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Evaluation of time stability indices for soil water storage upscaling

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SUMMARY

Time stability index (TSI) is usually used to evaluate time stability of soil water storage (SWS) at point scales for SWS upscaling. The objective of this study was to evaluate seven TSIs for estimating mean SWS. Included were six indices used for indirect estimation (i.e., standard deviation of relative difference (SDRD), mean absolute bias error (MABE), width of the 90% empirical tolerance interval of relative water content (T), chi-squared statistic (χ^2), root-mean-squared differences (D), and temporal coefficient of variability (CV_t)); and one index used for direct estimation (i.e., root mean square error (RMSE)). Five goodness-of-fit indices (GFIs), including root mean squared deviations (RMSD), Nash–Sutcliffe coefficient of efficiency (NSCE), coefficient of determination (R^2), absolute mean difference (BIAS), and relative bias error (RBIAS) were selected for evaluating mean SWS estimation quality in both calibration and validation periods. The minimum number of sampling occasions needed to identify the most time-stable location was identified considering different starting dates of sampling. Evaluation of the TSIs was performed using SWS data of 0–1.0 m layer obtaining from the Canadian Prairie landscape and the Chinese Loess Plateau. The results showed that MABE, χ^2, D, and CV_t outperformed SDRD and T irrespective of the GFI used. If RMSD and NSCE were used, D was the best TSI. If BIAS and RBIAS were adopted, MABE was the best TSI. Mean SWS estimation by the indirect method was more accurate than that by the direct method. For both study areas, the minimum number of sampling occasions needed to identify the most time-stable location varied with starting dates of SWS measurement, and generally five to seven sampling occasions was needed to identify the most time-stable location with D and MABE.

1. Introduction

Soil water storage (SWS) varies with time as influenced by a series of hydrological processes. However, if a field is repeatedly surveyed for SWS, there is a high probability that a location displaying certain wetness characteristics (i.e., wet, dry and intermediate) will have that characteristics persist on subsequent occasions. This phenomenon was first defined as time stability (TS) by Vachaud et al. (1985). It was observed at a large variety of scales ranging from plot (Pachepsky et al., 2005) to region (Martínez-Fernández and Ceballos, 2003). Related studies have covered a wide range of terrains, sampling schemes, sampling depths, investigation periods, and land uses (Biswas and Si, 2011d; Brocca et al., 2009; Hu et al., 2010a; Tallon and Si, 2004; Vachaud et al., 1985).

Time stability can be classified into two ways. One is for describing the overall similarity of soil moisture spatial pattern between measurement occasions (Biswas and Si, 2011d; Cosh et al., 2006; Kachanoski and de Jong, 1988; Vachaud et al., 1985). The other is for describing the time persistence of a given location to evaluate the mean SWS of an area either by direct or indirect method. The direct method estimates mean SWS directly by measuring SWS at a time-stable location (Brocca et al., 2009; Cosh et al., 2008; Grayson and Western, 1998; Martínez-Fernández and Ceballos, 2005). The indirect method estimates mean SWS by considering the offset between the mean and the measurement value at a time-stable location (Grayson and Western, 1998; Han et al., 2012; Starks et al., 2006). If the most time-stable location of an area can be identified from its soil, land use, topography features in advance, direct method should be preferred as previous SWS campaigns is unnecessary. Otherwise, indirect method may be better as the constraint of having a mean relative difference (MRD) closest to zero is not easily satisfied. In addition, other approaches, such as random combination method, can also be used to evaluate mean soil water content of an area by randomly selecting some locations without previous sampling campaigns, but usually more than one sampling locations is needed (Hu et al., 2008; Brocca et al., 2010).

There are many time stability indices (TSIs) available to evaluate the degree of TS at a point scale. TSIs for the indirect mean SWS estimation include: standard deviation of relative difference

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Nomenclature

$\overline{\mathrm{SWS}_j(i)'}$	mean SWS estimate at time j by the SWS measurement value at location i
$\overline{\beta_i}$	mean of relative SWS over time for location i
$\overline{\delta_i}$	mean relative difference over time for location i
$\beta_j(i)$	relative SWS at time j for location i
$\beta(i)_{P=0.95}$	relative SWS values at cumulative probability of 95 %
$\sigma(\beta_i)$	standard deviation of relative SWS over time for location i
m	number of SWS sampling occasions
$\overline{\mathrm{SWS}_j}$	mean SWS over space at time j
$\langle\overline{\mathrm{SWS}_j(i)'}\rangle$	mean value of $\overline{\mathrm{SWS}_j(i)'}$ in a time domain
$\langle\overline{\mathrm{SWS}_j}\rangle$	mean value of $\overline{\mathrm{SWS}_j}$ in a time domain
$\delta_j(i)$	relative difference of SWS for each sampling location i at measurement time j
$\beta(i)_{P=0.05}$	relative SWS values at cumulative probability of 5%
$\mathrm{SWS}_j(i)$	SWS value measured at location i and measurement time j
$\overline{\mathrm{SWS}_j}$	true value of mean SWS at time j
BIAS	absolute mean difference
CV_t	temporal coefficient of variability
D	root-mean-squared differences
GFIs-DM	goodness-of-fit indices in terms of mean SWS estimation by direct method
GFIs-IM	goodness-of-fit indices in terms of mean SWS estimation by indirect method
GFIs-IM-DM	goodness-of-fit indices values by indirect mean SWS estimation method at the best location in terms of direct mean SWS estimation
LYMQ	LaoYeManQu watershed on the Chinese Loess Plateau
MABE	mean absolute bias error
MRD	mean relative difference
NSCE	Nash–Sutcliffe coefficient of efficiency
R^2	coefficient of determination
RBIAS	relative bias error
RD	relative difference
RE	relative error
RMSD	root mean squared deviation
RMSE	root mean square error
Rs	Spearman's rank correlation coefficient
SDNWA	St. Denis National Wildlife Area in Saskatchewan, Canada
SDR	standard deviation of relative SWS
SDRD	standard deviation of relative difference
SWS	soil water storage
T	width of the 90% empirical tolerance interval of relative water content
TS	time stability
TSI-DM	time stability index in terms of mean SWS estimation by direct method
TSIs-IM	time stability indices in terms of mean SWS estimation by indirect method
V_m	TSI or MRD value when datasets from m occasions after a certain starting time were considered
V_t	TSI or MRD value when all datasets after a certain starting time were involved
β	relative SWS
χ^2	chi-squared statistic

(SDRD) (Mohanty and Skaggs, 2001; Schneider et al., 2008; Vachaud et al., 1985), standard deviation of relative SWS (SDR) (Pachepsky et al., 2005), mean absolute bias error (MABE) (Hu et al., 2010a,b), temporal coefficient of variability (CV_t) (Starr, 2005), width of the 90% empirical tolerance interval of relative soil water content (T) (Guber et al., 2008), chi-squared statistic (χ^2) (Guber et al., 2008), and root-mean-squared differences (D) (Guber et al., 2008). The direct method takes SWS measurement at a time-stable location with the MRD closest to zero and the minimum associated SDRD over time as representative of the mean (Brocca et al., 2009; Grayson and Western, 1998; Martínez-Fernández and Ceballos, 2005). Although a number of studies have proven the feasibility of representing the mean soil water content directly by the soil water measurement of a time-stable site, identification of time-stable location tends to be subjective when the location with MRD closest to zero does not coincide with that having the minimum SDRD. For this reason, Jacobs et al. (2004) combined these two indices and produced a single metric, root mean square error (RMSE) of relative SWS difference. Although many TSIs are available to identify TS of a location for mean SWS estimation, little work has been done to compare their performances except that of Hu et al. (2010a,b) and Gao et al. (2011) in which only the performance of MABE and SDRD was compared. It is important to compare the performances of different TSIs to obtain a more suitable index for evaluating TS of a location in terms of mean SWS estimation.

The performance of TSIs in terms of mean SWS estimation should be judged by a goodness-of-fit index (GFI). Many GFIs have been used to evaluate the mean SWS estimation quality by time-stable location. The widely used indices include root mean squared deviations (RMSD) (Fernandez-Galvez et al., 2006; Jacobs et al., 2010; Martínez-Fernández and Ceballos, 2005; Schneider et al., 2008), Nash–Sutcliffe coefficient of efficiency (NSCE) (De Lannoy et al., 2007; Perry and Niemann, 2007), correlation coefficient (R) or coefficient of determination (R^2) (Brocca et al., 2010; De Lannoy et al., 2007; Martínez-Fernández and Ceballos, 2005), absolute mean difference (BIAS) (Cosh et al., 2004; De Lannoy et al., 2007; Martínez-Fernández and Ceballos, 2005), and absolute bias relative to mean (RBIAS) (Hu et al., 2010b). However, performance of TSIs may change with the chosen GFI.

Time stability indices were usually developed without consideration of mean SWS estimation quality or were developed while only considering a specific GFI (Hu et al., 2010b). It is therefore meaningful to evaluate the performance of different TSIs in relation to different GFIs in order to evaluate time stability of a location in terms of a specific GFI. The study aimed to evaluate the performance of different TSIs in terms of their mean SWS estimation quality for a specific GFI both in calibration and validation periods. Specific attention was paid to: (a) performance of TSIs in terms of indirect mean SWS estimation quality judged by different GFIs and (b) comparison of indirect and direct methods in terms of mean SWS estimation quality. The minimum number of measurements over time needed to identify the most time-stable location for different TSIs was also discussed considering different starting dates of measurements. One dataset from a transect in Canadian prairie area and another from a watershed on the Chinese Loess Plateau were used to compare performance.

2. Materials and method

2.1. Time stability indices

Seven TSIs were evaluated. The first six are usually used to identify time stable location for mean SWS estimation by the indirect method, and the seventh is usually used to identify time stable