Available online at www.sciencedirect.com

ScienceDirect

Journal of Terramechanics 51 (2014) 53–66

Journal of Terramechanics

www.elsevier.com/locate/jterra

Application of a hillslope-scale soil moisture data assimilation system to military trafficability assessment

Alejandro N. Flores [a,*], Dara Entekhabi [b,c,1], Rafael L. Bras [d,2]

[a] Department of Geosciences, Boise State University, 1910 University Dr., Boise, ID 83725-1535, United States
[b] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, United States
[c] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, United States
[d] Departments of Civil and Environmental Engineering and Earth and Atmospheric Sciences, Georgia Institute of Technology, 225 North Ave., Atlanta, GA 30332-0325, United States

Received 5 February 2013; received in revised form 7 October 2013; accepted 24 November 2013
Available online 28 December 2013

Abstract

Soil moisture is an important environmental variable that impacts military operations and weapons systems. Accurate and timely forecasts of soil moisture at appropriate spatial scales, therefore, are important for mission planning. We present an application of a soil moisture data assimilation system to military trafficability assessment. The data assimilation system combines hillslope-scale (e.g., 10s to 100s of m) estimates of soil moisture from a hydrologic model with synthetic L-band microwave radar observations broadly consistent with the planned NASA Soil Moisture Active–Passive (SMAP) mission. Soil moisture outputs from the data assimilation system are input to a simple index-based model for vehicle trafficability. Since the data assimilation system uses the ensemble Kalman Filter, the risks of impaired trafficability due to uncertainties in the observations and model inputs can be quantified. Assimilating the remote sensing observations leads to significantly different predictions of trafficability conditions and associated risk of impaired trafficability, compared to an approach that propagates forward uncertainties in model inputs without assimilation. Specifically, assimilating the observations is associated with an increase in the risk of “slow go” conditions in approximately two-thirds of the watershed, and an increase in the risk of “no go” conditions in approximately 40% of the watershed. Despite the simplicity of the trafficability assessment tool, results suggest that ensemble-based data assimilation can potentially improve trafficability assessment by constraining predictions to observations and facilitating quantitative assessment of the risk of impaired trafficability.

Keywords: Soil moisture; Military trafficability; Data assimilation; Remote sensing; Microwave radar; Hillslope scale

1. Introduction

The purpose of this study is to demonstrate how forthcoming satellite radar observations that are sensitive to soil moisture can potentially be used to improve assessment of military vehicle trafficability by combining those observations with information from a hydrologic model. Estimation of the spatiotemporal distribution of soil moisture is critical for weather, climate, and hydrologic forecasting [1]. As a military battle-space environment variable, moreover, soil moisture exerts considerable influence on mobility and trafficability [2]. At scales of individual hillslopes (10s to 100s of m), for instance, soil wetness can limit mobility of military vehicles and personnel over the land surface, thereby potentially impacting mission outcomes and decision-making. Because of the importance of soil moisture on mission planning and execution, improving the accuracy, timeliness, and spatial resolution of soil moisture can enhance military decision support systems.

---

* Corresponding author. Tel.: +1 208 426 2903.
E-mail addresses: lejoflores@boisestate.edu (A.N. Flores), darae@mit.edu (D. Entekhabi), rlbras@gatech.edu (R.L. Bras).
[1] Tel.: +1 617 253 9698.
[2] Tel.: +1 404 385 2700.

0022-4898/$36.00 © 2013 ISTVS. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jterra.2013.11.004

An increasingly important methodology for estimating soil moisture is data assimilation – the mathematical combination of model- and observation-based soil moisture information [3,4]. Advantages of data assimilation as a soil moisture estimation technique include the ability to: (1) use observations and models of different spatial resolutions [5], (2) ingest observations of geophysical variables that are indirectly related to soil moisture [6–8], and (3) constrain model soil moisture predictions to observations that are intermittently available [9]. Ensemble-based techniques, such as the ensemble Kalman Filter (EnKF) [10,11] and Markov Chain Monte Carlo [12] methods, are a particular class of data assimilation methods that support the use of Monte Carlo simulation to resolve the spatiotemporal distribution of soil moisture in a probabilistic way. Other techniques, known as smoothers [13], can use observations to update model estimates at all times. For the sake of simplicity, we limit our discussion to the introduction of data assimilation techniques based on the EnKF. Readers interested in a broader review of data assimilation techniques should refer to reviews by [14].

In the EnKF framework, uncertainties in boundary (e.g., soil properties, rainfall forcing) and initial (e.g., soil moisture) conditions are represented explicitly by producing stochastic realizations of model states (e.g., soil moisture and temperature), parameters (e.g., soil and vegetation parameters) and forcings (e.g., precipitation and humidity). Stochastic realizations of initial and boundary conditions are then propagated through the hydrologic forecasting model. The output is an ensemble of soil moisture realizations (referred to as the *forecast*) from which the sample mean, variance, and covariance are computed. These sample statistics are assumed to approximate the underlying spatial probability density function of soil moisture. The ensemble of model soil moisture estimates is conditioned on observations that are also associated with uncertainty, expressed as an error covariance matrix. The conditioned ensemble of model soil moisture estimates (referred to as the *analysis*) is an initial condition to the hydrologic model, which is evolved forward in time (under still-uncertain boundary conditions) until a new observation is available. This forecast-analysis process repeats for every subsequent observation.

We use the outputs of a soil moisture data assimilation system as input to a simple model of vehicle mobility. The vehicle mobility model is based on the concept of the Rating Cone Index (RCI) [15,16], a measure of soil surface load-bearing capacity, and a Vehicle Cone Index (VCI) [16,17], vehicle-specific critical values of RCI that are indicative of impaired mobility. The soil moisture data assimilation system, described in detail by Flores et al. [8], uses a physics-based ecohydrology model (described below) to simulate the spatiotemporal distribution of soil moisture at the hillslope scale. Uncertainty in boundary conditions is represented in: (1) soil parameters using a Latin-hypercube based sampling strategy (see [18]), and (2) hydrometeorologic forcings using a stochastic weather generator (see [8,19]). Observations used to condition soil moisture ensembles take the form of synthetic L-band microwave radar images broadly consistent with NASA's forthcoming Soil Moisture Active–Passive (SMAP) satellite [20]. Because this satellite is not yet in orbit, we use an Observing System Synthetic Experiment (OSSE) approach in which the ecohydrologic model is used to simulation a notionally true realization of the spatiotemporal distribution of soil moisture. Output from the ecohydrology model is supplied as input to the Integral Equation Model [7,21–23] to yield synthesized images of radar backscatter in two polarization states (see [8]). Because topography is correlated with factors affecting reflection of microwave energy like soil moisture (e.g., [24]) and controls the local incidence and polarization, the observation synthesis approach explicitly accounts for topography (e.g., [25,26]).

We seek to address the following applied science questions:

(1) Do improvements in the accuracy of soil moisture knowledge correspondingly improve the accuracy of trafficability maps?
(2) For a given vehicle, does constraining model-derived soil moisture to satellite observations significantly change the perceived risk of impaired trafficability conditions?

In Section 2 below we describe the study methods. This includes a brief overview of the data assimilation system used to obtain soil moisture ensembles used for trafficability assessment and the trafficability assessment technique. Section 3 presents the results of the simulation experiments. Key findings, implications, and potential directions for future study are discussed in Section 4.

2. Methods

The SMAP satellite is not scheduled for launch until late 2014 and there is currently no L-band radar satellite that provides adequate spatial resolution and temporal revisit to support military trafficability assessment using the data assimilation approach described here. An OSSE approach is therefore required. The OSSE framework is commonly used in geophysical inversion, remote sensing, and data assimilation studies to develop inversion algorithms and test the accuracy of data assimilation routines prior to the availability of actual observations [6–8]. In an OSSE framework, a model of the physical system is used to produce a synthetic (i.e., hypothetical) distribution of soil moisture that is conceptually "true." A geophysical forward model is then used to create a corresponding set of synthetic observations of the variable that is observed by the sensor (i.e., brightness temperature for passive microwave, or radar backscatter or travel time for radar). Synthetic observations are then perturbed with noise that is consistent with the anticipated observational error to produce synthetic satellite products that are used in a data