Here is a summary of some of the current activities in my research group, together with a list of some potential thesis projects. Note that this list is just a sampler, and I am always happy to discuss other ideas and interests. Generally, my research group focuses on quantitative, process-oriented geomorphology. A typical dissertation project involves a combination of fieldwork and numerical modeling. Sometimes experimental work is involved as well. Often, the project takes shape around a "natural experiment": a case study that exemplifies a particular process or suite of processes, with enough clues to reconstruct its history and rates of change. These natural experiments provide valuable windows into how the earth's erosional engine operates on various time and space scales and in different kinds of environment.

CURRENT GRADUATE STUDENT THESIS PROJECTS:

Debris Flows and Landscape Evolution (Scott McCoy, Ph.D. student):

Debris flows appear to be responsible for carving the steep, capillary-like lacework of channels that form much of the relief in steep terrain. Yet we know very little about the mechanics of debris incision into rock, and how the processes responsible translate into a "debris flow erosion rule" over geologic time. This project brings together monitoring of debris flows at the Chalk Cliffs, Colorado (in collaboration with the USGS Landslide Hazards Team), analysis of terrain morphometry in regions prone to debris flows (including Central and Southern Italy and the San Gabriel Mountains of southern California), and numerical modeling of granular mechanics. (For more see: McCoy et al., 2010)

The Role of Large Floods and Riparian Vegetation in Shaping River and Floodplain Morphology (Mariela Perignon, Ph.D. student):

Large floods can strongly impact river valleys. A powerful flood can alter channel geometry and conveyance capacity, erode or bury riparian vegetation, enhance or degrade the fertility of floodplain soils, and in extreme cases even change the entire channel pattern. A fundamental goal in fluvial hydrology is to understand these impacts at a quantitative and ultimately predictive level. Currently, our ability to forecast potential flood impacts is limited by a lack of good test cases, and a lack of fully coupled morphodynamic models. We are addressing this knowledge and technology gap by developing a numerical model that couples flow routing with the physics of erosion and deposition on the timescale of a major flood. We are testing this coupled model using a unique data set from the Rio Puerco in New Mexico. In 1926, saltcedar was introduced to the Rio Puerco watershed to limit erosion and prevent the infilling of Elephant Butte Reservoir. In September 2003, herbicide spraying along a 12 km section of the Rio Puerco killed all woody vegetation. A major flood 3 years later caused extensive erosion and channel widening along the devegetated reach; the eroded material was deposited downstream where living vegetation prevented erosion. Because the vegetation was the only factor that varied along the middle reach of the river, the 2006 Rio Puerco flood makes an excellent natural experiment for testing coupled hydraulic-morphodynamic flood models.

From Peaks to Prairie: Two Natural Experiments in Decadal Landscape Evolution (Francis Rengers, Ph.D. student):

Numerical models of landscape evolution play a vital role in geomorphology, but there remains a pressing need to test these models against field data. We are developing two case studies for model-data comparison testing. The two case studies are sites of rapid, decadal landscape change. The decadal scale is particularly important because (1) it is a critical time scale for societal adaptation to rapid environmental change, (2) it is short enough to take advantage of historical records, and (3) models of longer-term landscape dynamics should be consistent with shorter-term behavior. The study pairs two very different environments: a low-relief, semi-arid, soft-rock setting dominated by rapid gully erosion and scarp retreat, and a steep, montane, forested, crystalline-rock setting responding to a 1996 wildfire. The first site, located on the high plains of eastern Colorado, provides a unique opportunity to reconstruct erosion rates and channel growth patterns over a 70-year period. The second site, in the Colorado Front Range, contains an extraordinarily rich 14-year database of post-fire geomorphic response, thanks to intensive monitoring efforts by the U.S. Geological Survey. The project relies on a variety of methods, including aerial photo analysis, reservoir sediment volumes, ^{137}Cs measurements, LiDAR DEM analysis, and oral history interviews. Modern hydrology and geomorphology are documented with a network of rain gauges and flow sensors, combined with biennial tripod-laser scans to measure rates of channel-head retreat (estimated at ~0.5m/yr). The two data sets are used to test a physically based numerical model of landscape evolution using a Monte Carlo calibration method.

Coupled Hydrology and Rock Weathering (Abby Langston, Ph.D. student):

Rock weathering is a key element of the rock cycle, yet our present knowledge of how hydrology, chemical weathering, and physical weathering interact is quite limited. This project, rooted in the Boulder Creek Critical Zone Observatory, seeks to document and model the feedbacks between water movement in the subsurface and the role of that water in altering the chemical and physical properties of rocks underground. We use soil-moisture sensors to monitor the recharge of water to the subsurface, and numerical models of groundwater flow to study the subsurface flow paths and their relation to rock fabric texture. Sampling of surface and near-surface rocks in the Boulder Creek watershed, together with subsurface investigation, provides a window into the “critical zone” and its architecture. By combining flow models with rock alteration models, we are developing insight into the patterns by which the weathered zone takes shape. This also provides a link to the deeper geological history of the Rockies, as variations in the nature and rate of rock alteration may have played an important role in the region's landscape evolution and Tertiary stratigraphy.

POTENTIAL RESEARCH OPPORTUNITIES:

Dynamics of Sediment Dispersion:

During the height of the Manhattan Project, unknown quantities of plutonium were thrown into desert washes around Los Alamos. The plutonium, adhered onto sediment grains, began moving downstream, eventually making its way to the Rio Grande River. This is just one of many examples of the process of sediment dispersion. When sediment grains move down a river or hillslope or coastline, they spread apart. The speed with which they move, and the rate at which they spread, has important theoretical and practical implications. How fast will a plume of contaminated sediment move? How will its concentration change over time and space? How much time will sediment grains spend in active transport, where they are subject to abrasion and bombarded by cosmogenic radiation? How much time do they spend stored, where they can weather and weaken? Amazingly, there is little theory or data available to answer these questions. Hence, there is a great opportunity to improve our state of knowledge. Field data using various environmental tracers – radio-tagged cobbles, tagged sand or silt grains, etc. – can reveal patterns of transport and spread in different environment, while experimental facilities provide a window into dispersion at the grain-motion level. New mathematical and numerical techniques provide the tools to interpret data. Some first steps on this path are discussed by Bradley et al. (2010) and Tucker and Bradley (2010).

Climate Change, Fault Motion, and Hillslope Evolution:

A very recent study we did in central Italy suggests that it ought to be possible to "read" the erosional influence of glacial-interglacial climate oscillation in the morphology of bedrock hillslopes and normal-fault scarps. There's a great opportunity to expand this database to look at other faults and other mountain ranges, such as the Wasatch Front (Utah), Grand Tetons (Wyoming), Pelleponnese (Greece), and other locations with active normal faulting in resistant bedrock. Essentially, it is possible to quantify the difference in erosion rate between glacial and interglacial conditions by looking at hillslope morphology along faults with a known slip rate. With such data in hand, it's a simple step to begin exploring and testing process-based models to interpret the data and apply it to other environments. This is a particularly exciting project because so little is known at present about when and how strongly climate controls erosion rates.

Speeding up Landscape Evolution Models:

River basins and their networks occupy the vast majority of the earth's land surface. Most of us live in a river basin and depend on its ability to gather water over a large area and focus it into a narrow channel. However, the same mechanism gathers sediment and contaminants and can produce floods. A fundamental research goal in earth-surface science (geomorphology, hydrology, sedimentology) is to develop mathematical (usually numerical) models that describe the formation of river basins over geologic time and their response to natural and anthropogenic forcing over human time scales. Within the last two decades, the potential for building, testing, and applying such models has advanced significantly thanks to three parallel developments. First, the emergence of cosmogenic nuclide analysis allows us to measure millennial-scale erosion rates and their variability in space. Second, there has been significant progress in the development of rate laws for processes such as soil production and down-slope transport in specific environments. Third, rapid advances in digital mapping technology, such as LiDAR and synthetical aperture radiometry, are producing an unprecedented volume of terrain data that have a resolution comparable to the scale on which key transport processes operate. We now have the opportunity to construct models of landscape change that are grounded in the physics and chemistry of the governing processes, and able to address the dynamics of river basins on scales of tens to thousands of square kilometers. However, computational efficiency is now a key limiting factor. Because of nonlinearities in the governing equations, current models cannot, for example, handle an area larger than a few hectares at the resolution of a typical LiDAR image (1 m^2). Significant coarsening is not an option because of the loss of important terrain characteristics. To address this obstacle, we are engaged in a collaborative effort between geoscientists and applied mathematicians, aimed at developing efficient numerical algorithms for solving the equations that govern the evolution of a topographic surface. A major emphasis is on the application of Discrete-Event Simulation methods to geomorphic and hydrologic models. Preliminary work on this shows that there is huge potential in this method for advancing computational geomorphology, sedimentology, hydrology, and related fields.

Component-Based Software Architecture for Landscape Modeling:

This project addresses an important limitation to scientific productivity in fields that rely on computational modeling of landscape processes. Landscape models compute flows of mass, such as water, sediment, glacial ice, volcanic material, or landslide debris, across a gridded terrain surface. Science and engineering applications of these models range from short-term flood forecasting to long-term landform evolution. At present, software development behind these models is highly compartmentalized and idiosyncratic, despite the strong similarity in core algorithms and data structures between otherwise diverse models. We believe that progress across the range of fields that use landscape models can be transformed by introducing a component-based approach to software development. We have proposed to NSF a proof-of-concept study in which an existing landscape model code is adapted and enhanced to provide a set of independent, interoperable components. These will include: (1) a gridding engine to handle both regular and unstructured meshes, (2) an interface for space-time rainfall input, (3) a surface hydrology component, (4) an erosion-deposition component, and (5) a simulation driver. The components will communicate with each other using an interface design based on recommendations of the Community Surface Dynamics Modeling System (CSDMS), and will be fully compatible with the CSDMS Modeling Toolkit. The components will be tested with a trial application that addresses runoff and erosion on post-wildfire landscapes, using the Weather Research and Forecasting (WRF) model to provide space-time rainfall input. The components will be deployed to the surface-process community, and feedback will be collected from users, by (1) adding the components to the CSDMS library, and (2) providing hands-on training sessions at annual meetings of the CSDMS Terrestrial Working Group.

Natural experiments in landscape evolution:

This is not one project, but many. One theme of my group's research is to refine and test process-based landscape evolution models. A powerful way to do this is to identify natural experiments: case studies where nature provides us with enough clues to piece together the history and/or rate of landscape development. There are plenty of these to be found around the world, on a wide variety of time scales. They include volcanic landforms (where the initial condition is known), post-glacial landscapes, badlands (where change is rapid enough to measure in near-real time, using techniques such as ground-based laser scanning), landscapes impacted by fire or deforestation, regions (like southern Italy and Sicily) where marine terraces and cosmogenic nuclides provide constraints on tectonic uplift rates, and many others. A thesis centered on a natural experiment makes a great opportunity to develop skills in a variety of techniques, and to wrestle with the challenge of understanding how process physics and chemistry have shaped the landscape (or seascape) in question. (For more, see Tucker, 2009, and Tucker and Hancock, 2010)

Long-Term Landscape Evolution of the Colorado Front Range and its Foreland:

This project is closely linked with the Boulder Creek Critical Zone Observatory. In his book "Rising from the Plains," John McPhee wrote eloquently about the late Tertiary "exhumation of the Rockies" – a regionwide switch from net deposition to net erosion in the basins bounding the Rocky Mountain uplifts, accompanied by cutting of canyons into adjacent ranges. The driving question is why this occurred, and why it was preceded by regionwide deposition of the Ogallala series fluvial gravels, in a sheet that extends from South Dakota to Texas. The project basically involves compiling and synthesizing the stratigraphic record from the western High Plains, and using numerical modeling of post-orogenic range and foreland evolution provides to discover which hypotheses, among the many that have been offered, are viable. (For more, see Wobus et al., 2010)

Toward a Comprehensive Theory of Channel Width:

Understanding what controls the shape and size of natural rivers has long been a "holy grail" for fluvial geomorphologists and hydrologists. Part of the answer lies in the physics by which fluid forces act on the materials making up the bed and banks of a river channel. Models that we recently developed compare well with data from bedrock rivers (Wobus et al., 2006, 2008; Yanites and Tucker, in press). Now the challenge is to generalize these models to honor a range of material types – from loose sand to vegetated mud to solid rock. There is also a need to account for the role of variability in water and sediment flux through a channel. A wealth of old and new data on river-channel geometry, as well as experimental data, exists to support this approach; what's most needed are computational models that can make testable predictions about how channel form should vary under different material properties and hydrologic regimes. It's hard to understate how important a contribution it would be to show that, using fundamental principles of water flow, erosion and sediment transport, it is possible to explain the shape and size of natural channels under different conditions. This is a great project for someone who wants to really grab hold of a classic scientific problem and crack it open.

Post-Glacial Landscape Evolution, Western New York State:

This project, which has some momentum behind it already, centers on the landscape of western New York. Here, streams that now drain to Lake Erie have carved a network of canyons since the ice sheet retreated about 17,000 years ago. Because the channels are carved into a low-relief, ice-deposited surface, it is possible to reconstruct the pre-erosion geometry of the surface. Using OSL and radiocarbon dating on preserved sediments and wood fragments, it is possible to reconstruct the timing of erosion. The project has an applied element as well: it happens to be a site where erosion threatens to exhume buried hazardous waste related to a former nuclear-fuel reprocessing mill. Thus, the better we can test and calibrate models of millennial-scale erosion and landscape change, the better equipped we are to forecast potential future erosion.

ABOUT CU'S SURFACE PROCESSES PROGRAM:

We have a thriving geomorphology and surface processes team, with four faculty members (Greg Tucker and Bob Anderson in Geological Sciences and Suzanne Anderson and John Pitlick in Geography) and about 10 graduate students and postdocs. The CU group meets each week for a reading and discussion seminar (available as a 1-credit course), and my own lab group also meets weekly. We are able to take advantage of the amazing intellectual resources available via the CIRES and INSTAAR research institutes, the Community Surface Dynamics Modeling System (CSDMS, headquartered at CU), the USGS and NOAA laboratories, UNAVCO, NCAR, and the wider CU community. Other resources include the CSDMS supercomputer facility, the cosmogenic radionuclide laboratory, and the Boulder Creek Critical Zone Observatory.

REFERENCES:

Bradley, D.N., Tucker, G.E., and Benson, D. (2010) Fractional dispersion in a sand-bed river: *Journal of Geophysical Research*, v. 115, F00A09, doi:10.1029/2009JF001268.

McCoy, S.W., Kean, J.W., Coe, J.A., Staley, D.M., Wasklewicz, T.A., and Tucker, G.E. (2010) Evolution of a natural debris flow: in situ measurements of flow dynamics, video imagery, and terrestrial laser scanning: *Geology*, v. 38, p. 735-738, doi:10.1130/G30928.1.

Tucker, G.E. (2009) Natural experiments in landscape evolution: *Earth Surface Processes and Landforms,* v. 34, p. 1450-1460, doi:10.1002/esp.1833.

Tucker, G.E., and Bradley, D.N. (2010) Trouble with diffusion: reassessing hillslope erosion laws with a particle-based model: *Journal of Geophysical Research*, v. 115, F00A10, doi:10.1029/2009JF001264.

Tucker, G.E., and Hancock, G.R. (2010) Modelling landscape evolution: *Earth Surface Processes and Landforms*, v. 35, p. 28-50.

Wobus, C.W., Kean, J.W., Tucker, G., and Anderson, R.S. (2008) Modeling the evolution of channel shape: balancing computational efficiency with hydraulic fidelity: *Journal of Geophysical Research*, v. 113, F02004, doi:10.1029/2007JF000914.

Wobus, C.W., Tucker, G.E., and Anderson, R.S. (2006) Self-formed bedrock channels: *Geophysical Research Letters,* v. 33, L18408, DOI: 10.1029/2006GL027182, 6pp.

Wobus, C.W., Tucker, G.E., and Anderson, R.S. (2010) Does climate change create distinctive patterns of landscape incision?, *Journal of Geophysical Research*, v. 115, F04008, doi:10.1029/2009JF001562.

Yanites, B.J., and Tucker, G.E. (in press) Controls and limits on bedrock channel geometry: *Journal of Geophysical Research*, doi:10.1029/2009JF001601.

-Greg Tucker, November 1, 2010