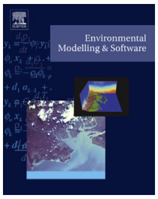
Environmental Modelling & Software 104 (2018) 153–170

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft



Estimation of regional scale effective infiltration using an open source hydrogeological balance model and free/open data

Mauro Rossi*, Marco Donnini

Consiglio Nazionale delle Ricerche, Istituto di Ricerca per la Protezione Idrogeologica, Perugia, Italy

ARTICLE INFO

Article history:
Received 29 May 2017
Received in revised form
24 November 2017
Accepted 15 March 2018

Keywords:
Effective infiltration
Hydrogeological balance
Free/open data
Open software
Alps
Central apennines
HYDRO-BM

ABSTRACT

Effective infiltration (EI) is the amount of precipitation infiltrating into the soil and recharging the aquifers. EI is estimated using direct or indirect methods or using water balance models. Direct and indirect methods lead to biased EI estimates, since based on simplified schemas of groundwater bodies and of their recharge mechanisms. Water balance models include different processes and variables, but they are seldom applied due to the limited availability of the input data, particularly at regional scales. We propose a method for EI estimation over large areas based on a monthly water balance model exploiting open source software and free/open data. The model integrates procedures to estimate EI and other water balance components, accounting for the uncertainty of input data. The model is calibrated in the Central Apennines (Italy), where EI reference values are available from the literature, and later applied in the Alps, where regional EI estimates are missing.

1. Introduction

Effective infiltration (EI) is the amount of meteoric water per unit surface that yearly infiltrates into the soil and recharges aquifers. EI reflects the capability of a hydrogeological complex to absorb meteoric water. Estimating this parameter in a given area, requires a detailed knowledge of its lithological, morphological and climatic setting (Mastrorillo et al., 2009). EI can be estimated using direct or indirect methods or using water balance models.

The direct method consists of estimating EI by dividing the average volume of water discharged by the springs in one year by their recharge area. Pioneering analyses of the infiltration process for aquifer recharge using direct methods were done at yearly (Aronis et al., 1961; Burdon and Papakis, 1961; Burdon, 1965) and sub-yearly (Kessler, 1957, 1965) scales starting from the ‘50s. Boni and Bono (1982) and Boni et al. (1986) applied the direct method to estimate the EI of the main aquifers in Central Italy. The method has been successively applied by Mastrorillo et al. (2009) and Mastrorillo and Petitta (2010) for carbonate aquifers in the Umbria-Marche region (Central Italy). Mastrorillo et al. (2009) suggest that the application of EI direct estimation is difficult and that this may lead to biased estimates, mainly because hydrogeological bodies may be characterized by deep groundwater circulation with unknown springs and unknown hydraulic connections with other groundwater bodies. The direct method also suffers some limitations due to the limited accuracy when defining the boundaries of aquifer recharge areas and due to the scarce availability of the spring discharge data. As highlighted by Mastrorillo et al. (2009), in these conditions the effective infiltration can be deduced indirectly as a percentage of precipitation (i.e., indirect method).

This indirect method is based on the use of an empirical coefficient, named the effective infiltration coefficient (EIC). This dimensionless coefficient ranges between 0 and 1 and varies for different lithology. The EIC is defined as the percentage of precipitation that infiltrates at depth, and it is estimated at the catchment scale by dividing the volume of spring discharge by the volume of total rainfall (Drogue, 1971; Bonacci, 2001; Civita, 2005, Mastrorillo et al., 2009; Allocca et al., 2014). Such indirect effective infiltration estimation is biased, since it is based on a rough parameterization of the permeability of the different lithologies outcropping in the recharge areas. Moreover, values of EIC are in general inferred from the literature and do not consider the real lithological setting of the investigated recharge areas. The suitability of this indirect effective infiltration estimation method depends on the reliability of the precipitation values, for which long and complete time series are

---

* Corresponding author.
E-mail address: mauro.rossi@irpi.cnr.it (M. Rossi).

https://doi.org/10.1016/j.envsoft.2018.03.005
1364-8152/

List of variables used in the model

Variable	Description	Units
AET	Actual evapotranspiration	mm
AWC_SUB	Subsoil water capacity	mm·m^{-1}
AWC_TOP	Topsoil water capacity	mm·m^{-1}
Coef_inf	Effective infiltration coefficient	dimensionless
d	Number of days in a month	#
D	Mean monthly hours of daylight	units of 12 h
Deepstor	Amount of water stored in depth (used as a proxy of the Effective Infiltration, EI)	mm
$Deepstor_m$	*Deepstor* in the considered month (*m*)	mm
$Deepstor_{m-1}$	*Deepstor* in the previous month (*m-1*)	mm
DR	Depth to rock	m
DRO	Direct runoff	mm
drofact	Fraction of direct runoff for a given precipitation (returned directly by the hydrological system),	dimensionless
Elev	Elevation	m a.s.l.
meltmax	Factor controlling the dependence of snow melt fraction (*SM*) with respect to elevation	dimensionless
$Meltmax_0$	*Meltmax* for elevation of 0 m.	dimensionless
$Meltmax_{1000}$	*Meltmax* for elevation of 1000 m.	dimensionless
P	Mean monthly precipitation	mm
P_{AET}	Precipitation available for the evapotranspiration	mm
PET	Potential evapotranspiration	mm
P_{max}	Maximum mean monthly precipitation	mm
P_{min}	Minimum mean monthly precipitation	mm
PMH	Hydrogeological type of parental material	dimensionless
pmpe	If positive it is the water that can potentially infiltrate into the soil, if negative it is the water potentially withdrawable by evapotranspiration from the soil	mm
prestor	Soil moisture storage for the previous month	mm
pmhfact	Fraction of water infiltrating in a month into depth	dimensionless
P_{rain}	Mean monthly precipitation in the form of rainfall	mm
P_{snow}	Mean monthly precipitation in the form of snowfall	mm
Remain	Water remaining as surface soil water storage in a month (this is transferred to the successive month for water balance calculations)	mm
$Remain_m$	*Remain* in the considered month (*m*)	mm
$Remain_{m+1}$	*Remain* in the successive month ($m + 1$)	
rfact	Fraction of water becoming runoff in a month after infiltration and evapotranspiration withdrawal	dimensionless
RO	Runoff generated from the soil water storage	mm
ROtotal	Monthly total runoff	mm
SM	Snow melt fraction	mm
Snowstor	Snow storage	mm
ST	Soil-moisture storage	mm
STW	Soil-moisture storage withdrawal	mm
SUR	Excess water that cannot either infiltrate or evapotranspirate	mm
T	Mean monthly temperature	°C
TEXT_SRF_DOM	Dominant surface textural class	dimensionless
T_{max}	Maximum mean monthly temperature	°C
T_{min}	Minimum mean monthly temperature	°C
T_{rain}	Above this temperature threshold, all precipitation is rain	°C
T_{snow}	Below this temperature threshold, all precipitation is snow	°C
T_{snow0}	Temperature threshold for elevation of 0 m. Below this threshold, all precipitation is snow	°C
$T_{snow1000}$	Temperature threshold for elevation over 1000 m. Below this threshold, all precipitation is snow	°C
UP_{max}	Maximum precipitation uncertainty	mm
UP_{min}	Minimum precipitation uncertainty	mm
UT_{max}	Maximum temperature uncertainty	°C
UT_{min}	Minimum temperature uncertainty	°C
WHC	Water Holding Capacity	mm
Wt	Saturated water vapour density term	g·m^3
Year_prec	Total precipitation in a year	mm

rare or partial, particularly in the mountainous areas where a significant part of the aquifer recharge process occurs. Where lacking, these data are obtained through elevation-precipitation correlation methods, that, albeit extremely rigorous, may fail to estimate the actual precipitation values and their seasonal distributions.

The other methods proposed in the literature are based on the use of infiltration models at different spatial and temporal scales (e.g., balance models, hydrologic models, etc.). These methods are more demanding in terms of input data (e.g. Boni et al., 1982; Guowei and Yifeng, 1991; Kostka and Holko, 1994; Jain, 2012) that are rare, in particular when modelling infiltration over large areas.

The main scope of this work is to present a method for estimating EI and the other water balance components over large areas, based on a monthly water balance model following the Thornthwaite-Mather approach (Thornthwaite, 1948; Mather, 1978, 1979). The method is implemented as a model named HYDRO-BM, it is coded in R, an open source software environment for statistical computing and graphics (R Core Team, 2013), and it is applied over large areas in Europe using free/open data (http://opendefinition.org/). The model was first applied in the Central Apennine Range, where EI and EIC values were available from the literature (Boni et al., 1986), in order to calibrate/validate the model. Next, the proposed approach was applied to the Alpine region where EI and EIC data are rare and often incomplete. This work is focused on the use of free/open data and open source software, which is a fundamental step for the replication of any scientific result depending on computation, to allow reproducibility (Ince et al., 2012) of the proposed method but also to facilitate its application in different areas.

In the following, we describe the free/open data used as input to