**$581,000**

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request
Travel Outside Minnesota	Conference Registration Miles/Meals/Lodging	Two domestic conference trips for 1–2 participants	Plan to attend AGU to present results of this LCCMR-funded work

Non ENRTF Funds

Category	Specific Source	Use	Status	Amount
State				
			State Sub Total	**-**
Non-State				
			Non State Sub Total	**-**
			Funds Total	**-**

Total Project Cost: $581,000

This amount accurately reflects total project cost?

Yes

Attachments

Required Attachments

Visual Component

File: a1e32018-712.pdf

Alternate Text for Visual Component

This visual provides an overview of the proposed project aimed at addressing Minnesota's urgent need for a reliable tool to identify fracture characteristics in fractured and karst aquifers. The figure illustrates the process of collecting field data, developing machine learning-enabled models, and reconstructing fracture networks for improved groundwater modeling....

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Support letter from Itasca Minneapolis	15d7cf0b-353.pdf
SPA letter UMN	23b79d19-2a2.pdf

Administrative Use

Does your project include restoration or acquisition of land rights?

No

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

Yes, I understand the UMN Policy on travel applies.

Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?

No

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

N/A

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

N/A

Does your project include original, hypothesis-driven research?

Yes

Does the organization have a fiscal agent for this project?

Yes, Sponsored Projects Administration

Does your project include the pre-design, design, construction, or renovation of a building, trail, campground, or other fixed capital asset costing $10,000 or more or large-scale stream or wetland restoration?

No

Do you propose using an appropriation from the Environment and Natural Resources Trust Fund to conduct a project that provides children's services (as defined in Minnesota Statutes section 299C.61 Subd.7 as "the provision of care,

treatment, education, training, instruction, or recreation to children")?

No

Provide the name(s) and organization(s) of additional individuals assisting in the completion of this proposal:

Otto Strack (Co-PI); Peter Kang (Co-PI); Enoch Pan (CEGE Accountant) <pan00121@umn.edu>; Christina Doherty (UMN Sponsored Projects Administration) <Doher170@umn.edu>

Do you understand that a named service contract does not constitute a funder-designated subrecipient or approval of a sole-source contract? In other words, a service contract entity is only approved if it has been selected according to the contracting rules identified in state law and policy for organizations that receive ENRTF funds through direct appropriations, or in the DNR's reimbursement manual for non-state organizations. These rules may include competitive bidding and prevailing wage requirements

N/A