H23A-1173 AUTOMATIC CALIBRATION OF A DISTRIBUTED RAINFALL-RUNOFF MODEL, USING THE DEGREE-DAY FORMULATION FOR SNOW MELTING, WITHIN DMIP2 PROJECT

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1. Abstract

This work presents the assessment of the TETIS distributed hydrological model in mountain basins of the American and Carson rivers in Sierra Nevada (USA) at hourly time discretization, as part of the DMIP2 Project. In TETIS each cell of the spatial grid conceptualizes the water cycle using six tanks connected among them. The relationship between tanks depends on the case, although at the end in most situations, simple linear reservoirs and flow thresholds schemes are used with exceptional results (Vélez et al., 1999; Francés et al., 2002). In particular, within the snow tank, snow melting is based in this work on the simple degree-day method with spatial constant parameters.

2. Introduction

Melt modelling is a crucial element in any attempt to predict runoff from snow-covered or glacierised areas, as well as to assess changes in the cryosphere associated with climate change. In mountainous regions, snow and ice significantly affect catchment hydrology by temporarily storing and releasing water on various time scales (Jansson et al., 2003). Hence, success of runoff modelling in such areas largely depends on accurate quantification of the melt process (Hock, 2003). Snowmelt modelling is complex and dependent on elevation, slope, vegetation type, surface roughness, radiation load, and energy exchange at the snow-air interface (Baron, 1992; Barros and Lettenmaier, 1993; Becker et al., 1994; Cline, 1995; Elder et al., 1991). This paper describes the application of the *degree-day* method for snowmelt modelling at hourly time discretization, which is implemented in the distributed and conceptually based hydrological model TETIS, as well as the evaluation of results.

3. Case of Study

The model has been applied to the Sierra Nevada basins, in *USA*: the *American River* (886 km^2) and the *Carson River* (922 km^2) [*Figure 1*], as a part of the *Distributed Model Intercomparison Project, second phase* (DMIP2), of the *National Oceanic and Atmospheric Administration's National Weather Service* (NOAA/NWS), in which we are participating. These basins are geographically close, but their hydrological regimes are quite different: the *Carson River* is a high altitude basin with a snow dominated regime; while the *American River* drains an area that is lower in elevation with precipitation falling as rain and mixed snow and rain (Jeton et al., 1996). Details on the basins' features are available in Smith et al. (2006).

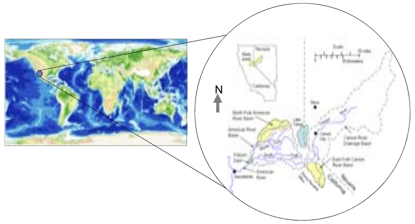


Figure 1. Location map of the *American* and *Carson River* Basins (after Jeton et al., 1996)

4. TETIS model conceptualization

The TETIS model is a distributed hydrological conceptual model, which is able to simulate continuously the main components of the hydrological cycle. This model has been developed by our Research Group during the last ten years, with good results in different climatic scenarios with a wide range of basin areas in Spain and France (Vélez, 2001; Francés et al., 2002; Vélez et al., 2002a, 2002b and 2002c, Vaskova et al., 2004). As shown in *Figure 2*, the proposed conceptualization in TETIS for runoff production at each cell consists of five vertical tanks, each one representing the different water storages in an ''extended soil column''. These tanks are called static, surface, gravitational, aquifer and in the case of snow, an additional tank is activated to represent the snow cover. This conceptualization prevents all parameters losing their physical meaning (Francés et al., 2007). At each cell the main soil properties need to be estimated previously using topographical, environmental, land use, geological and soil maps.

The TETIS model uses geographic information, inputs y parameters (*Figure 3* and *Figure 4*). The slope, flow direction and flow accumulation were estimated from a DEM. Concerning the parameters: the Static Storage (H_u), the saturated soil hydraulic conductivity (k_S), and saturated deep soil (or base rock) hydraulic conductivity (k_p) were estimated from a land use map, soil map, and soil texture information. This information was provided by NOAA/NWS.

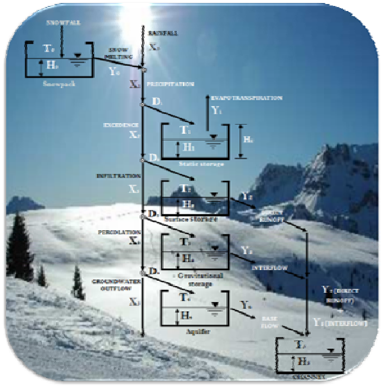


Figure 2. General description of hydrologic Behaviour of TETIS model at cell scale

4.1. Snowmelt submodel of TETIS

The *degree-day* method in the TETIS model, assuming an empirical relationship between air temperatures and melt rates, applied and refined (e.g. Clyde, 1931; Collins, 1934; Corps of Engineers, 1956; Hoinkes and Steinacker, 1975; Braithwaite, 1995). The snow (initial values) and temperature are interpolated at each cell with *inverse distance squared algorithm* with a *linear* correction with altitude. The degree-day method was implemented with a simple and parsimonious parameterization using one melting coefficient for rainy and another for not-rainy time.

$$Y_0 = \begin{cases} M_f \left(T - T_b\right), si T \ge T_b \\ 0, si T < T_b \end{cases}$$

Where Y_0 is daily melt, M_f is a melt factor, T is daily mean temperature and T_b is a threshold temperature beyond which melt is assumed to occur.

4.2. Inputs of model

The TETIS model uses the inverse distance method to interpolate spatially temporal the inputs of rainfall, evapotranspiration, temperature and the snow water equivalent initial value.

4.3. Raster information

The resolution of the used DEM was set to 400*m* resolution, with *Albers Equal-Area Conic* reference system. Maps obtained from the DEM and used by the model are shown in *Figures 3*.

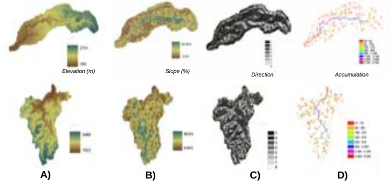


Figure 3. shown: **A)** Digital Elevation Model (DEM), **B)** Slope, **C)** Flow Direction and **D)** Flow Accumulation

4.4. Parameters of model

The TETIS model needs the parameters of static storage (H_u), saturated upper soil hydraulic conductivity (k_s) y saturated deep soil (or base rock) hydraulic conductivity (k_p) [*Figures 4*]. The rest of the cell parameters are based on the H_u, k_s and k_p maps, as indicated in *Table 1*.

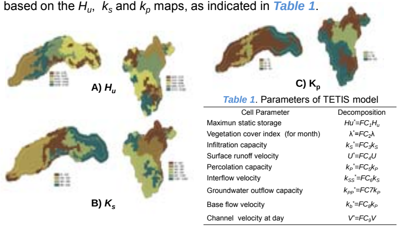


Table 1. Parameters of TETIS model

Cell Parameter	Decomposition
Maximun static storage	$Hu^*=FC_1H_u$
Vegetation cover index (for month)	$\lambda^*=FC_2\lambda$
Infiltration capacity	$k_S^*=FC_3k_S$
Surface runoff velocity	$U^*=FC_4U$
Percolation capacity	$k_P^*=FC_5k_P$
Interflow velocity	$k_{SS}^*=FC_6k_S$
Groundwater outflow capacity	$k_{PP}^*=FC7k_P$
Base flow velocity	$k_b^*=FC_8k_P$
Channel velocity at day	$V^*=FC_9V$

Figure 4. Show: **A)** Static Storage (*mm*), **B)** *Saturated soil hydraulic conductivity* (*cmh*$^{-1}$) and **C)** saturated deep soil (or base rock) hydraulic conductivity (*cmh*$^{-1}$)

5. Model Calibration

The TETIS model includes an automatic calibration module, based on the SCE-UA algorithm (Duan et al., 1992; Duan et al., 1994) and the model effective parameters are organized following a split structure, as presented by Francés and Benito (1995) and Francés et al. (2007). In this way, the calibration involves in TETIS up to 9 correction factors (CFs), which correct globally the different parameter maps instead of each parameter cell value, thus reducing drastically the number of variables to be calibrated. This strategy allows for a fast and agile modification in different hydrological processes preserving the spatial structure of each parameter map.

The process of automatic calibration was carried out three steps (*Figure 5*). In **calibration I and III** the automatic calibration methodology used was *Shuffled Complex Evolution – University of Arizona* (SCE-UA) proposed by Duan et al. (1992). The TETIS model allows one to choose the objective function during the calibration process, in the case study the Nash and Sutcliffe efficiency coefficient (NSE) has been selected. The **calibration II** snowmelt submodel was performed manually. Calibration is carried out by comparing observed and simulated streamflow only at the three designated basin outlets (*Clementine* and *Gardnerville*) and SNOTEL show in *Figure 6*.

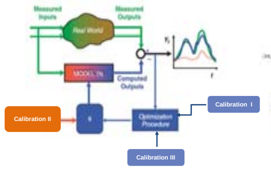


Figure 5. General description of the model calibration process

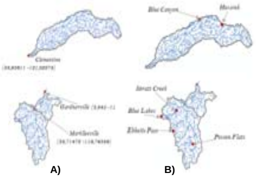


Figure 6. Location of USGS (**A**) and SNOTEL (**B**) gages

5.1. Automatic calibration I

With the snowmelt submodel, automatic model calibration was carried out in three steps, separating the calibration of rainfall-runoff and snowmelt parameters. In the first step, the automatic calibration of the CFs during the period 05/20/1990 to 07/31/1990 in the American River (without snow influence), gave a Nash-Sutcliffe Efficiency (NSE) index of 0.92. *Figure 7* shows the optimization of the episode selected (without snow). Initial extensive ranges of search were established for the CFs, with a total of 950 iterations of the SCE algorithm.

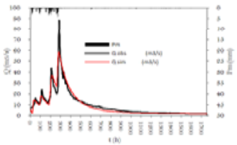
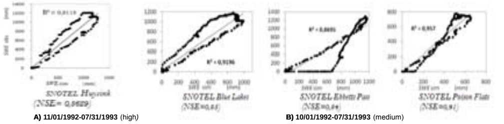


Figure 7. Calibration results for the American river basin

5.2. Calibration II (degree-day submodel)

The calibration of the three degree-day parameters was done using all the SNOTEL stations in the American and Carson rivers. In the calibration of the snowmelt submodel in both basins three episodes of low, medium and high snow cover were used the parameters for the America river basin: T_b=2.8, M_{f1}=2.7 y M_{f2}=5.0 and for the Carson river: T_b=2.5, M_{f1}=2.6 y M_{f2}=3.8. The results obtained are shown in *Figure 8* [0<NSE≤0.86 for American river and 0<NSE≤0.91 for Carson River basin].

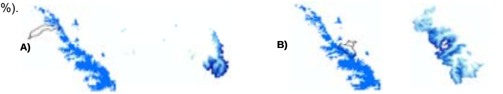


A) 11/01/1992-07/31/1993 (high) **B) 10/01/1992-07/31/1993** (medium)

Figure 8. Simulated and observed SWE of two episodes for the *American* (**A**) and *Carson* river (**B**) DMIP2 basins

5.2.1. Assessing spatial distribution of snow

The evaluation of the modeling results was performed using the observed snow water equivalent (SWE) at daily scale, hourly discharges at the basin outlet and some snow-covered images provided by NOAA/NWS (*Figure 9* and *Table 2*). The temporal and spatial validation using five periods must be considered in both rivers excellent for discharges (NSEs higher than 0.76) and good for snow distribution (daily spatial coverage errors ranging from -10 to 27%).



Snow-covered area mapped over the *American River* basin (7%) [01/05/1994]
Snow-covered mapped of TETIS (4%) [01/05/1994]
Snow-covered area mapped over the *Carson River* basin (40%) [01/05/1994]
Snow-covered mapped of TETIS (43%) [01/05/1994]

Figure 9. Show comparison of snow-covered NOAA/NWS and snow-covered TETIS (01/02/1994-05/29/1994)

Table 2. Comparison of snow-covered NOAA/NWS and snow-covered TETIS

American River

Date	Area (km^2)		Snow–covered over basin (%)		
	Image	TETIS	Image	TETIS	DIFF (%)
Jan-05-94	242.24	298.66	27.36	33.73	6.37
Jan-10-94	132.81	271.63	15.00	30.68	15.68
Jan-12-94	164.18	261.31	18.54	29.51	10.97
Jan-18-94	145.49	185.9	16.43	20.99	4.56
Jan-27-94	395.10	638.96	44.62	72.16	27.54
Feb-12-94	433.14	581.86	44.62	65.71	21.09
Feb-21-94	0.00	748.54	0.00	84.53	84.53
Feb-24-94	465.18	630.95	52.53	71.25	18.72
Mar-07-94	266.96	350.08	30.15	39.53	9.38
Mar-12-94	284.31	312.01	32.11	35.24	3.13
Mar-27-94	164.18	205.81	18.54	23.24	4.7
Apr-01-94	150.83	137.33	17.03	15.51	-1.52
Apr-12-94	130.81	85.03	14.77	9.60	-5.17
Apr-15-94	116.80	58.88	13.19	6.65	-6.54
May-01-94	63.40	30.95	7.16	3.80	-3.36
May-10-94	33.37	18.14	3.77	2.05	-1.72
May-22-94	8.01	12.27	0.90	1.39	0.49
May-29-94	3.34	3.91	0.38	0.44	0.06

Carson River

Date	Area (km^2)		Snow–covered over basin (%)		
	Image	TETIS	Image	TETIS	DIFF (%)
Jan-05-94	541.26	636.29	58.70	69.01	10.31
Jan-10-94	531.92	576.53	57.69	62.53	4.84
Jan-12-94	583.98	550.19	63.34	59.67	-3.67
Jan-18-94	512.56	433.51	55.59	47.02	-8.57
Jan-27-94	788.87	922	85.56	100.00	14.44
Feb-12-94	922	922	100.00	100.00	0
Feb-21-94	922	922	100.00	100.00	0
Feb-24-94	922	922	100.00	100.00	0
Mar-07-94	857.61	779.49	93.02	84.54	-8.48
Mar-12-94	791.54	725.06	85.85	78.64	-7.21
Mar-27-94	630.03	642.17	68.33	69.65	1.32
Apr-01-94	597.32	538.81	64.79	58.44	-6.35
Apr-12-94	527.91	485.98	57.26	52.71	-4.55
Apr-15-94	509.23	436.71	55.23	47.37	-7.86
May-01-94	372.41	396.15	40.39	43.00	2.61
May-10-94	341.71	244.59	37.06	26.53	-10.53
May-22-94	240.93	291.18	26.13	31.58	5.45
May-29-94	102.11	92.85	11.07	10.07	-1

5.3. Automatic calibration III

The model was calibrated against three hydrologic episodes (*Table 3*), of horary measured runoff at the basin outlet (*American* and *Carson*). The CFs set and NSE obtained by automatic calibration is shown in *Table 4*. In the *Figure 10* shows measured and simulated streamflow [A) Oct/01/1989-Sep/30/1994 and B) Oct/01/1990-Sep/30/1994].

Tabla 3. Episodes of model calibration

Basin	Episode	Warm Up	Calibration III
American River	1	Dec/01/1988-Feb/01/1989	Feb/01/1989-Jun/30/1989
	2	Nov/01/1990-Feb/01/1991	Feb/01/1991-Jul/31/1991
	3	Aug/01/1992-Nov/01/1992	Nov/01/1992-Jul/31/1993
Carson River	1	Aug/01/1990-Oct/01/1990	Oct/01/1990-Jul/31/1991
	2	Aug/01/1991-Oct/01/1991	Oct/01/1991-Jul/31/1992
	3	Aug/01/1992-Oct/01/1992	Oct/01/1992-Jul/31/1993

Tabla 4.The CFs calibrated using the SCE-UA and NSE objective function

American River basin

Episode	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	NSE
1	1.40	1.20	0.99	8.00	0.58	260.98	0.00	38.17	0.50	0.88
2	1.47	1.13	0.74	8.00	0.90	290.81	0.00	29.85	0.59	0.84
3	1.30	1.05	0.93	5.00	0.78	305.11	0.00	57.17	0.50	0.85
A)	1.48	1.16	0.73	8.00	0.99	259.31	0.00	22.48	0.59	0.79

Carson River basin

Episode	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	NSE
1	1.19	0.60	0.75	13.70	0.46	41.39	0.24	22.90	0.55	0.81
2	1.49	1.33	0.35	13.70	0.76	526.01	0.0001	19.04	0.53	0.73
3	1.46	0.53	0.57	8.00	0.40	75.89	0.22	45.18	1.16	0.84
B)	1.44	0.50	0.44	8.00	0.47	114.75	0.07	55.43	2.31	0.81

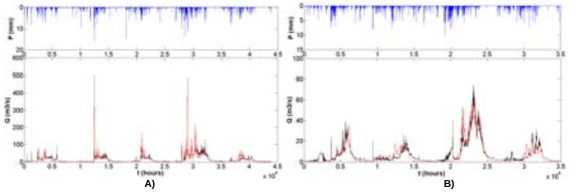


Figure 10. Measured and calculated horary streamflow after the automatic model calibration for the *American river* (**A**) [0.79] and *Carson* basin (**B**) [0.81].

6. Model Validation

Distributed models were validated temporally, spatially and spatiotemporally, according to the available data (*Table 5*). The first case is validation using the same gauge station used during the calibration but with a different period of time. Spatial validation is performed using the same period of time used during the calibration but in an other subbasin, usually located upstream. And the spatial-temporal validation is performed using a different period of time and a different gauge station. The *Figure 11* shows the results.

Tabla 5. Episodes of model validation

Basin	Station	Validation			NSE
		Temporally	Spatially	Spatiotemporally	
American	Clementine	Oct/01/1994-Sep/30/1997 (**A**)			0.76
Carson	Gardnerville	Oct/01/1994-Sep/30/1996 (**B**)			0.75
	Markleeville		Oct/01/1990-Sep/30/1994 (**C**)		0.87
				Oct/01/1994-Sep/30/1996 (**D**)	0.76

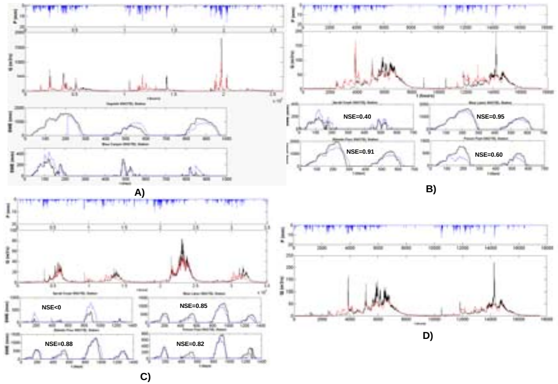


Figure 11. Measured and calculated horary streamflow after the model validation for the *American river* (**A**) and *Carson* basin (**B**, **C** and **D**) . SWE simulated (blue) and SWE observed (black)

7. Conclusions

As expected, the model does not reproduce the fluctuations observed in the outflow hydrograph, caused by diurnal melting. The results obtained are acceptable according to the Nash-Sutcliffe coefficient, but excellent at daily scale. Concerning the SWE, the results are very good, taking into account we are dealing with point observations in space. Also, it must be underline that such results are better at higher altitude stations than in lower altitude ones.

The results are acceptable, but indicate the need to add information of radiation to the snowmelt model in order to improve the *energy-balance* and the sensitivity of the model against spatial-temporal changes in the energy fluxes and assess what degree of complexity is recommended for snowmelt model, based on the results and the principle of parsimony. In conclusion, this work demonstrates:

- The viability of automatic calibration of distributed models, with the corresponding personal time saving and maximum exploitation of the available information.
- The good performance of the degree-day snowmelt formulation even at hourly time discretization, in spite of its simplicity.

Acknowledgements

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