Research Statement

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Statement of the Problem

According to the U.S. National Science Foundation, the discovery of solutions to future geoscience challenges will require the fusion and mining of mutual information from big data. The fusion of big data variables, however, is computationally challenging because they tend to be disparate, noisy, nonlinear, redundant, scale-dependent, sparse, spatially-limited, and uncertain.

State of the Art

Research in devising and testing alternate data-fusion paradigms and uncertainty quantification techniques represents the state-of-the-art in computational geoscience. To date, I established the scientific basis, extended theory, and developed and implemented relevant Geoscientific data fusion and knowledge discovery schemes to solve previously unanswered research questions associated with six research themes: Climate and Land-use Change, Core Science Systems, Ecosystems, Energy and Minerals, Natural Hazards, and Water. My work aims to enhance mutual information for knowledge discovery with reduced uncertainty through fusion of big data sets using three computational paradigms: numerical joint-inversion (novel constraints and solvers), artificial adaptive systems (evolutive and machine-learning), and hybrid models (combination of the former and statistical models). I continued direction for these research efforts based on my own work and/or in collaboration with PhD candidates, visiting scientists, and faculty and colleagues.

Progress to Date

My research involving these three data-fusion paradigms solved previously intractable problems as described for each of the following themes: Climate and Land-use Change, Core Science Systems, Ecosystems, Energy and Minerals, Natural Hazards, and Water. Advancements in each of these themes are briefly described next.

<u>Climate and Land-use Change</u>: (1) I identified scale-dependent telconnections among climate variables and El Niño-Southern Oscillation (ENSO) events (Friedel, 2010a, Friedel, 2012). This study demonstrates that it is possible to integrate and simultaneously analyze relations of scale-dependent (local to global and modern to ancient time) climate variables. (2) I extended modern annual tropical Pacific land-air-sea temperature data to the millennial scale (Friedel, 2010b, Friedel, 2012). This study provides a 2,000 year temperature and precipitation series at an annual frequency for trend analysis and future use in calibrating global circulation (numerical) models. The application of quantile regression to these data provides alternative interpretation in trends whose uncertainty can be quantified annually as empirical density functions. Quantile trends reveal that the ENSO phenomenon operates over a continuum of temporal and spatial scales. This finding suggests that any forcing influencing the frequency or intensity of climate change will increase the likelihood for drought hazards placing national and global security at risk. (3) I estimated the number of annual global ENSO events over the past 2,000 years (Friedel, 2011, Friedel, 2012). This study provides data used to quantify the persistence for annual warm season El Niño, Neutral, and La Niña events over the past two millennia, and identify delays in global teleconnections and distribution of cooling and warming periods. These findings have broad economic, political, and social implications with respect to developing water resource policies. (4) I identified that climate variables have a fractal and long-memory process (Esfahani and Friedel, 2012) and performed a 50-year climate forecast for southern and southwestern United States (Esfahani and Friedel, 2011, Esfahani and Friedel, 2014). This study demonstrates the self-similar nature of reconstructed climate variables. This finding of long-memory processes supports the forecasting of climate change in

temperature and precipitation. Also, this study provides the first short-term (<50 years) forecast of annual precipitation and temperature at local and regional scales across southwestern US. This information can be used by water managers to formulate water-resource and security planning. This application can be extended from annual to monthly time scale and from local to global spatial scales. (5) I classified the likelihood of landscape soil and vegetation components in Brazil from space-borne satellite data (Vicente et al., 2011; Vicente et al, 2013a; Vicente et al., 2014; Friedel, 2016; Vicente et al., 2013b). This study classifies landscape characteristics from hyperspectral satellite data without the use of traditional multiple linear regression equations beset by poor resolution. This approach is generalized for climate applications in collaboration with researchers at the Brazilian agricultural research institute (Empresa Brasileira de Pesquisa Agropecuária) and university research institute (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas a Agricultura). (6) I downscaled climate models for generating alcohol production in Brazil (Lins et al., 2013a). (7) I modeled tropical land-use and land-cover change in relation to sugar cane (Vicente et al., 2013c). (8) I integrated vegetation index time series and meteorological data to understand land use/land cover seasonality (Lins et al., 2013b). (9) I evaluated influence of global volcanic processes on climate modulation in the southwestern US (Friedel and Esfahani, 2013).

<u>Core Science Systems:</u> (1) I determined depth, orientation, weight, and type of buried munitions and explosives of concern (Asch and Friedel, 2011; Friedel, 2012; Friedel et al., 2012). (2) I predicted the magnitude of earthquakes for a region of china (unpublished). (3) I estimated uncertainty in lithospheric boundaries determined using a joint seismic inversion (Moreira et al., 2010; Moreira et al., 2013a). (4) I improved resolution of lithospheric boundaries using joint inversion of receiver function and surface wave dispersion (Moreira et al., 2012a; Moreira et al., 2013b; Friedel and Moreira, 2013) and receiver function and surface wave dispersion and magnetotelluric measurements (Moreira and Friedel, 2011; Moreira et al., 2012b; Moreira and Friedel, 2013; pub. 106). (5) I co-developed a hybrid evolutionary-gradient solver for numerical inversions (Moreira and Friedel, 2015).

<u>Ecosystems</u>*:* (1) I predicted mineral-resource effects on aquatic ecosystems (Friedel, 2010); Climate-change effects on ecosystem services (Friedel, 2011). (2) I determined connectivity among mining-aquatic ecosystem variables (Friedel et al., 2012a). (3) I developed an aquatic-mining ecosystem model (Friedel et al., 2012b). (4) I developed and used an artificial adaptive system to select input for ecosystem modeling (Friedel, 2015). (5) I modeled the combined effects of natural and anthropogenic stressors on aquatic ecosystems (Friedel, 2014; Friedel, *draft*). (6) I demonstrated the usefulness of artificial adaptive system to select optimal information for unbiased predictions with reduced uncertainty (Friedel and Buscema, 2016). (7) I provided various applications of artificial adaptive systems in environmental science (Friedel and Buscema, 2015).

<u>Energy and Minerals:</u> (1) I identified multivariate relations among global deposit and mining characteristics (Friedel, 2011a**,** Friedel 2011b). (2) I identified heterogeneity in various grade and tonnage models (Friedel, 2011a**,** Friedel 2011b). (3) I imputed missing data in grade and tonnage models (Friedel, 2011a**,** Friedel 2011b). (4) I estimated true values of zeros in grade and tonnage models (Friedel, 2011a**,** Friedel 2011b). (5) I estimated the density of various types of porphyry copper deposits (Friedel, 2011a**,** Friedel 2011b). (6) I determined the economic feasibility of mining undiscovered porphyry copper deposits in British Columbia-Yukon territories (Friedel and Long, 2011; Friedel, 2012). (7) I predicted background and mine-related acidity and metals in river basins (Friedel, 2014). (8) I predicted the probable location of economic phosphate deposits (Moreira et al., 2014). (9) I performed hydrogeophysical modeling of geothermal field data (Friedel, 2015).

<u>Natural Hazards:</u> (1) I forecasted climate-change effects on the hydrology and geomorphology across post-fire landscapes in western U.S (Friedel, 2010a**;** Friedel, 2011a). (2) I provided a set of nonlinear debris-flow equations and quantified their uncertainty (Friedel, 2010b, Friedel, 2011b). (3) I modeled

hydrometeorological hazards for coastal cities of São Paulo, Brazil (Koga-Vicente and Friedel, 2010; Koga-Vicente and Friedel, 2012). (4) I evaluated the role of large earthquakes on aquifer dynamics (Friedel et al., 2016).

<u>Water:</u> (1) I estimated soil physical properties and quantified correlation structure across the Pocos de caldes basin Brazil (Iwashita et al., 2010a; Iwashita et al.., 2011a). (2) I estimated hydrogeologic properties and characterized hydrostratigraphy across the transboundary South American Serra Geral-Guarani aquifer system (Iwashita et al., 2011b; Iwashita et al., in review). (3) I predicted the hillslope chemical weathering processes across Paraná state, Brazil (Iwashita et al., 2010b; Iwashita et al., 2011c; Iwashita et al., 2011e; Iwashita et al., 2011e;). (4) I forecasted climate-change effects on ground-water recharge (Friedel, 2010a), (5) I predicted well yield in the semi-arid climate and fractured crystalline rocks of northeastern Brazil (Friedel, 2010b; Friedel et al., 2012a). (6) I estimated starting parameter values and geostatistical constraints for applications to spatially-limited numerical inverse problems (Friedel and Iwashita, 2013). (7) I performed near-real time airborne imaging of a heterogeneous surficial aquifer (Iwashita et al., 2011f; Friedel et al., 2012b; Friedel, 2013; Friedel et al., 2015a). (8) I computed continuous hydrostratigraphy for conceptual groundwater models by integrating geophysical-hydrogeologic data-integration scheme (Friedel et al., 2015c, Friedel and Rawlinson, 2015; Friedel, 2015; Friedel, in review-b). (9) I devised scaling equations for ground-water recharge measurements (Friedel, 2015). (10) I predicted climate-change effects on ground water recharge in the Midwestern United States (Friedel, 2015; Friedel, draft). (11) I evaluated significance of climate and hydrology in the formation of natural acid-rock drainage (Johnson et al., 2009). (12) I upscaled rainfall-recharge for groundwater modeling (Friedel, 2013). (13) I estimated missing groundwater-surface water hydrochemistry values in a sparse data set (Rawlinson et al., 2014; Daughney et al., 2015). (14) I evaluated lithologic controls on GW/SW interaction (Friedel et al., 2015).

Impact – The application of data-fusion and knowledge discovery is new to GNS, USGS and most other earth science organizations. This body of work demonstrates efficacy of intelligent data fusion and analysis that transcends USGS research themes. This approach is significant because it provides alternative modeling paradigms to solve previously unanswered big data challenges that plague traditional methods. My shift in thinking toward these paradigms resulted in invitations for me to give an invited lecture to US Army Corps of Engineers, co-convene and give a Keynote address at NATO advanced research workshops (Climate Change and its Effect on Water Resources, 2011); edit a NATO sponsored climate-change book, serve as an associate editor of the new Journal of Water and Energy Security, convene an AGU Union Session on Computational Intelligence in Earth and Space Systems, and mentor a visiting USGS scientists and two Fulbright Scholars. Outside the USGS, I had requests by Brazilian agencies (Agricultural Institute, Climate and Meteorological Institute, Dept. Environment and Society, and Geological Survey) for research collaboration, technical assistance, and teaching of university courses (University of Campinas, and University of Brasilia), and participate in a 2013 State Department sponsored US-Italy scientific exchange between Center for Computational and Mathematical Biology, University of Colorado, Denver, CO and Semeion Research Center of Sciences of Communication, Rome, Italy. Ongoing data fusion and prediction research collaboration with Brazil scientists involves climate-change applications to agriculture and natural hazards.

In 2014, I was hired by GNS Science, New Zealand to develop and apply data fusion and knowledge discovery algorithms as part of the the Smart Aquifer Characterization program (geophysics, remote sensing, and tracer validation tasks) funded by the New Zealand Ministry of Business (MBIE), Innovation and Employment. Since arriving to GNS, I received requests and began collaboration with principal scientists from other departments/divisions to evaluate these methods for application to Earthquake hydrology funded by the Royal Society of New Zealand, Influence of regional groundwater flow on geothermal system funded by MBIE, Effects of climate change induced sea-level rise on coastal aquifers funded by GNS Strategic Development Fund, and Real-time satellite mapping of gold and geothermal deposits funded by GNS Strategic Development Fund. Various international requests for assistance in devising computational-intelligent solutions include: the Director of Strategic Directions in Hydrogeology, Geoscience Australia, Australia to help with real-time mapping of surficial aquifer structure and properties in southwest Pacific; a Professor of Geophysics, Geoscience Department, Federal University of Natal, Brazil to map cratonic basins for locating offshore oil & gas; a professor of environmental sciences at Sun Yat-sen University and Chinese Academy of Sciences, China to collaborate on a proposal for groundwater as a climate adaption funded by MBIE as part of the strategic NZ-China alliance; the Director of Geophysics, Tblisi State University, Georgia to evaluate relations and devise model accounting for hydrology and earthquake parameters; a professor at University of Brasilia to develop hybrid solver (software) for joint geophysical and joint hydrogeophysical inverse solutions; the Director of Semeion Institute, Italy to develop software for selecting optimal subsets of variables and estimate missing data in sparse matrices; a research Fellow, University of Florence to map soil age in satellite imagery; a PhD candidate, Earth and Environmental Sciences, Victoria University, NZ to quantify likelihood for unconventional on-shore shale-gas prospects in NZ; a PhD candidate, Institute of Environmental Assessment and Water Research, Spain to quantify groundwater recharge in a semi-arid environment.

Future Directions

The field of Geoscientific data fusion and knowledge discovery is in its infancy. Future directions for my research will continue to focus on methods development and applications involving the numerical joint inversion, artificial adaptive systems and hybrid modeling paradigms. Examples of methods development for numerical joint inversion will include: (1) extending an evolutionary (global)-gradient (local) solver to accommodate n-joint solutions, (2) testing and integration of reduced order methods to speed the global solution and optimal subset selection, (3) evaluating Bayesian regression trees to quantify uncertainty, and (4) evaluating model worth using a measure theoretic approach. Some methods development for artificial adaptive systems will include: (1) the parallelizing of a modified self-organizing map technique for real-time classification and estimation and estimation of nonlinear uncertainty limits by stochastic cross-validation, (2) reduced-order methods for optimal information selection and uncertainty reduction, and (3) symbolic regression for evolutive spatiotemporal scaling equations. Examples of some methods development for hybrid modeling include: evaluating novel algorithms that combine numerical, artificial adaptive systems, and multivariate statistical approaches with recurrent training schemes to address data sparseness, enhance mutual information, and reduce uncertainty.

Applications of these developments will benefit seven research themes: Climate and Land-use Change; Core Science Systems; Ecosystems; Energy and Minerals; Natural Hazards; Water; and Energy, food, water security nexus. <u>Climate and Land-use Change</u>: Reconstruction and forecasting of climate-change variables on a monthly time scale at local, regional, and global spatial scales (Global Change, GNS, NZ; University of Campinas, BR); spatiotemporal downscaling of climate variables and large scale surface fluxes (Hydrogeology, GNS NZ; NIWA, NZ); real-time satellite remote mapping of landscape components (Minerals and Geothermal, GNS, NZ; Satellite Monitoring, EMBRAPA, BR); and spatiotemporal scaling of hyperspectral sensor footprints for agricultural and earth science (Massey University, NZ). <u>Core science systems</u>: Earth structural and geological mapping of the USA by joint-inversion of national magnetotelluric and seismic data (University of Brasilia, BR). <u>Ecosystems</u>: Modeling effects natural and anthropogenic stresses on aquatic ecosystems (Semeion Institute, IT).

<u>Energy and Minerals</u>: Unconventional shale-gas prospecting in NZ (Victoria University, NZ); unconventional off-shore oil-gas prospecting in BR (University of Natal, BR). <u>Natural hazards</u>: effects of climate change impacts on coastal environments (University of Campinas, BR); role of large earthquakes on aquifer dynamics (GNS, NZ; Victoria University, NZ; Tblisi State University, GA). <u>Water</u>: Airborne aquifer characterization and mapping of hydrostratigraphy (Smart Aquifer Characterization, GNS; Strategic Directions, Geoscience Australia, International Program, USGS); groundwater as an adaption (Sun-yet Sen University, CN); effect of sea-level rise on coastal groundwater supplies (Global Change, GNS; Hawkes Bay Regional Council); water footprint for regions of New Zealand (Gannan Normal

University, CN); effects of urban ecosystem on the climate system (National Research Program, USGS); transport of atrazine and dicamba through silt and loam soils (National Research Program, USGS). Energy, food, water security: Evaluating the role and interdependencies of energy, food, and water on risk to national and global security (National Research Program, USGS). Preliminary unpublished results revealed important relations that were useful for predicting pricing of commodities. I am currently supervising a visiting scientist and two PhD candidates.

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