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Parameter regionalization for a process-oriented distributed model dedicated to flash floods

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SUMMARY

This contribution is one of the first studies about the regionalization of parameter sets for a rainfall–runoff model process-oriented and dedicated to flash floods. MARINE model performances are tested on a large database of 117 flash floods occurred during the last two decades in the French Mediterranean region. Given the scarcity of flash flood data, the dataset used in this study represents a large sample of hydrology and landscapes from Pyrenean, Mediterranean, Cévennes–Vivarais and Provence regions. Spatial proximity and similarity approaches with several combinations of descriptors are tested. Encouraging results are obtained with two similarity approaches based on physiographic descriptors with two and three donor catchments. There is only a small decrease of performance of 10% from cal/val to regionalization for these two methods. For 13 catchments out of 16 there is at least one flood event simulated with rather good performance. This study highlights the importance of hydrological information that is available in calibration events for a gauged catchment and from donor catchment(s) for regionalization. Moreover it is found that regionalization is easier for catchments with an apparently more regular behaviour. The most sensitive parameter of MARINE model, C_Z, controlling soil volume and water balance, is rather well constrained by the two similarity approaches thanks to bedrock descriptors.

Keywords:
Mediterranean flash floods
Parameter sets regionalization
Process-oriented distributed model

1. Introduction

1.1. Context of the issue: flash floods predictions at ungauged locations

With the current and increasing water management requirements, prediction of hydrological variables for ungauged basins (PUB) has been singled out by the IAHS as one of the important challenges for the hydrological community (Sivapalan et al., 2003). Determining peak flow values of various return periods and the associated uncertainty is an indispensable prerequisite for planning mitigation measures which reduce or even prevent flood damages (see e.g. (Pilon, 2004)). This is particularly true in the case of flash floods, often constituting extreme catchment's response. They are one of the most destructive hazards in the world (Jonkman, 2005) and they caused casualties and billions euros of damages in France over the last two decades (Gaume et al., 2009). Regarding response time decreasing with catchment areas, small ungauged catchments ($\sim$10 km^2) are often the most destructive ones as for the extreme flash flood event of September 2002 in the Cévennes region (France) (Ruin et al., 2008).

In the literature, various approaches, in terms of perception and parameterization of the dominant hydrological processes, are proposed for flash flood events modelling and/or prediction (Braud et al., 2010; Moussa et al., 2007; Roux et al., 2011) among others for the North-Western Mediterranean region). Illustrating the current shift toward distributed modelling, these models often take advantage of available data in order to assign spatially distributed forcing as well as distributed catchment parameters.

The problem of rainfall measurement/prediction uncertainty is particularly crucial when attempting to develop flash-flood regionalization methodologies, especially on fast-responding catchments involving several difficult problems, such as structural, parametric or data uncertainties. For some catchments studied in this paper, rainfall spatial and temporal organization has been discussed in Garambois et al., 2014 and in Garambois et al., 2015 the latter also investigating the impacts of rainfall errors on the

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response surface and the performances of MARINE model. Systematic propagation of errors on forcing and initial conditions through a hydrological prediction system would be of prior interest. However, error structure itself appears to be complex and the development of error metrics, for example from geostatistical techniques, is still a research topic (e.g. (Delrieu et al., 2014a, 2014b)). In the present study most flash flood events are modelled with radar rainfalls recalibrated on raingauges with a spatial resolution of 1 km at 5 min time steps (hourly interpolated raingauges otherwise) (Garambois et al., 2014), rainfall moments integrated over storm duration (e.g. (Zoccatelli et al., 2011)) are reported in Appendix A, Table 1.

The process-oriented distributed model MARINE (Roux et al., 2011) has already been tested without parameter calibration on 2.5–99 km^2 ungauged catchments in the Cévennes region for the purpose of dominant processes analysis (Braud et al., 2010). Simulations were assessed using post field estimates of timing and maximum discharge of peak flow and the authors show the importance of soil characteristics and initial water content before a flash flood event. From those studies, it appears that a better knowledge about the dependency of hydrological processes on catchment properties can be useful for tailoring physics-based hydrological models for predicting floods in ungauged areas.

In the present study, the soil saturation is systematically initialized from a continuous water balance model for each catchment as performed by Roux et al. (2011), Tramblay et al. (2010), Vincendon et al. (2010). Using a process-oriented model such as MARINE model on a mesh at a few hundred meters resolution, i.e. on a finer grid than rainfall's one, allows coupled modelling of non-linear hydrological processes for flash flood generation at the scale of catchment areas of a few hundred square kilometres. Indeed the SIM model does not take into account the kind of flow processes giving rise to flash flood hydrograph.

As a matter of facts, it is not possible to calibrate data-driven models at ungauged locations. Hydrologists have therefore been attempting for 40 years to develop estimation methodologies describing rainfall to runoff process without calibration (see e.g. (James, 1972)). Originally dealing with hydrological regime classification and catchment grouping (e.g., (Gottschalck et al., 1979; Pardé, 1933)), the term regionalization was later extended to the transfer of rainfall–runoff model parameters from a gauged donor catchment to ungauged ones. Transferring parameters is often performed in the case of geographically close catchments. However, nearby catchments can present significant contrasts in terms of physiographic properties and hydrological behaviours, especially during floods or even flash floods involving rapid responses and highly nonlinear and coupled physical processes in time and space as their generating storm (Borga et al., 2008; Garambois et al., 2014).

1.2. Regionalization methods: a compromise between available physical descriptors, stream gage density and rainfall runoff model features

Among the numerous techniques proposed for the regionalization of catchment model parameters, generally for continuous (conceptual) rainfall runoff models, three kinds of approaches can be distinguished with their specific advantages and inherent drawbacks (Oudin et al., 2008): regression based methods, geographical proximity, and similarity methods. Several regionalization studies mostly for rather large datasets are briefly presented in (Table 2).

Regionalisation problem for catchment hydrology has been explored for several (instrumented) regions of the world with different catchments datasets without reaching a consensus on the method, the modelling options of the hydrological process or the physical descriptors to use. Even for large datasets, modellers' choices, rainfall to runoff model's structure and parameterization (Bárdossy, 2007; Kay et al., 2006), or physical descriptors availability (Merz et al., 2006) influence regionalization performances and the possible physical interpretations.

A comparison of the three methods mentioned above with two lumped conceptual models (GR4J and TOPMO) shows that in France, where the gauging network is relatively dense, spatial proximity provides the best regionalization results for a 913 catchments dataset (Oudin et al., 2008). It is argued that the failure of methods based on catchment descriptors might be attributable to the lack of key physical descriptors of soil hydrology, and that there is room for progress by learning how to merge the different methodologies. For example, for a regionalization study in Switzerland built on 140 catchments and tested on 49 catchments, the most favourable regionalization results are those obtained by combining nearest neighbour, spatial krigging of parameters and regression (Viviroli et al., 2009).

Those regionalization studies are generally performed with continuous models on mesoscale catchments. Tackling the problem of flash flood regionalization on a large data set with an event-based rainfall–runoff model, process-oriented and spatially distributed has not yet been documented in the literature to our knowledge. Following results of other regionalization studies on very large datasets (Table 2), the choice is made not to explore regression methods given the lower performances compared to other methods using donor catchments for entire parameter sets. As shown later, single correlation coefficients found between calibrated parameters and physiographic attributes are not high enough to ensure good predictions and build regional regressions to calculate model parameters at ungauged location. Moreover, calibrated parameter sets contain some compensation of measurements and model errors.

The present study uses the MARINE model which is spatially distributed and as exposed in Section 2.2, unique multiplicative constants are applied to parameter maps (Bandaragoda et al., 2004; Francés et al., 2007; Pokhrel et al., 2008; Roux et al., 2011; Vélez et al., 2009; Vieux et al., 2003). Calibrated parameter sets composed of calibrated multiplicative constants will be transferred from gauged catchments to ungauged ones.

1.3. Scope of the paper: regionalization with an event physically based distributed model

The present paper seeks to explore the potential of a process-oriented distributed model for regionalization in the case of a large and various flash floods dataset. It focuses on flash floods in the French Mediterranean region which is quite complex in terms of soils, geology and flood-triggering rainfall patterns. Storm variability along with catchment properties engenders nonlinear physical processes, which makes the understanding of flash floods not straightforward, especially when catchments are small with moderate dampening effect on rainfall signal. In that case, catchment behaviour can be very different from one flood event to another and compensations with hydrologic model parameters can be more difficult; particularly for longer time scales. The core idea of the research published here is to evaluate whether a physically based distributed hydrological model can be used for predicting flash floods at ungauged locations within the French Mediterranean region. In the context of Mediterranean flash floods two questions can be formulated: how is catchment's uniqueness reflected in a regionalization procedure (Wagener and Wheater, 2006) and how and which information is best transferred (Merz et al., 2006)? Regionalization methods are elaborated in view to predict flash floods for ungauged catchments. Its originality lies in:

Table 1

General characteristics of the 117 flash flood events dataset. No rainfall indices are calculated for 8 events on the Salz since only one raingauge is available. Initial soil moisture is 50 for the Réal Martin, Nartuby, Gapeau and Aille catchments since we do not dispose of SIM data for these 4 locations.

Catchment	Area (km^2)	Event	Initial soil moisture (%)	Cumulated rainfall (mm)	Delta1 (–)	Delta2 (–)	Specific peak flow discharge ($m^3\ s^{-1}\ km^2$)	Lag time (h)	Runoff coefficient (–)
Agly	216	04_12_2003	57	81	0.67	0.39	0.69	4	0.44
Agly	216	21_02_2004	56	50	0.94	0.85	0.25	5	0.30
Agly	216	15_11_2005	70	97	0.98	0.80	0.70	3	0.56
Agly	216	11_10_2010	43	176	1.03	0.84	0.91	5	0.47
Agly	216	15_03_2011	60	172	0.99	0.77	1.08	5	0.71
Cesse	231	27_02_1981	58	91	0.91	0.75	0.62	7	0.90
Cesse	231	02_12_1987	60	317	1.03	0.70	1.99	10	0.67
Cesse	231	18_10_1994	60	139	1.00	0.92	1.58	6	0.30
Cesse	231	13_10_1996	60	117	1.00	0.93	0.56	10	0.35
Cesse	231	04_12_1996	48	249	1.02	0.77	1.13	9	0.47
Cesse	231	03_11_1997	50	50	0.95	0.66	0.30	4	0.20
Cesse	231	11_11_1999	55	254	1.05	0.92	1.30	8	0.35
Cesse	231	04_12_2003	62	73	0.95	0.94	0.64	7	0.90
Cesse	231	15_11_2005	61	131	0.95	0.88	1.13	9	0.78
Cesse	231	28_01_2006	58	133	1.00	0.95	1.13	6	0.74
Cesse	231	16_03_2011	51	299	1.06	0.86	2.27	4	0.70
Gardons	545	13_10_1995	62	177	0.85	0.57	2.60	4	0.51
Gardons	545	10_11_1996	56	220	1.03	0.69	1.28	6	0.39
Gardons	545	17_05_1999	56	133	1.08	0.67	1.30	5	0.48
Gardons	545	28_09_2000	51	203	1.02	0.78	1.45	6	0.23
Gardons	545	14_03_2002	57	66	0.58	0.47	1.23	5	0.37
Gardons	545	08_09_2002	48	284	0.79	0.86	6.69	4	0.39
Gardons	545	18_10_2006	56	237	1.07	0.66	2.65	10	0.36
Gardons	545	22_10_2008	47	139	0.62	0.47	1.98	5	0.24
Gardons	545	31_10_2008	56	75	1.04	0.66	1.93	10	0.90
Gardons	545	10_11_2011	57	258	1.01	0.72	1.91	7	0.90
Herault	786	18_10_2006	65	154	0.90	0.88	0.98	12	0.61
Herault	786	02_11_2008	64	157	0.87	0.76	0.59	8	0.55
Herault	786	15_03_2011	57	263	1.01	0.89	0.50	17	0.51
Herault	786	03_11_2011	58	312	0.93	0.88	1.34	8	0.59
Orbieu	263	12_02_1990	57	157	1.06	0.85	0.87	7	0.23
Orbieu	263	05_05_1991	57	122	1.07	0.80	0.57	8	0.38
Orbieu	263	26_04_1993	56	92	1.00	0.94	0.49	10	0.37
Orbieu	263	23_12_1993	57	69	1.10	0.68	0.30	7	0.30
Orbieu	263	09_01_1996	55	45	1.17	0.65	0.53	7	0.48
Orbieu	263	09_01_2004	57	33	1.08	0.87	0.28	6	0.74
Orbieu	263	13_10_2005	46	113	0.94	0.73	0.88	10	0.47
Orbieu	263	15_11_2005	55	149	0.97	0.85	2.65	5	0.71
Orbieu	263	28_01_2006	55	229	1.11	0.93	1.27	4	0.46
Orbieu	263	10_10_2010	42	211	1.06	0.88	0.97	8	0.37
Orbieu	263	16_03_2011	51	172	1.05	0.84	0.68	6	0.72
Reart	145	16_11_2003	62	128	0.89	0.51	0.44	3	0.31
Reart	145	04_12_2003	66	100	0.91	0.87	0.25	8	0.24
Reart	145	16_04_2004	61	60	1.01	0.94	0.90	8	0.21
Reart	145	03_05_2004	66	54	1.06	0.85	0.23	3	0.22
Reart	145	15_11_2005	61	111	0.90	0.77	0.71	5	0.18
Reart	145	03_11_2011	57	62	0.93	0.83	0.08	3	0.17
Rosieres	212	18_10_2006	55	202	1.14	0.53	1.07	6	0.43
Rosieres	212	16_11_2006	58	146	1.03	0.71	1.12	4	0.51
Rosieres	212	18_04_2008	52	142	1.04	0.78	0.75	4	0.74
Rosieres	212	20_10_2008	57	206	0.87	0.79	1.34	4	0.37
Rosieres	212	31_10_2008	65	283	1.10	0.62	1.44	6	0.66
Rosieres	212	05_05_2010	53	102	1.02	0.74	0.72	5	0.57
Salz	144	20_04_1981	50	71	–	–	0.56	7	0.55
Salz	144	14_01_1982	50	98	–	–	1.63	5	0.89
Salz	144	03_04_1988	50	55	–	–	1.03	4	0.87
Salz	144	23_04_1988	50	66	–	–	0.49	4	0.60
Salz	144	23_03_1991	50	124	–	–	1.10	7	0.58
Salz	144	09_01_1996	50	44	–	–	0.74	4	0.72
Salz	144	30_11_1996	50	64	–	–	0.69	6	0.47
Salz	144	10_06_2000	57	113	1.04	0.99	1.40	5	0.73
Salz	144	20_12_2000	50	141	–	–	1.42	8	0.45
Salz	144	10_01_2004	64	49	0.97	0.96	0.46	5	0.29
Salz	144	11_10_2010	47	136	1.05	0.91	2.19	7	0.59
Tech	250	02_12_1991	50	396	1.02	0.89	1.56	6	0.68
Tech	250	25_09_1992	50	213	1.13	0.97	2.51	3	0.20
Tech	250	13_11_1999	50	294	0.95	0.87	1.15	7	0.18
Tech	250	23_12_2000	50	226	1.04	0.98	0.79	8	0.25
Tech	250	24_02_2003	54	70	1.07	0.99	0.57	8	0.30

(*continued on next page*)

Table 1 (*continued*)

Catchment	Area (km^2)	Event	Initial soil moisture (%)	Cumulated rainfall (mm)	Delta1 (−)	Delta2 (−)	Specific peak flow discharge (m^3 s^{-1} km^2)	Lag time (h)	Runoff coefficient (−)
Tech	250	04_12_2003	55	30	0.96	0.96	0.62	8	0.30
Tech	250	15_11_2005	60	99	0.85	0.80	0.63	7	0.24
Tech	250	28_01_2006	49	128	1.08	0.71	1.08	6	0.79
Tech	250	15_03_2011	47	281	1.04	0.83	2.24	8	0.64
Tet	776	15_04_2004	55	125	0.86	0.64	0.58	5	0.35
Tet	776	02_05_2004	60	113	1.02	0.86	0.51	7	0.38
Tet	776	15_03_2011	53	87	0.82	0.98	1.13	10	0.22
Verdouble	299	08_05_1991	50	56	1.11	0.95	0.41	8	0.39
Verdouble	299	05_12_1996	71	65	0.94	0.85	2.04	9	0.86
Verdouble	299	09_11_1999	55	179	0.95	0.73	3.00	10	0.80
Verdouble	299	11_04_2002	69	169	1.02	0.76	0.95	4	0.76
Verdouble	299	04_12_2003	66	133	1.09	0.89	0.70	9	0.89
Verdouble	299	21_02_2004	63	50	0.98	1.00	0.43	10	0.52
Verdouble	299	15_11_2005	70	215	0.90	0.82	3.30	6	0.82
Verdouble	299	28_01_2006	64	249	1.01	0.99	1.96	5	0.99
Verdouble	299	10_10_2010	52	262	1.01	0.88	1.47	12	0.88
Verdouble	299	12_03_2011	59	217	1.01	0.82	1.23	7	0.82
Vogue	619	18_10_2006	56	140	1.16	0.51	0.89	10	0.57
Vogue	619	16_11_2006	61	186	1.01	0.73	1.13	7	0.54
Vogue	619	18_04_2008	55	120	1.02	0.76	0.48	6	0.59
Vogue	619	20_10_2008	62	195	0.93	0.72	1.45	9	0.46
Vogue	619	31_10_2008	70	211	1.16	0.52	1.62	11	0.94
Vogue	619	05_05_2010	55	98	1.01	0.70	0.76	11	0.45
Vogue	619	03_11_2011	54	369	1.12	0.67	1.34	8	0.77
Réal Martin	283	09_12_2008	50	197	1.04	0.88	0.60	9	0.41
Réal Martin	283	25_01_2009	50	42	1.03	0.95	0.29	7	0.66
Réal Martin	283	14_06_2010	50	140	1.04	0.92	0.48	6	0.40
Réal Martin	283	21_12_2010	50	113	1.06	0.84	0.31	6	0.31
Réal Martin	283	14_03_2011	50	131	1.07	0.95	0.26	8	0.43
Nartuby	196	02_12_2006	50	93	1.00	0.85	0.20	7	0.11
Nartuby	196	21_12_2009	50	37	1.05	0.84	0.09	5	0.23
Nartuby	196	21_12_2010	50	96	0.98	0.88	0.20	6	0.29
Nartuby	196	14_03_2011	50	45	1.05	0.82	0.13	6	0.49
Nartuby	196	03_11_2011	50	240	1.02	0.86	0.54	6	0.27
Gapeau	535	09_12_2008	50	164	0.99	0.83	0.40	8	0.44
Gapeau	535	25_01_2009	50	35	0.98	0.89	0.21	10	0.66
Gapeau	535	21_12_2009	50	111	0.99	0.92	0.33	5	0.45
Gapeau	535	14_06_2010	50	116	1.00	0.81	0.30	9	0.34
Gapeau	535	21_12_2010	50	108	1.01	0.83	0.38	7	0.39
Gapeau	535	03_11_2011	50	291	1.07	0.77	0.60	7	0.43
Aille	227	02_12_2006	50	115	1.00	0.83	0.20	7	0.24
Aille	227	03_11_2008	50	102	0.93	0.75	1.04	4	0.53
Aille	227	09_12_2008	50	234	0.99	0.84	0.91	5	0.66
Aille	227	21_12_2009	50	104	1.01	0.88	0.72	3	0.65
Aille	227	14_06_2010	50	196	0.94	0.84	2.30	6	0.65
Aille	227	21_12_2010	50	134	1.01	0.78	0.70	4	0.70
Aille	227	04_06_2011	50	32	0.81	0.64	0.20	3	0.12
Aille	227	03_11_2011	50	333	1.00	0.79	1.30	6	0.82

- The attempt of regionalizing the parameters of a flash-flood dedicated model: to our knowledge, this is the first study of regionalization for flash flood events.
- MARINE parsimonious formulation and parameters physical meaning (cf. Section 2).
- The large dataset of catchments and flash floods gathered, including radar rainfalls at 5 min time step, despite the difficulties involved in monitoring flash floods (cf. Section 2).
- The possibility of investigating the link between catchment's flood behaviours with soil and bedrock structure, thanks to the availability of spatially distributed pedological and geological data for the French catchments of interest.

This study is organized as follows. Section 2 presents the modelling framework, the study zone and the flash flood events. Physiographic descriptors of catchment are presented along with MARINE model and the calibrated parameter sets, the cost functions used to assess model performance and the regionalization methodologies. Section 3 discusses the results from calibration/validation to regionalization. Documentation about calibration/validation efficiencies is provided for the whole flash flood events dataset. In the light of those performances, regionalization results are analysed with global statistics on model efficiency for the whole dataset, for each catchment and for each event.

2. Modelling framework

2.1. Study zone and selected catchment descriptors

This study is based on data from 16 small to medium-sized catchments with areas ranging from 144 to 786 km^2 (Fig. 1) and contrasting physiographic properties (Table 3). These 16 gauged catchments are located in the French Mediterranean region (Table 3), represent a large sample of landscapes from Pyrenean, Mediterranean, Cévennes–Vivarais and Provence regions. The

Table 2
Some regionalization studies and three broad categories of regionalization methods.

Method	Main idea	References	Description and main results
Regression based	Interpolation of model parameters. Model parameters related to catchment characteristics in a statistical manner	Abdulla and Lettenmaier (1997)	34 catchments of the Arkansas-Red River basin (USA), 3 parameters of VIC-2L
		Kokkonen et al. (2003)	13 catchments of the North Carolina–Coweeta River basin (USA), 6 parameters of the IHACRES model. "If a gauged catchment resembles the ungauged one in terms of hydrological behaviour, (...) worthwhile to adopt entire calibrated parameter sets"
		Hundecha and Bárdossy (2004)	95 catchments in the Rhine basin (Germany), 12 parameters of the HBV-IWS model
		Merz and Blöschl (2004)	300 Austrian catchments, 11 parameters of the HBV model
		Oudin et al. (2008)	913 French catchments, 4 parameters of GR4J model or 6 parameters of TOPMODEL
		Viviroli et al. (2009)	Built on 140 catchments in Switzerland and tested on 49, 12 parameters of PREVAH model
Geographical proximity	Geographically close catchments behave similarly; homogeneity of climate and physiographic properties	Vandewiele and Elias (1995)	75 Belgian catchments, 5 parameters conceptual model, **Krigging performs better than proximity**
		Merz and Blöschl (2004)	300 Austrian catchments, 11 parameters of the HBV model. Best regionalization method: average of upstream and downstream neighbours or krigging
		Parajka et al. (2005)	320 Austrian catchments, 11 parameters of the HBV model
		Oudin et al. (2008)	913 French catchments, 4 parameters of GR4J model or 6 parameters of TOPMODEL. **Proximity provides best results** with a rather dense gaging network
		Viviroli et al. (2009)	Built on 140 catchments in Switzerland and tested on 49, 12 parameters of PREVAH model
		Patil and Stieglitz (2012)	756 US catchments, regionalization of a multiple drainage-area ration method based on donor-receptor proximity. Detection of hydrologic regions, **low predictability for drier regions**
Catchment similarity	Hydrological behaviour can be explained by catchment descriptors, and transferred to ungauged catchments similar in terms of those descriptors	McIntyre et al. (2005)	127 UK catchments and the 5 parameters PDM model. Physical similarity outperforms regression methods
		Parajka et al. (2005)	320 Austrian catchments, 11 parameters of the HBV model. Slightly better efficiency for similarity approach compared to krigging
		Oudin et al. (2008)	913 French catchments, 4 parameters of GR4J model or 6 parameters of TOPMODEL. "Lack of a key physical descriptor..."; they suggest to combine the three kind of approaches
		Viviroli et al. (2009)	Built on 140 catchments in Switzerland and tested on 49, 12 parameters of PREVAH model. **Best results when combining the three kinds of approaches**
		Wallner et al. (2013)	41 German catchments, regionalization of the HBV model based on similarity measured with self-organizing maps (neural networks). **Mean Nash on the order of 0.55 comparable to lots of other regionalization studies**

proximity with the sea and the steep surrounding topography can foster heavy precipitation events. The highest flooding risk is in autumn with wet soils and maximum rainfall rates. Summers are hot and dry; however summer storms also represent a non-negligible flooding risk. For this study, radar rainfall records (Fig. 1, orange[1] dots) readjusted on the raingauge network are available. Three types of data are used to derive input maps for MARINE model (Fig. 2):

- A DEM data file of the study site with a grid scale of 25 m was available from the National Geographic Institute (BD TOPO® © Institut Géographique National – Paris – 2008. © (*SCHAPI*, Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations)). For these catchments with a highly marked topography, the mean elevation ratio is 0.035 mm^{-1} (Height difference/Longest flow path).
- Soil thicknesses and textures were available from soil surveys BDSol-LR (Robbez-Masson et al., 2002) (IGCS – BDSol-LR – version n° 2006, INRA – Montpellier SupAgro) and BDSol-Ardèche. For catchments 13–16 in Provence, no detailed soil survey was available and the same soil thickness and textures as SIM model (Habets et al., 2008) have been used.
- Soil saturated hydraulic conductivities, saturated water contents and soil suctions are determined with Rawls and Brakensiek (1985) pedotransfer functions as proposed by Manus et al. (2009).

A vegetation and land-use map (Corine Land Cover provided by the Service de l'Observation et des Statistiques (SOeS) of the French Ministry of Environment, www.ifen.fr) is used to derive distributed surface roughness. Most catchments' surfaces are forested with Mediterranean or Alpine vegetation, or occupied by vineyard.

Gathering appropriate attributes to characterize catchments properties and unicity is an important step for regionalization purpose. For example the UK Flood Estimation Handbook (IH, 1999)

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[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

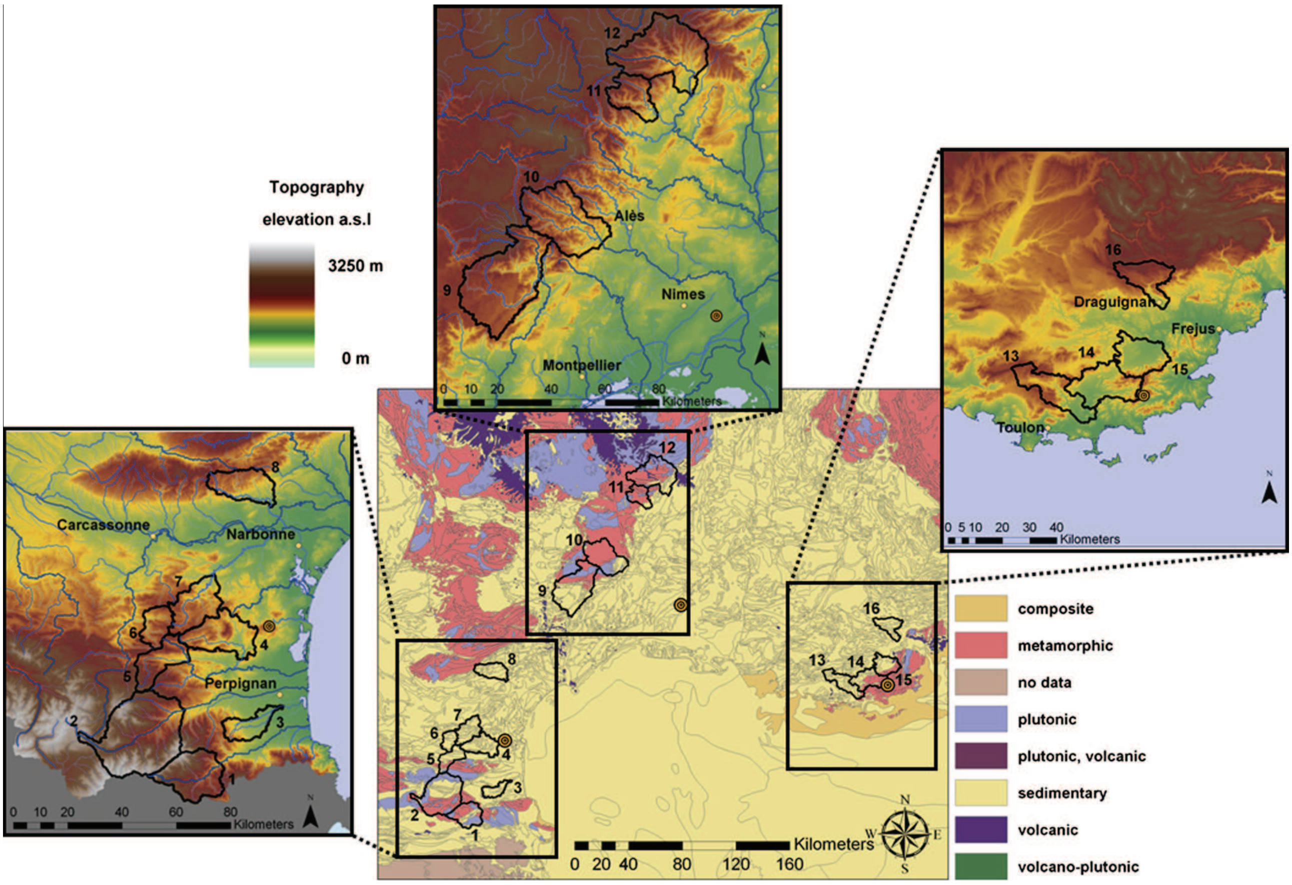

Fig. 1. (Center) Simplified bedrock composition of the French Mediterranean region (*source*: (Bd Million-Géol, BRGM)) and (periphery) topography. (Black contours) 16 unregulated catchments of interest. (West to the east) Opoul, Nîmes and Collobrières meteorological radars from Météo France network (orange dots with black concentric circles).

recommends the use of 3 catchment descriptors for model parameter transfer, Samaniego and Bardossy (2005) used 7 attributes for their study.

Simplified bedrock composition (Fig. 1) is derived from lithological data (source: (Bd Million-Géol, BRGM)). Among the variety of pedologic data that can be found in soil surveys, maps are derived for some hydrodynamic parameters of the soil represented in MARINE model (cf. § 2.2) and several catchment averaged descriptors can therefore be calculated. Simple descriptors of soil and bedrock are presented in Table 3.

To sum up, a total of 13 physiographic attributes are considered for this regionalization study. It constitutes an important number of attributes regarding other regionalization studies (IH, 1999; Samaniego and Bardossy, 2005).

2.2. MARINE flash flood physics-based model and calibrated parameter sets

2.2.1. Model basics

For flood event modelling, and especially flash floods, the modeller is facing the challenge of choosing a rainfall runoff model, then calibrating a parameter set able to simulate flood events and related hydrograph shape accurately, and last but not least evaluating performance on each event with a cost function.

In this study the distributed model MARINE for flash flood forecasting (Roux et al., 2011) with subsurface transfer module is used. The predominant factor determining the formation of runoff is represented by the topography: slope and downhill directions. Both infiltration excess and saturation excess are represented within MARINE which is structured into three main modules (Fig. 2). The first module allows separating the precipitation into surface runoff and infiltration using the Green and Ampt model; the second module represents subsurface downhill flow with an approximation of the Darcy's law and the third one the overland flow (over hillslopes and in the drainage network): the transfer function component allows routing the rainfall excess to the catchment outlet using the kinematic wave approximation. The spatial discretization of the catchment is performed using the Digital Elevation Model grid resolution, a regular grid of 200 m squared cells. Evapotranspiration is not represented since the model purpose was to simulate individual flood events during which such process is negligible. For a complete description of the MARINE model the reader can refer to Roux et al. (2011).

In order to avoid a model over-parameterization, spatial patterns of several parameters are derived from soil surveys and a unique correction coefficient is then applied to each parameter map. This approach has been chosen for three parameters, namely the distributed saturated hydraulic conductivity K, the lateral transmissivity T_0 and soil thickness Z. The calibration procedure consists in estimating: three coefficients of correction for spatialized data; one for the saturated hydraulic conductivities, named C_K, another one C_{KSS} for the lateral subsurface flow transmissivities (T_0), and the last one for the soil thicknesses, named C_Z, the Strickler roughness coefficient of the main channel K_{D1} and the Strickler roughness coefficient of the overbanks of the drainage network K_{D2} (Garambois et al., 2013; Roux et al., 2011). Concerning the transmissivity K_{ss}, the spatial variability is taken from the hydraulic conductivity map.

Table 3

Catchments' shape, soil and bedrock descriptors. In the following PrimG = Plut + Volc. H_{soil} is the soil depth, _std means standard deviation.

Catchment	N°	Area (km^2)	Height difference (m) (Deniv)	Median altitude (m) (Alt_{Q50})	Sedimentary (% area) (Sedi)	Plutonic (% area) (Plut)	Metamorphic (% area) (Meta)	Primary Geology (% area), (PrimG)	H_{soil}_min (m)	H_{soil}_max (m)	H_{soil}_mean (m)	H_{soil}_std (m)	Soil volume (m^3) (v_{soil})	Saturated hydraulic conductivity ($mm\,h^{-1}$) (K_{sat})
Tech (Pas du Loup)	1	250	2730	1464	27	32	41	73	0	0.69	0.16	0.13	5.33E+07	2.5
Têt (Marquixane)	2	776	2540	1573	38	27	36	63	0	0.64	0.19	0.15	1.50E+08	2.8
Réart (Saleilles)	3	145	780	398	98	0	0	0	0.06	0.74	0.41	0.25	5.76E+07	1.4
Verdouble (Tautavel)	4	299	915	526	100	0	0	0	0.08	0.63	0.33	0.16	1.03E+08	2.4
Agly (St Paul de F.)	5	216	1640	1031	81	4	15	19	0	0.5	0.25	0.11	5.31E+07	1.6
Salz (Cassaignes)	6	144	995	994	100	0	0	0	0	0.74	0.31	0.19	4.19E+07	3.9
Orbieu (Lagrasse)	7	263	840	521	100	0	0	0	0	0.74	0.38	0.16	9.93E+07	3.8
Cesse (Bize Minervois)	8	231	970	533	99	0	1	1	0.05	0.69	0.28	0.15	6.62E+07	2
Hérault (Ganges)	9	786	1495	850	61	12	26	38	0	0.79	0.23	0.12	1.55E+08	4.7
Gardon (Anduze)	10	543	1065	665	21	16	63	79	0.08	0.64	0.28	0.12	1.54E+08	5
Beaume (Rosières)	11	212	1360	817	14	13	73	86	0.05	0.49	0.25	0.07	5.15E+07	8.7
Ardèche (Vogüé)	12	619	1380	837	22	23	47	70	0.05	0.5	0.28	0.08	1.72E+08	8.7
Gapeau (Hyères)	13	535	980	495	73	0	27	27	0	10.8	0	90.4	1.76E+09	1.5
Réal Martin (La Crau)	14	283	740	398	52	0	48	48	0	19.2	0	137.2	8.42E+08	5.3
Aille (Vidauban)	15	227	728	394	68	0	29	29	0	11.6	1.2	134	6.80E+08	10.1
Nartuby (Trans en Pce)	16	196	1060	638	100	0	0	0	0	0	0	71.6	4.88E+08	1.4

A continuous soil moisture model (SIM) (Habets et al., 2008) is used for the initialization of the soil moisture at the beginning of an event within MARINE model. The root zone soil moisture from SIM is used (Hu_2 index cf. (Marchandise and Viel, 2009)). Hu_2 index is calculated as follows: $Hu_2 = wg_2/wg_{sat2}$ where wg_2 is the volumetric water content of the root zone and wg_{sat2} is the saturated volumetric water content of the root zone. Hu_2 index (%) at the beginning of each event is applied to each cell within catchment discretization. It has been shown that initial soil moisture condition has to be set for each event for a robust calibration (Roux et al., 2011). Indeed, results show that there is a non-negligible sensitivity of the model response to the initial soil moisture. Following this study, it has been chosen to use Hu_2 index, when available, as soil moisture initialization for the MARINE.

MARINE model is the result of a mechanistic approach representing flow components that are considered predominant in Mediterranean flash flood genesis. Several sensitivity analysis and calibration/validation (cal/val) of the model have been performed for catchments of the French Mediterranean region with areas ranging from about 100 km^2 to 700 km^2 (Garambois et al., 2013, 2015; Roux et al., 2011). The results of these studies show that soil depth and lateral water transfer through the subsurface zone have a significant impact on soil saturation dynamics and flood hydrograph. Drainage network reveals to be important also.

2.2.2. Calibrated parameter sets

The choice of a cost function is of prior importance to assess rainfall runoff modelling performances. Timing and maximum discharge of peak flow are important features to compare the shape of flash floods hydrographs'. They will be taken into account thanks to the L_{NP} cost function (Eq. (1)) (Roux et al., 2011):

$$L_{NP} = \frac{1}{3}\text{Nash} + \frac{1}{3}\cdot(1 - dQ_p) + \frac{1}{3}\cdot(1 - dT_p) \tag{1}$$

with

$$\text{Nash} = \cdot 1 - \frac{\sum_{i=1}^{N_{obs}}(Q_s^t - Q_o^t)^2}{\sum_{i=1}^{N_{obs}}(Q_o^t - \overline{Q_o})^2}; \quad dQ_p = \frac{|Q_s^p - Q_o^p|}{Q_o^p};$$

$$dT_p = \frac{|T_s^p - T_o^p|}{T_o^c} \tag{2}$$

where N_{obs} is the number of observation data, Q_s and Q_o are respectively the simulated and the observed runoff, Q_s^p and Q_o^p are respectively the simulated and observed peak runoff, T_P^s and T_P^o are respectively the simulated and observed time to peak, T_o^C is the time of concentration of the catchment determined by averaging Bransby formula ($T_o^c = \frac{21.3L}{A^{0.1}S^{0.2}}$, L is the channel length (m), A is the catchment area (m^2) and S the linear profile slope (m/m)). Compared to the Nash cost function (Eq. (2)), the L_{NP} cost function grants more importance to peak flow value and timing, which is particularly appropriate for the MARINE model, which focuses more on flash flood peak flow modelling than on baseflow or recession. This multi criteria cost function is used to assess model performances for each flood event in order to avoid classical significance problems of Nash criterion used alone for flood events (Moussa, 2010).

Our approach to test MARINE model potential for flash flood regionalization is to calibrate MARINE model parameters for each gauged catchment (Table 4). For 16 catchments with sufficient flash flood records for calibration and validation, parameters sets were calibrated on several events per catchment ((Nash, L_{NP}) ~ (0.8; 0.8), cf. Table 6). Extreme events, such as September 2002 in the Cévennes, are not used for calibration. The full procedure of event selection for calibration can be found in Garambois et al. (2015).

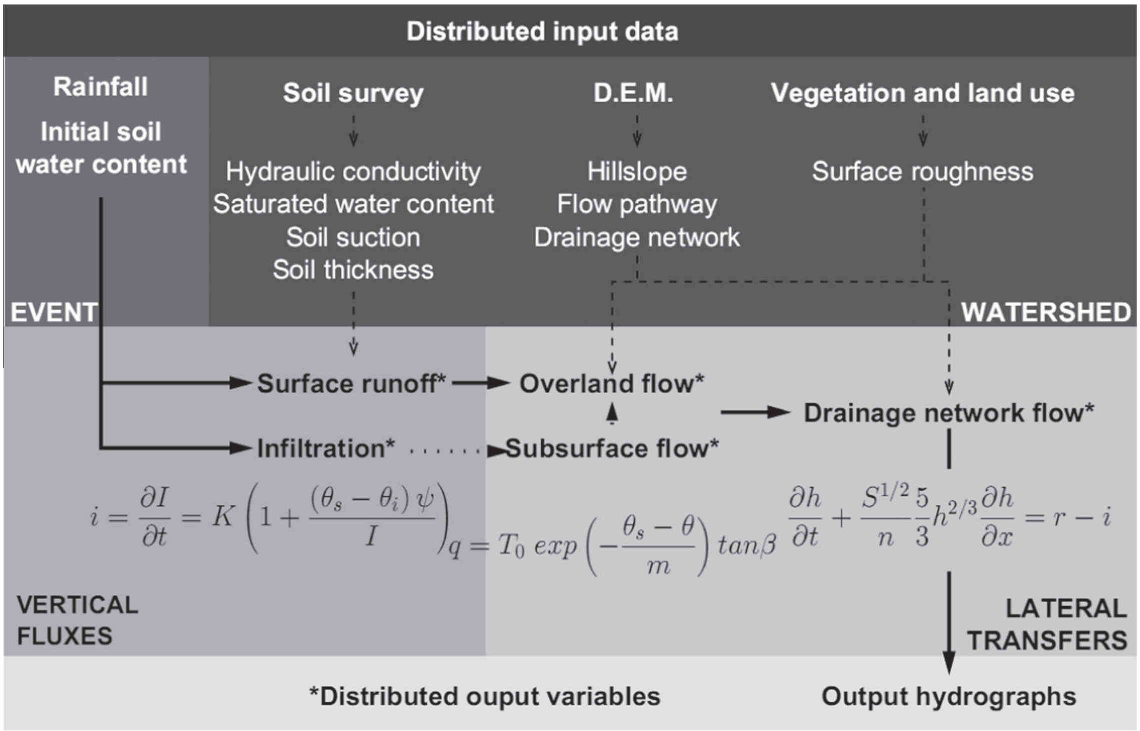

Fig. 2. MARINE model structure, parameters and variables. Infiltration rate i (m s^{-1}), cumulative infiltration I (mm), saturated hydraulic conductivity K (m s^{-1}), soil suction at wetting front ψ (m), saturated and initial water contents are respectively θ_s and θ_i (m^3 m^{-3}). Local transmissivity of fully saturated soil T_0 (m^2 s^{-1}), saturated and local water contents are θ_s and θ (m^3 m^{-3}), transmissivity decay parameter is m (–), local slope angle β (rad). Water depth h (m), time t (s), overland flow velocity u (m s^{-1}), space variable x (m), rainfall rate r (m s^{-1}), infiltration rate i (m s^{-1}), bed slope S (m m^{-1}), Manning roughness coefficient n (m$^{-1/3}$ s).

Table 4
Calibrated parameter sets for gauged catchments.

Catch.	C_Z (–)	C_K (–)	C_{KSS} (–)	K_{D1} (m$^{1/3}$/s)	K_{D2} (m$^{1/3}$/s)
Tech	4.3	11	1515	5	3.2
Têt	6.1	19.8	10,000	11.8	3.4
Réart	4.29	15	1242	5.7	30
Verdouble	1.3	15	4486	5	4
Agly	1.6	20	4304	7.5	2.2
Salz	1	20	5595	5	5
Orbieu	1.3	15	10,000	9.1	2
Cesse	1.26	7.7	10,000	5	6.3
Hérault	3.6	17.8	4764	8.2	5
Gardon	4.6	10.3	4540	11.7	9.7
Beaume	5.3	7.4	3712	21.4	14.7
Ardèche	3.4	2.1	4891	10	19.1
Gapeau	1.2	4.76	1200	14	20.8
Réal Martin	1.28	3	415	19.7	5
Aille	0.4	4	715	31.2	7
Nartuby	1.12	10.5	4525	22	5

Parameter sets are then tested on several recent strong events ((Nash, L_{NP}) ~ (0.7, 0.7), (Fig. 3)) since one of the objectives is flash flood forecasting. The comparison between observed and simulated maximum specific discharges (Fig. 3) highlights good performances of MARINE model even for specific discharges up to 6.3 m^3 s^{-1} km^{-2}; keeping in mind that gauging uncertainty can be close to ±20% or even 30% for such high flows (see e.g. (Delrieu et al., 2005)).

MARINE model parameters present few interactions during peak flow simulations as shown with temporal variance analysis on 6 Mediterranean catchments (Garambois et al., 2013). This probably stems from model parsimony and physical formulation. Reducing parameter interactions and equifinality problems is important especially for flood forecasting at gauged and ungauged locations.

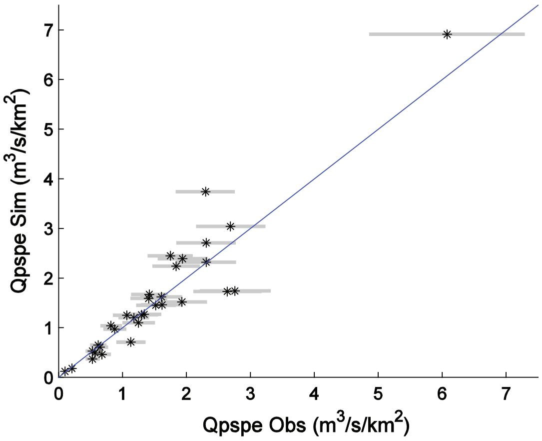

Fig. 3. (Black stars) Maximum simulated specific discharges versus observed for validation events which are recent strong events. (Grey bars) Representation of an indicative ±20% gauging error for peak discharge observation (see e.g. (Delrieu et al., 2005)).

2.3. Regionalization methodology

As stated before, 5 tuneable parameters of MARINE model are calibrated for catchments with sufficient flood records (Section 2.2), but the application of MARINE model in the case of ungauged catchments requires a regionalization method. MARINE model parameters are estimated using two approaches namely the nearest neighbours and a similarity approach. The issue of selecting information that is best transferred from donor catchment(s) to the ungauged one is addressed. Proximity measure and/or catchment physiographic descriptors are used to derive a similarity measure between gauged and ungauged catchments.

2.3.1. Single correlations

As a first step, correlations between calibrated model parameters and catchment descriptors have been tested. The single regressions are established for all the 16 gauged catchments. The correlation coefficients of the regressions equations between the model parameter values and 13 descriptors are usually lower than 0.5 (Table 5). Other regionalization studies find also correlation coefficients usually lower than 0.5 for continuous rainfall runoff models (Merz et al., 2006; Oudin et al., 2008). The highest correlations are found for C_Z, the multiplicative constant of the soil depths (Table 5), which is also the most sensitive parameter of the model (Garambois et al., 2013, 2015). Indeed, the soil depth multiplicative constant explains 80% of model output variance when most hydrographs are peaking (Garambois et al., 2013). Catchment soil volume from pedologic data has to be adjusted with C_Z which is the most influent parameter of MARINE model on average. Within our modelling framework C_Z values larger than 1 indicates that catchment storage capacity needs to be increased for flash flood modelling purpose. For catchments with comparable areas, soil volumes and bedrocks such as the Cesse, the Verdouble or the Agly, C_Z is close to one which is three times lower than those necessary to correctly reproduce rainfall to runoff conservation on the Hérault and Ardèche. The C_Z on the Tech, Têt and Gardon are even larger. Moreover for initial soil moisture of approximately 50%, the soil volume is nearly entirely solicited as shown by maximum soil saturation condition in the range of 80–90% at the end of an event. A significant volume of flood triggering rainfall might percolate to deeper fractured layers as proposed by other authors (Castaings et al., 2009; Garambois et al., 2015; Roux et al., 2011). C_Z could then be related to catchments' bedrock descriptors that are not taken into account in the model. This may be due to the fact that the soil depth from soil surveys used in modelling only takes soil horizons A (surface soil) and B (subsoil) into account. Horizons C (parent rock) and R (bedrock) are not taken into account even though they may be hydrologically active (Garambois et al., 2015). The higher C_Z values are for catchments areas developing on primary era bedrock such as the Tech, the Têt, the Gardon, the Beaume or the Ardèche (Table 4 and Fig. 1). This is in agreement with recent results, obtained for different time scales through streamflow recession and cumulated rainfall analysis: Vannier et al. (2013) highlight relations between geology and drainage-storage capacity for 23 catchment areas (0.2–291 km^2) located in the Cévennes–Vivarais region.

2.3.2. Distance measure

For both geographical proximity and similarity approaches a measure of distance is required to evaluate the proximity of an ungauged catchment from potential donors. A common method consists in calculating the Euclidian distance between two catchments in the n-dimensional space of catchment attributes (Viviroli et al., 2009). We use attributes normalized by their maximum value because of their different variation ranges (Table 3) and the Euclidian distance for two catchments i and j is written as:

$$D_w(i,j) = \sqrt{\sum_{k=1}^{n} w_k[\text{attrib}_k^*(i) - \text{attrib}_k^*(j)]^2}$$

where attrib* refers to the n normalized attributes, w_k are user-specified weights than can be assigned for attributes to take into account their varying importance. In the following, attributes will be considered of equal importance and D_w will be minimized in order to find the most similar catchment(s) given an ungauged one.

2.3.3. Assessment of regionalization tests

In order to assess the relative performances of the different methods for discharge estimation at ungauged location, the jack-knife technique was employed to compute and consequently evaluate the regionalization results. Catchments are successively considered as gauged and ungauged and parameters are retrieved from the other calibrated catchments. In the following, each catchment is treated as ungauged in turn. The combinations of parameters sets are calculated from gauged catchments using the proposed regionalization methods. The 16 catchments of interest representing a total of 117 events will be used in the following for regionalization trials (Garambois, 2012). For these catchments hydrographs simulated following a regionalization method can be compared to observed flood hydrographs. The efficiency of the methods are evaluated with L_{NP} criterion (cf. §2.2), Nash, dQ_p and dT_p.

3. Results and discussion

3.1. Model performance and calibration uncertainty

The events selected are the strongest flood responses recorded during the period 1980–2011 for the catchments of interest. Specific peak flow discharges are superior to 0.2 m^3 s^{-1} km^2 for the selected catchments (cf. Table 1 in section 0. Appendix A) As a preliminary, MARINE model was run for the whole flash flood events data set with the calibrated parameter sets (Table 6). For several catchments, floods of the 80's and 90's with rainfall fields derived from interpolated raingauges were considered. Indeed as far as possible we aim to evaluate predictive power of both MARINE model and regionalization methods on the largest dataset. Regionalization results will be presented hereafter for the 117 flood events with MARINE performances evaluated in (Table 6) and ranging from (Nash; L_{NP}) = (0.2; 0.26) to (0.86; 0.88). For all catchments floods the mean values of (Nash; L_{NP}) are (0.54; 0.56) and more than 60 events are simulated with $L_{\mathrm{NP}} > 0.7$ i.e. approximately 4 events on average for each catchment.

Fig. 4 shows event cal/val performances for each catchment. The lowest efficiency is for the Nartuby which catchment area is mostly karstic, the Cesse catchment area is also karstic but performances are slightly better. 17 flood events out of 117 present L_{NP} coefficients close to 0 when testing calibrated parameter sets, with 8 of them for the Cesse and the Nartuby. However it appears interesting and more realistic to consider events with contrasted performances for the regionalization process and more generally to test the predictive abilities of an event flash-flood model.

The spreading of model performances can be important for some catchments like the Verdouble or Agly which are neighbours located in the Corbières Mountains or the Tech which is a steep catchment of the Pyrenean foothills. This can be attributable to

Table 5
Gauged catchments' simple correlations (Pearson's R^2) between calibrated parameter sets (on 61 events) from (Table 4) and catchment physical descriptors (Table 3).

	Area	Deniv	Alt$_{50}$	Sedi	Plut	Meta	PrimG = Meta + Plut	Hsoil$_{\text{\_min}}$	Hsoil$_{\text{\_max}}$	Hsoil$_{\text{\_mean}}$	Hsoil$_{\text{\_ std}}$	Vsoil	K_{sat}
C_Z	0.21	0.39	0.32	0.48	0.61	0.34	0.50	0.17	0.09	0.42	0.00	0.04	0.01
C_K	0.00	0.11	0.23	0.13	0.00	0.21	0.11	0.34	0.02	0.20	0.32	0.23	0.26
C_{KSS}	0.05	0.03	0.08	0.04	0.01	0.09	0.03	0.23	0.00	0.18	0.03	0.09	0.04
K_{D1}	0.01	0.07	0.10	0.05	0.03	0.14	0.05	0.52	0.00	0.28	0.28	0.10	0.34
K_{D2}	0.00	0.08	0.12	0.01	0.00	0.02	0.01	0.00	0.01	0.08	0.04	0.08	0.01

Table 6
Performance of MARINE model over the catchments and flood sets. The 16 catchments of interest represent a total of 117 flash floods. Number of calibration events in the first column between parentheses.

	Multiple events calibration (Nash)	Validation Nash (recent strong events monitored with radar)	Validation L_{NP} (recent strong events monitored with radar)	All events' Nash (including interpolated raingauges)	All events' L_{NP} (including interpolated raingauges)	Number of events per catchment for regionalization trials
Number of events	61	23	23	117	117	117
Tech (Pas du Loup)	0.90 (3)	0.70	0.73	0.46	0.37	9
Têt (Marquixane)	0.80 (3)	0.79	0.82	0.73	0.78	4
Réart (Saleilles)	0.86 (4)	0.60	0.67	0.46	0.62	6
Verdouble (Tautavel)	0.88 (4)	0.82	0.79	0.40	0.41	10
Agly (St Paul de F.)	0.80 (3)	0.76	0.75	0.51	0.47	5
Salz (Cassaignes)	0.88 (3)	–	–	0.60	0.55	11
Orbieu (Lagrasse)	0.78 (5)	0.67	0.65	0.51	0.57	10
Cesse (Bize Minervois)	0.80 (3)	0.80	0.87	0.44	0.42	11
Hérault (Ganges)	0.76 (3)	0.56	0.76	0.65	0.71	4
Gardon (Anduze)	0.75 (6)	0.86	0.88	0.63	0.71	10
Beaume (Rosières)	0.77 (3)	0.49	0.71	0.60	0.68	6
Ardèche (Vogüé)	0.83 (5)	0.87	0.85	0.86	0.88	7
Gapeau (Hyères)	0.80 (4)	0.75	0.82	0.58	0.64	6
Réal Martin (La Crau)	0.81 (4)	0.58	0.52	0.66	0.66	5
Aille (Vidauban)	0.81 (4)	0.65	0.72	0.48	0.53	8
Nartuby (Trans en Pce)	0.60 (4)	–	–	0.20	0.26	5
Mean	0.80	0.67	0.72	0.54	0.56	7
Median	0.80	0.70	0.75	0.55	0.59	7

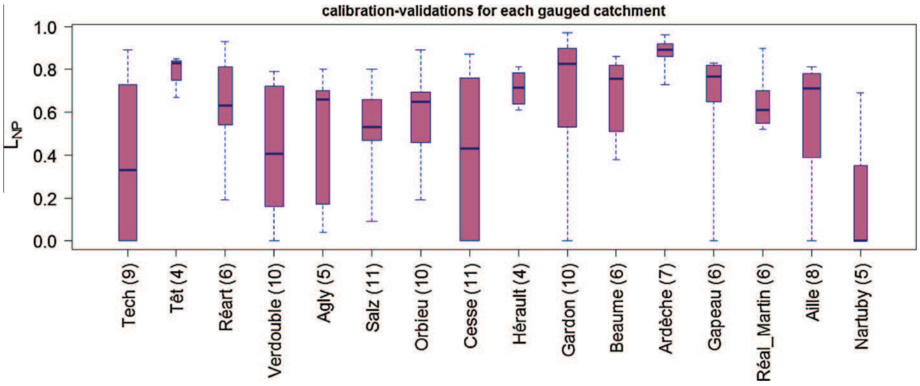

Fig. 4. MARINE model performances with calibrated parameter sets over the whole catchment-flood dataset, number of flash flood events between parentheses for each catchment.

several sources of error, and firstly to rainfall measurement errors that can be non negligibles in some cases, for example when radar or raingauge network or both have not seen a significant part of rainfall distribution explaining flood response (Garambois et al., 2015). Other significant sources of error can be: the hypothesis of time-independent parameter sets (and so uncertainty), the high flow gauging errors for several catchments.

It is important to notice that model performances are higher for catchments with an apparently more regular behaviour like the Ardèche or Gardon (Table 6). Regular behaviour means that the behaviour of the catchment seen by the model for validation events is close from the average behaviour found with calibration. A parameter set calibrated over several events is indeed supposed to reflect an average performance. For example, with similar performances in calibration (Nash = 0.88) for the Salz and Verdouble catchments, for a large number of flood events (10) performances in validation are better for the Salz (Nash, L_{NP}) = (0.60, 0.55) than for the Verdouble (Nash, L_{NP}) = (0.40, 0.41). This might result from different hydrological behaviours between floods, maybe also depending on the variability of rainfall patterns in time and space. This joins the idea of unusual hydrological behaviour, i.e. a flood event not covered by the past calibration events (extrapolation case) (see e.g. (Singh and Bárdossy, 2012)); whereas with a regular behaviour, a new flood event is supposed to be covered by the past calibration events (interpolation case).

3.2. Regionalization approaches

In this section several combination of descriptors and number of donor catchments are tested. Results are compared to observations and "calibrated" simulations. The results and best performances presented here for flash flood events on Mediterranean catchments can depend on the selection of physical descriptors used to define the physical similarities and on the availability of soil and bedrock data in particular as it will be shown. That is why extrapolation to other region of the world might not be warranted. Moreover, stream gauging network density, meteorological and climatological indices are not considered in this study.

While making the choice during the regionalization process of an event physically based model for flash floods, several questions arise, as for continuous model regionalization (see e.g. (Oudin et al., 2008)), and are discussed below.

3.2.1. *When can a catchment be kept as donor for regionalization?*

It is not straightforward to answer the question of catchments outliers, with a particular behaviour regarding the other catchments of a dataset. Modelling performances in calibration/validation for each catchment and physical meaning of catchment parameter sets can be considered as two important features of regionalization methods in the context of that study. First a threshold on model efficiency in cal/val mode could be used to exclude poorly modelled catchments for predictions at ungauged locations. Such a method would be very selective, for example a threshold of 0.7 would lead to consider only 4 donors (Table 6, 6th column), and so narrowing the possibilities for parameter sets and physical behaviours for ungauged catchments. Indeed, each catchment (parameter set) represents a possible operating point for MARINE model in the space defined by 5 parameters (Table 4), in other words a diversity of hydrological behaviours. We do not use a threshold on model efficiency hereafter.

The choice is made not to use 4 catchments as donors (Gapeau, Réal Martin, Aille, Nartuby) for the other 12 since pedologic data for these 4 catchments come from SIM model instead of soil surveys for the other 12 (§ 2.1). Indeed, these data could have an impact on calibration process and consequently affect parameters' physical meaning.

One can wonder whether a relation between cal/val and regionalization performances exists. To shed more light on this issue, Fig. 5 shows the relationship between the efficiency of calibrated parameter sets on donor gauged catchments and the efficiency of MARINE model on pseudo ungauged catchments, in the particular case of a single donor selected with spatial proximity. Results suggest that using a well-modelled catchment as donor does not warrant good performances on pseudo-ungauged catchments. However conversely, parameter sets from poorly-modelled catchments can produce higher performances when transferred to pseudo-ungauged catchment than in cal/val. The operating point in the model parameter space that it is possible to reach with cal/val can sometimes better reproduce ungauged catchment behaviour. This highlights the fluctuating quantity of hydrological information that is available in calibration events used to constrain parameter sets for a given gauged catchment.

3.2.2. *How many donor catchments should we consider for regionalization?*

In order to explore this issue, regionalization tests with a number increasing from 1 to 11 donor catchments are performed. Among the available catchment descriptors (cf. Table 3) the choice is made to present results for soil, bedrock and altitude difference descriptors. The use of other descriptors resulted in lower model efficiencies at ungauged locations.

Fig. 6 shows that for most regionalization methods based on similarity, the best performances are obtained with a few number of donor catchments between 2 and 4. This number must depend on the descriptors used to calculate the similarity measure and their information content about hydrological controls. Using only one donor catchment decreases the performance of regionalization as increasing the number of gauged donor catchments. Increasing the number of donors results in selecting catchments with more and more distant hydrological behaviours regarding the catchment of interest. For a large number of donor catchments the efficiencies of the different regionalization schemes tend to sensibly increase, strong errors in peak flow simulation might be partially avoided by smoothing the model behaviour with different sources. Would those two trends be true for an even larger dataset? This is an open question; however, for all the combination of descriptors tested, the best performances are for 2–4 donors. In other words, for an ungauged catchment, the unicity of its behaviour may be better approximated by a parameter set calculated on few donors highlighting some physiographic and potentially similarities of behaviour, for this database.

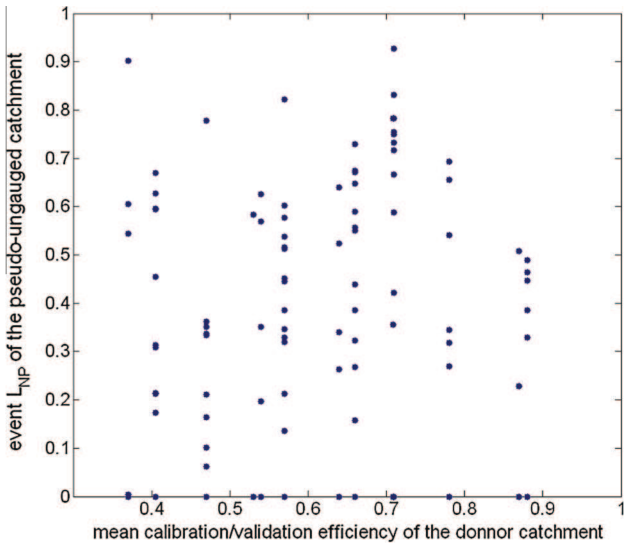

Fig. 5. Relationship between the mean cal/val efficiency of MARINE model for the donor gauged catchment and efficiency on pseudo ungauged catchment; case of the spatial proximity approach with one donor catchment. Number of event per catchment can be found in the last column of Table 6, L_{NP} values lower than zero are plotted as zero.

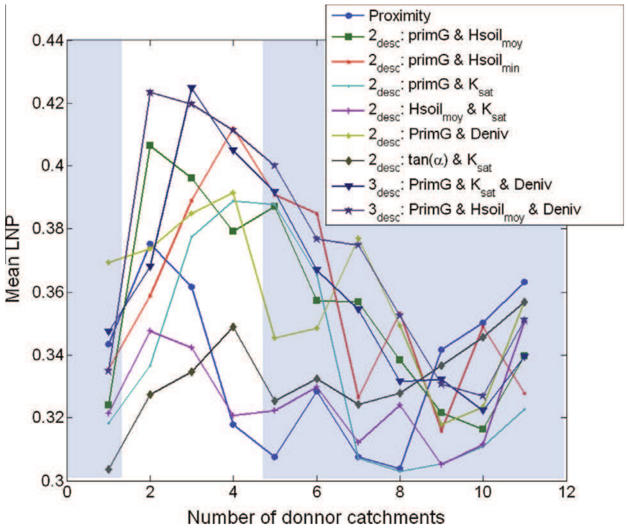

Fig. 6. Impact of the number of gauged catchment used for each regionalization scheme on averaged model efficiency. (8 methods × 117 events × 12 number of donors = 11,232 simulations).

3.2.3. *How to select information for regionalization?*

Selecting donor catchments to derive hydrological information to the site of interest is still an open question in regionalization context. Indeed, in function of the chosen combinations of descriptors or even the regionalization methods, different combinations of donor catchments can be obtained for an ungauged catchment. Proximity method and similarity method based on $Hsoil_{mean}$ and K_{sat} produce the weaker performances (Fig. 6), whereas some combinations of descriptors containing the index of catchment's primary era bedrock (PrimG) seem the most relevant to select donor catchments. Increasing the number of descriptors from 2 to 3 slightly increases the performances but a fourth descriptor about soil, bedrock or topography is useless probably because it contains redundant information. Hereafter we will discuss in more details the results obtained with two combinations of descriptors involving PrimG.

Having examined the three above questions, the following choices are made for the regionalization:

- For gauged catchment selection, we do not use any threshold on model efficiency as regard to catchments' parameter set transferability.
- 4 catchments (Gapeau, Réal Martin, Aille, and Nartuby) are not considered as donors for the 12 other catchments since pedologic data come from a different source.
- Regionalization schemes with 2, 3 or 4 gauged donor catchments are preferred.
- Results produced by geographical proximity (2 donors) and the 2 methods presenting the best performances according to Fig. 6 – PrimG-K_{sat}-Deniv (3 donors) and PrimG-Hsoil$_{mean}$-Deniv (2 donors) – will be investigated in more details.

3.3. Analysis of the efficiency of three simple regionalization schemes

3.3.1. General comparison

Following the choices made earlier, in this section we examine in more details the results produced by three simple regionalization schemes (Table 7). Regionalization methods are assessed in terms of flood estimation. It is useful to recall that the methods are based on calibrated parameter sets presented in Table 4. The L_{NP} cost function and its three components values are presented in Fig. 7. Statistics are calculated over all catchments. With median L_{NP} efficiencies of 0.47 for Reg2 and 0.45 for Reg3, these two regionalization schemes perform slightly under the range of cal/val whose median L_{NP} is 0.59 for the 117 flood events. For the two similarity approaches flood hydrographs features are acceptable. Concerning peak flow, the median efficiency is 0.57 for Reg2 and 0.51 for Reg3; for peak timing median $1 - dT_p$ is 0.52 for Reg2 and 0.58 for Reg3. Median Nash efficiencies are slightly lower with 0.31 and 0.37. However in the case of flash floods, Nash efficiencies can easily collapse; for example when a very peaky hydrograph is shifted in time. The approach with geographical proximity Reg1 is less efficient with a L_{NP} of 0.37.

Table 7
Regionalization schemes for MARINE model detailed in this paper.

Regionalization method	Kind	Attributes	Number of donors
[Reg1]	Proximity	Geographical proximity	2
[Reg2]	Similarity	Percentage of catchment area on Primary bedrock (PrimG), spatial average of saturated hydraulic conductivity (K_{sat}) and altitude difference (Deniv)	3
[Reg3]	Similarity	Percentage of catchment area on Primary bedrock (PrimG), spatial average of soil depth (Hsoil$_{mean}$) and altitude difference (Deniv)	2

The distribution of performances for pseudo ungauged catchment for the three regionalization methods is acceptable with rather narrow interquartile range and best catchment's L_{NP} above 0.7. The few outliers at the low end of box plots might indicate that methods' robustness could be improved. It is interesting to notice that for the three regionalization methods, these low performances occurred for the Nartuby catchment (see Fig. 8) where modelling is not easy even in cal/val as explained before (cf. Section 3.1), and the Réart catchment. For this particular catchment that behaves like an intermittent river but where cal/val results were better, it seems that there are no good donor catchments within the dataset.

In summary, regionalized parameter sets with these 3 methods based on model calibration yield to encouraging results as regards to standard scores obtained for each catchment in cal/val over the dataset (Fig. 8). Moreover the decrease of about 10 percents in performances between cal/val and regionalization is comparable to what is found in the literature for continuous models. In the following, we investigate in more details MARINE model performances over each catchment and the donor catchments selected with the regionalization methods.

3.3.2. Catchment performances

Fig. 8 highlights some cases where performances of regionalization methods are largely under cal/val performances (Réart, Hérault, Ardèche, Réal Martin). For those catchments this might be either the descriptors used for regionalization either the possible donor catchments within our dataset that do not contain enough relevant hydrological information to constrain MARINE model and reproduce particular catchment behaviour. For the 12 other catchments average regionalization efficiency is close to cal/val performances (for example: Verdouble, Gardon, Beaume) which is a very encouraging result given the difficulties involved in flash flood modelling and forecasting.

Cal/val results are expected to represent the upper limit for regionalization. But in some cases, regionalization slightly outperforms cal/val: the Verdouble, the Agly, the Gardons and the Cesse. This could question the "optimality" of the operating point found in the parameter space during calibration process. In the case of the Gardons, cal/val and regionalization efficiencies are higher than for the Verdouble, the Agly and the Cesse, approximately of 0.7. In

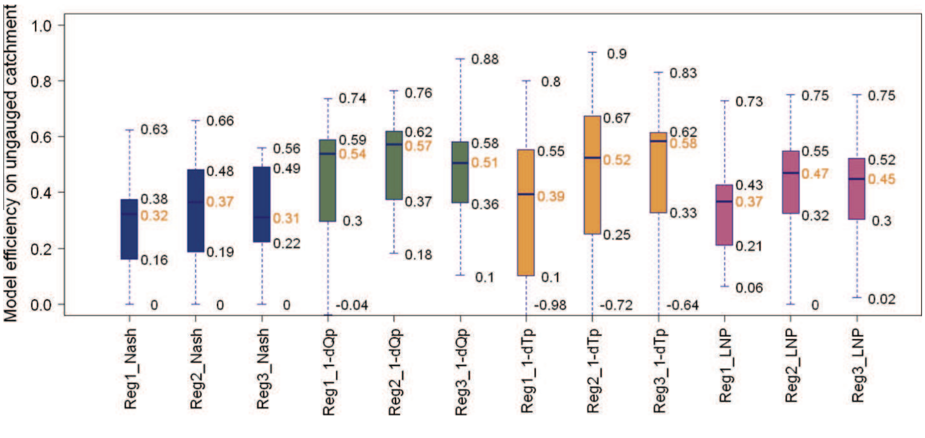

Fig. 7. Comparison of the efficiency in terms of (Nash), $(1 - dQ_p)$, $(1 - dT_p)$ and (L_{NP}) for three regionalization schemes: Geographical proximity (2 donors) [Reg1], PrimG-K_{sat}-Deniv (3 donors) [Reg2] and PrimG-Hsoil$_{mean}$-Deniv (2 donors) [Reg3].

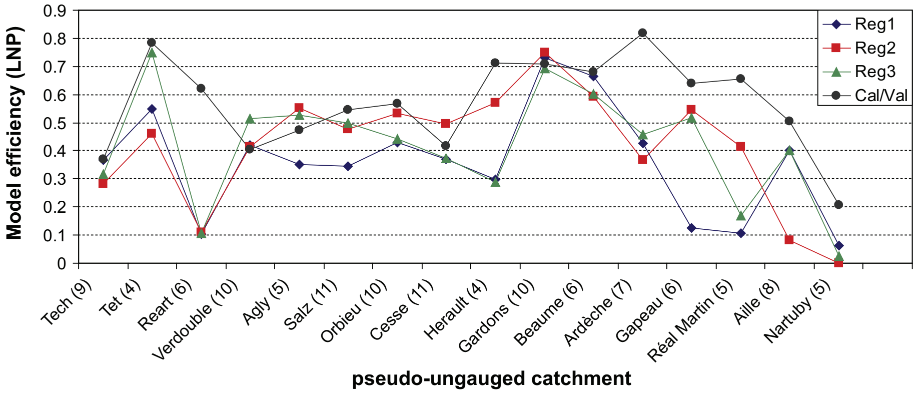

Fig. 8. Efficiency in terms of L_{NP} for each pseudo ungauged catchment for three regionalization schemes: Geographical proximity (2 donors) [Reg1], PrimG-K_{sat}-Deniv (3 donors) [Reg2] and PrimG-Hsoil$_{mean}$-Deniv (2 donors) [Reg3]. Number of flash flood events in parenthesis.

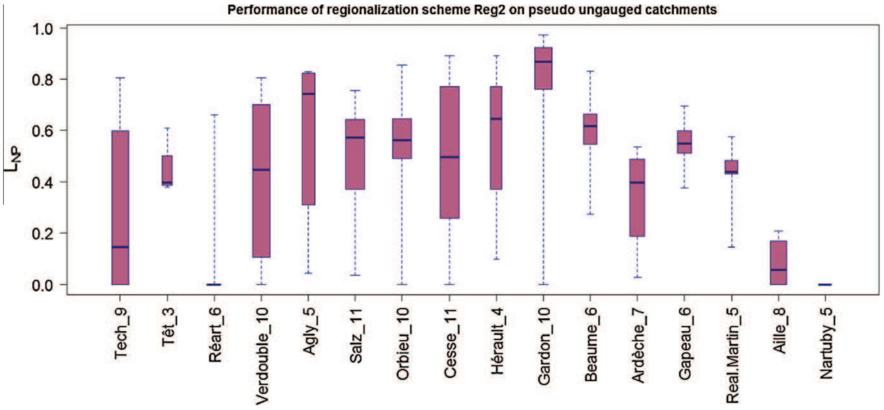

Fig. 9. Boxplot of MARINE model performances over the whole catchment-flood dataset, parameter sets are determined with Reg2, i.e. similarity method with PrimG-K_{sat}-Deniv (3 donors) [Reg2]. Number of flash flood events specified after each catchment's name.

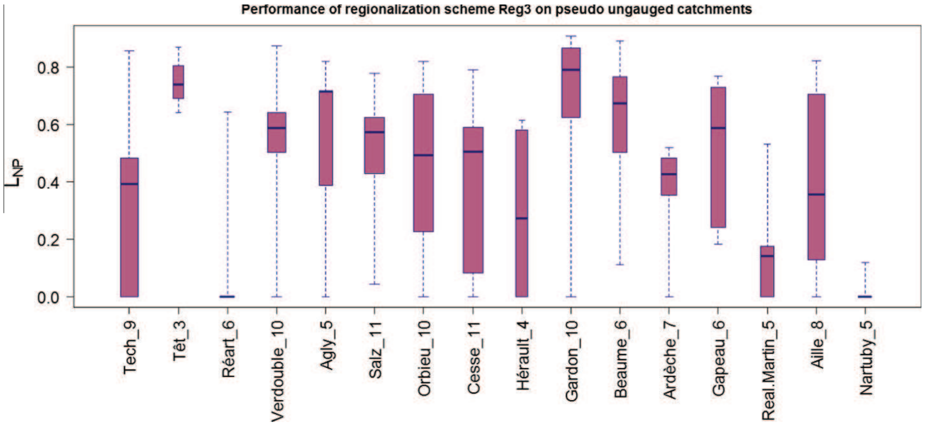

Fig. 10. Boxplot of MARINE model performances over the whole catchment-flood dataset, parameter sets are determined with Reg3, i.e. similarity method with PrimG-Hsoil$_{mean}$-Deniv (2 donors) [Reg3]. Number of flash flood events specified after each catchment's name.

the cases of Agly and Verdouble, or the Cesse which a karstic catchment, the lack of flash flood events and/or relevant hydrological information for calibration can be pointed out. In the case of the Gardons, slightly more relevant hydrological information is found with regionalization than with calibration.

In other words, for some catchments flood records might not be rich enough regarding hydrological information to calibrate parameter sets able to predict a large spectrum of flash floods.

3.3.3. Event performances

In the section above, it is shown that for 12 catchments out of 16, the average regionalization efficiency is close to cal/val performances. The number of events in function of the L_{NP} values is presented for each catchment in Fig. 4 for calibrated parameter sets and in Fig. 9 and Fig. 10 for the parameter sets obtained with similarity approaches.

Performances degradation from cal/val to regionalization can be depicted in terms of event efficiencies for each catchment for

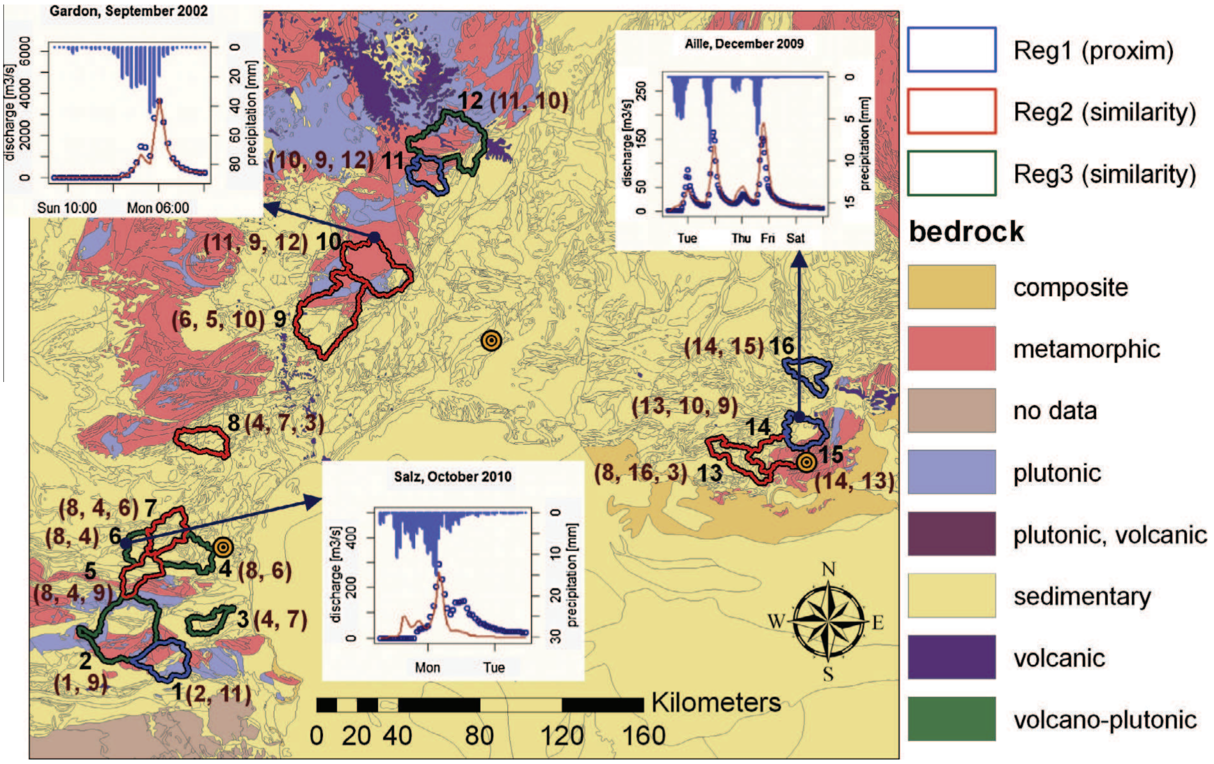

Fig. 11. Pseudo ungauged catchments numbered in black with the regionalization scheme which performed the best (catchment boundary in blue, red or green) and the donor catchments (brown numbers). Simplified bedrock composition at the background. Hydrographs simulated with regionalized parameter sets of Table 8 (blue dots = observations, red line = simulated discharge). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8

Comparison of calibrated and regionalized parameter sets for the best regionalization scheme performance (Reg2 if 3 donors, Reg3 if 2 donors).

Pseudo ungauged catchment	Donor catchments	C_Z (−) Cal.	C_Z (−) Reg.	C_K (−) Cal.	C_K (−) Reg.	C_{KSS} (−) Cal.	C_{KSS} (−) Reg.	K_{D1} ($m^{1/3}/s$) Cal.	K_{D1} ($m^{1/3}/s$) Reg.	K_{D2} ($m^{1/3}/s$) Cal.	K_{D2} ($m^{1/3}/s$) Reg.
Tech (#1)	[Têt(#2), Beaume(#11)]	4.3	5.5	11.0	9.7	1515	4908	5.0	19.6	3.2	12.6
Têt (#2)	[Tech(#1), Hérault(#9)]	6.1	3.8	19.8	16.2	10,000	4031	11.8	7.5	3.4	4.6
Réart (#3)	[Verdouble(#4), Orbieu(#7)]	4.3	1.3	15.0	15.0	1242	6004	5.7	6.3	30.0	3.3
Verdouble (#4)	[Cesse(#8), Salz(#6)]	1.3	1.2	15.0	11.6	4486	8603	5.0	5.0	4.0	5.9
Agly (#5)	[Cesse(#8), Verdouble(#4), Hérault(#9)]	1.6	2.1	20.0	13.6	4304	6322	7.5	6.1	2.2	5.1
Salz (#6)	[Cesse(#8), Verdouble(#4)]	1.0	1.3	20.0	10.9	5595	7592	5.0	5.0	5.0	5.3
Orbieu (#7)	[Cesse(#8), Verdouble(#4), Salz(#6)]	1.3	1.2	15.0	12.4	10,000	7274	9.1	5.0	2.0	5.3
Cesse (#8)	[Verdouble(#4), Orbieu(#7), Réart(#3)]	1.3	2.2	7.7	14.9	10,000	6577	5.0	7.9	6.3	10.5
Hérault (#9)	[Salz(#6), Agly(#5), Gardons(#10)]	3.6	2.4	17.8	16.5	4764	4843	8.2	8.1	5.0	5.9
Gardon (#10)	[Beaume(#11), Hérault(#9), Ardèche(#12)]	4.6	4.1	10.3	9.4	4540	4472	11.7	13.0	9.7	12.6
Beaume (#11)	[Gardons(#10), Hérault(#9), Ardèche(#12)]	5.3	3.9	7.4	13.1	3712	4706	21.4	9.6	14.7	8.5
Ardèche (#12)	[Beaume(#11), Gardons(#10)]	3.4	5.0	2.1	8.7	4891	4105	10.0	16.8	19.1	12.3
Gapeau (#13)	[Cesse(#8), Nartuby(#16), Réart(#3)]	1.2	2.3	4.8	11.2	1200	5157	14.0	10.8	20.8	14.1
Réal Martin (#14)	[Gapeau(#13), Gardons(#10), Hérault(#9)]	1.3	3.0	3.0	10.4	415	3299	19.7	11.5	5.0	12.6
Aille (#15)	[Réal Martin(#14), Gapeau(#13)]	0.4	1.2	4.0	4.1	715	884	31.2	16.3	7.0	14.4
Nartuby (#16)	[Réal Martin(#14), Aille(#15)]	1.1	0.9	10.5	3.4	4525	537	22.0	24.4	5.0	5.8

two combinations of descriptors. Interestingly, for all catchments except the Real Martin, the Nartuby and the Ardèche, there is at least one event simulated with a L_{NP} greater than 0.6 for the two regionalization schemes tested (Fig. 9 and Fig. 10). For several catchments, flood event performances in regionalization can be greater than $L_{NP} = 0.8$. From the comparison between Figs. 9, 10 and 4 and using Fig. 8, several cases can be highlighted:

- Catchments where cal/val results and regionalization results are similar; for example the Salz, the Gardons or the Beaume. For the Gardons, the donor catchments selected with the three methods (Table 9) present a bedrock composition mainly metamorphic and plutonic and therefore similar to the receptor bedrock (Fig. 11). This is also true for the Beaume catchment. The same comment can be made for the Salz: the two donors selected both with Reg3 and Reg 2, the Cesse and the Verdouble, present bedrocks that are mainly sedimentary. For those cases, receptor and donor catchments have comparable C_Z values in calibration (cf. Table 3). This means that the regionalization schemes and catchment descriptors combinations are pertinent. Moreover this means that there exist good donor catchments within the dataset. There is also the example of the Nartuby, which is a poorly modelled catchment in cal/val and in regionalization, probably because it is mostly karstic.

Table 9
Combinations of donor catchments given pseudo ungauged catchment for each of the 3 regionalization schemes: Geographical proximity (2 donors) [Reg1], PrimG-K_{sat}-Deniv (3 donors) [Reg2] and PrimG-Hsoil$_{mean}$-Deniv (2 donors) [Reg3]. Catchment number (#).

Pseudo ungauged	Proximity donors	PrimG K_{sat} Deniv (3 donors)	PrimG Hsoil$_{mean}$ Deniv (2 donors)
Tech(#1)	[Têt(#2), Réart(#3)]	[Têt(#2), Agly(#5), Hérault(#9)]	[Têt(#2), Beaume(#11)]
Têt(#2)	[Tech(#1), Agly(#5)]	[Tech(#1), Agly(#5), Hérault(#9)]	[Tech(#1), Hérault(#9)]
Réart(#3)	[Verdouble(#4), Tech(#1)]	[Cesse(#8), Verdouble(#4), Orbieu(#7)]	[Verdouble(#4), Orbieu(#7)]
Verdouble(#4)	[Orbieu(#7), Salz(#6)]	[Cesse(#8), Orbieu(#7), Réart(#3)]	[Cesse(#8), Salz(#6)]
Agly(#5)	[Orbieu(#7), Salz(#6)]	[Cesse(#8), Verdouble(#4), Hérault(#9)]	[Cesse(#8), Hérault(#9)]
Salz(#6)	[Orbieu(#7), Agly(#5)]	[Cesse(#8), Verdouble(#4), Orbieu(#7)]	[Cesse(#8), Verdouble(#4)]
Orbieu(#7)	[Verdouble(#4), Salz(#6)]	[Cesse(#8), Verdouble(#4), Salz(#6)]	[Verdouble(#4), Réart(#3)]
Cesse(#8)	[Verdouble(#4), Orbieu(#7)]	[Verdouble(#4), Orbieu(#7), Réart(#3)]	[Verdouble(#4), Salz(#6)]
Hérault(#9)	[Beaume(#11), Gardons(#10)]	[Salz(#6), Agly(#5), Gardons(#10)]	[Agly(#5), Ardèche(#12)]
Gardons(#10)	[Beaume(#11), Hérault(#9)]	[Beaume(#11), Hérault(#9), Ardèche(#12)]	[Beaume(#11), Ardèche(#12)]
Beaume(#11)	[Gardons(#10), Ardèche(#12)]	[Gardons(#10), Hérault(#9), Ardèche(#12)]	[Gardons(#10), Ardèche(#12)]
Ardèche(#12)	[Beaume(#11), Gardons(#10)]	[Beaume(#11), Gardons(#10), Hérault(#9)]	[Beaume(#11), Gardons(#10)]
Gapeau(#13)	[Réal Martin(#14), Aille(#15)]	[Cesse(#8), Nartuby(#16), Réart(#3)]	[Réal Martin(#14), Aille(#15)]
Réal Martin(#14)	[Aille(#15), Gapeau(#13)]	[Gapeau(#13), Gardons(#10), Hérault(#9)]	[Aille(#15), Gapeau(#13)]
Aille(#15)	[Réal Martin(#14), Gapeau(#13)]	[Réal Martin(#14), Hérault(#9), Ardèche(#12)]	[Réal Martin(#14), Gapeau(#13)]
Nartuby(#16)	[Réal Martin(#14), Aille(#15)]	[Cesse(#8), Verdouble(#4), Réart(#3)]	[Orbieu(#7), Réart(#3)]

- Catchments where cal/val results are good and only one regionalization scheme is efficient; for example the Têt [Reg3], the Orbieu [Reg2], the Hérault [Reg2], the Real Martin [Reg2], the Aille [Reg3]. Once again, the calibrated C_Z values are similar between receptor and donor catchments thanks to bedrock descriptors. But hydrological information might be better transferred depending on the choice of physiographic descriptors, K_{sat} for Reg2 and Hsoil$_{mean}$ for Reg3. The existence of good donors within the dataset is also important. Indeed, for the Réal Martin the bedrock is sedimentary for a half of the area and metamorphic for the other half, and the donors selected with the similarity method Reg2 have contrasted bedrocks and C_Z.
- Catchments where cal/val is satisfying but no regionalization scheme is efficient like for the Ardèche or the Réart. This can be attributable to the lack of donor catchments, at least for the combination of descriptors tested. Indeed, the best regionalization method gives a C_Z of 1.3 for the Réart, whereas the calibrated value was of 4.3, as shown in Table 8 which presents for each catchment the values of the parameter sets issued from calibration and regionalization.
- Catchments where regionalization outperforms cal/val such as the Verdouble [Reg3], the Cesse [Reg2] or Agly (Reg2 and Reg3). As stated before the calibrated parameter sets from donor catchments might contain more hydrological information than the events available for at site calibration.

For a given pseudo ungauged catchment, it is not the same flood events that are best simulated for each regionalization scheme since the parameter sets obtained are not the same. The behaviour of a catchment may change from one flood to another, depending on the resonance between spatial catchment properties and the spatial and temporal repartition of rainfall. This emphasizes the difficulty of predicting a large spectrum of flash flood behaviours for a given catchment and hydrological model complexity with a single parameter set.

3.4. Which hydrological information is best transferred?

To examine whether several spatial patterns exist in the performance of regionalization methods, the best regionalization solutions with MARINE model for each catchment are shown in Fig. 11, along with bedrock composition on which the regionalization schemes with similarity (Reg2 and Reg3) are based. For this dataset and our process oriented model, the physical similarity approach performs better than the proximity approach and there is no clear spatial pattern in donor catchments localization between the three regionalization methods tested.

The value of regionalized parameter sets are presented with calibrated values for each catchment in Table 8. As stated in §2.2 C_Z determines catchment storage capacity and has a great influence on peak discharge and runoff coefficient. The regionalized values of this parameter are close to calibrated ones for most catchments. When C_Z calibration and regionalization values are too different, performances of regionalization methods are largely under cal/val performances, like for the Réart or the Ardèche. Moreover the catchments with similar C_Z exchange their parameter sets. These catchments can be located in a geographical zone with similar properties or hydrological landscapes responsible for comparable hydrological behaviours: for example the Hérault, Gardon, Beaume or Ardèche (#9, 10, 11, 12 on Fig. 11); or another group composed of the Verdouble, Agly, Salz, Orbieu, Cesse (#4, 5, 6, 7, 8 on Fig. 11). Interestingly, the physiographic descriptor about primary bedrock reveals to be a powerful indicator to constrain MARINE model parameters and especially C_Z. It can be related to bedrock characteristics which might influence significantly flood water balance as already explained in § 2.3 and § 3.3 and detailed in Garambois et al., 2013.

4. Conclusions

This paper investigates the regionalization of MARINE process oriented model in the case of 117 recent flash floods of the French Mediterranean region. MARINE model performances in cal/val are ranging from (Nash; L_{NP}) = (0.2; 0.26) to (0.86; 0.88) with a mean (Nash; L_{NP}) of (0.54; 0.56). Cal/val is first compared to the simplest regionalization scheme consisting in spatial proximity method with one donor. Results show that using a well-modelled catchment as donor does not always produce good performances on pseudo-ungauged catchments and conversely, parameter sets from poorly-modelled catchments can produce higher performances when transferred to pseudo-ungauged catchment. Spatial proximity and similarity approaches with several combinations of descriptors are then tested for one to 12 donor catchments. Using 2–4 donor catchments gives the highest performances and the combinations of descriptors containing information about primary bedrock are the most relevant. Physiographic similarity approaches produce better results than the proximity approach for our flash flood data set.

Encouraging results are obtained with two similarity approaches based on physiographic descriptors with two and three donor catchments. There is only a small decrease of performances from cal/val with L_{NP} = 0.59 to regionalization with L_{NP} = 0.47 and 0.45 for these two methods.

Regionalization performances were then examined for each catchment and show the need of good donor catchments, i.e. with similar hydrological behaviours, within the dataset given pertinent combinations of descriptors. Interestingly, for some catchments regionalization outperforms cal/val. In that case, this suggests that more (relevant) hydrological information can be available from donor catchments than the events available for at site calibration. The same analysis can be made according to the results of regionalization with the spatial proximity method and one donor.

Event performances in regionalization are encouraging and for 13 catchments out of 16 there is at least one flood event simulated with a L_{NP} greater than 0.6 and sometimes 0.8. Different model behaviours are simulated through regionalization process and reproduce a mean catchment behaviour. The actual catchment behaviour however may change from one flood to another, which is probably why regionalization is found to be easier for catchment with an apparently more regular behaviour (as defined in § 3.1). This emphasizes the difficulty of predicting a large spectrum of flash flood behaviours for a given catchment and a given hydrological model complexity with a single parameter set.

The soil depth multiplicative constant C_Z is the most influent parameter of the MARINE model. As explained in §2.3, C_Z has a significant impact on water balance within the model and values larger than 1 indicates that catchment storage capacity needs to be increased for flash flood modelling purpose. Indeed, percolation in bedrock might play a significant role on flash flood water balance.

The C_Z greater than one found for catchment areas developing on metamorphic or plutonic bedrocks are in agreement with the results of Vannier et al. (2013). Probably because of its high influence, C_Z is rather well constrained by the two similarity approaches in regionalization. The unicity of catchments might be well accounted through the use of topography, soil and bedrock descriptors. This study demonstrates the predictive power of bedrock descriptor for regionalization in the case of Mediterranean flash floods.

It would be interesting to test this approach on a larger dataset and for other regions of the world with different physiographic characteristics and climate. Further studies could investigate the use of homogeneous regions in terms of climatology, meteorological indices, and particularly indices about extreme rainfall statistics at different space–time scales. This could be a way to search donor catchments in a hydrological neighbourhood with even more physical meaning. The uncertainties from rainfall and initial soil water contents could also be propagated into regionalization process for example with regionalization methods developed in probabilistic frameworks (see e.g. (Smith et al., 2014)).

Acknowledgments

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Appendix A

See Table 1.

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