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1 **RAPID applied to the SIM-France model**

2

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24 **Abstract**

25 SIM-France is a large connected atmosphere/land surface/river/groundwater modeling  
26 system that simulates the water cycle throughout metropolitan France. The work  
27 presented in this study investigates the replacement of the river routing scheme in SIM-  
28 France by a river network model called RAPID to improve the capacity to relate  
29 simulated flows to river gages and to take advantage of the automated parameter  
30 estimation procedure of RAPID. RAPID was run with SIM-France over a ten-year  
31 period and results compared with those of the previous river routing scheme. We found  
32 that while the formulation of RAPID improved the functionality of SIM-France, the flow  
33 simulations are comparable in accuracy to those previously obtained by SIM-France.  
34 Sub-basin parameterization was found to improve model results. A single criterion for  
35 quantifying the quality of river flow simulations using several river gages globally in a  
36 river network is developed that normalizes the square error of modeled flow to allow  
37 equal treatment of all gaging stations regardless of the magnitude of flow. The use of this  
38 criterion as the cost function for parameter estimation in RAPID allows better results than  
39 by increasing the degree of spatial variability in optimization of model parameters.  
40 Likewise, increased spatial variability of RAPID parameters is shown to enhance model  
41 performance.

42

43 **Keywords** stream flow, hydraulic network, network matrix, parameters, estimation, dam,  
44 quad-tree

45

## 46 **1. Introduction**

47 In the past two decades, several large scale river routing schemes have been used along  
48 with land surface models for hydrologic modeling. Among the most notable applications  
49 of large scale river routing are TRIP [Total Runoff Integrating Pathways, *Ngo-Duc, et al.*,  
50 2007; *Oki and Sud*, 1998], RiTHM [River-Transfer Hydrological Model, *Ducharne, et*  
51 *al.*, 2003], the routing model of Lohmann et al. [*Lohmann, et al.*, 1996; 1998a; 1998b;  
52 1998c; 2004; *Maurer, et al.*, 2001], that of Wetzel [*Abdulla, et al.*, 1996; *Nijssen, et al.*,  
53 1997; *Wetzel*, 1994], and that of Olivera et al. [2000]. These approaches have been used  
54 along with land surface parameterization schemes to calculate river flow from runoff at  
55 the regional, continental and the global scale. MODCOU [Modèle Couplé, *Ledoux, et*  
56 *al.*, 1989] is another model with routing capabilities that differs from the previously cited  
57 models in that it has separate horizontal routing of water for land surface and within the  
58 river system. MODCOU simulates flows throughout Metropolitan France (mainland  
59 France and Corsica) as part of the SIM-France modeling framework [*Habets, et al.*,  
60 2008].  
61 SIM-France (SAFRAN-ISBA-MODCOU-France) is a large connected atmosphere, land  
62 surface, river and groundwater model (see Figure 1) that involves coupling the national-  
63 scale atmospheric analysis system SAFRAN [Système d'Analyse Fournissant des  
64 Renseignements Atmosphériques à la Neige, *Durand, et al.*, 1993; *Quintana-Seguí, et al.*,  
65 2008], with the ISBA land surface model [Interactions Soil- Biosphere-Atmosphere,  
66 *Boone, et al.*, 1999; *Noilhan and Planton*, 1989], and with the MODCOU  
67 hydrogeological model [*Ledoux, et al.*, 1989]. ISBA computes the vertical water and  
68 energy balance between the land surface and the atmosphere. The improved physics of

69 the land surface parameterization of ISBA developed in Quintana-Seguí et al. [2009] that  
70 consist of an exponential profile for soil hydraulic conductivity and calibration of soil  
71 hydraulic conductivity and subgrid runoff are used in this study. Surface runoff and  
72 deep-soil drainage are computed by ISBA and transferred to MODCOU which computes  
73 the horizontal flow routing on the land surface, in rivers and in aquifers. Aquifers in  
74 MODCOU are modeled within the two main river basins of France, the Seine and the  
75 Rhône, which together represent 30% of the land area of France.

76 MODCOU handles the calculations of flow and volume of water within the river network  
77 of SIM-France. This river network is made up of grid cells divided into a quad-tree  
78 pattern and the calculations of MODCOU are made for groups of quad-tree cells. Using  
79 groups of cells for calculations is advantageous for reducing computational costs but it  
80 limits the modularity of MODCOU. In particular, the location and number of gaging  
81 stations are difficult to modify.

82 The work presented herein investigates the impact of replacing the routing module used  
83 in MODCOU by a river network model called RAPID [Routing Application for Parallel  
84 Computation of Discharge, *David, et al.*, 2011]. RAPID uses a matrix-based version of  
85 the Muskingum method to calculate flow and volume of water for each reach of a river  
86 network and has an automated parameter estimation procedure. RAPID therefore allows  
87 greater flexibility than the routing module in MODCOU with regards to changing the  
88 locations of computations in an existing domain or to running SIM on a new domain.

89 RAPID was previously applied to a GIS vector river network [*David, et al.*, 2011], and  
90 the present study shows how it can also be applied to a quad-tree gridded river network.  
91 In addition, RAPID is advantageous because of its ability to run in a parallel computing

92 environment. Finally, replacing the routing module of MODCOU by RAPID has already  
93 allowed helping quantify river/aquifer interactions at the regional scale [*Saleh, et al.*,  
94 2010].

95 In this paper, the original river routing of MODCOU as well as that of RAPID are briefly  
96 presented followed by a ten-year application (1995-2005) of SIM-France comparing the  
97 two river routing applications.

98

## 99 **2. Modeling framework**

### 100 **2.1. River modeling in SIM-France**

101 The computational domain of SIM-France includes all of Metropolitan France, including  
102 Corsica. Parts of Spain, Switzerland, Germany and Belgium are also included where  
103 their drainage area flows through France, as shown in Figure 2. The total surface area of  
104 the computational domain is 610,000 km<sup>2</sup>.

105 Surface routing and river routing in SIM-France are done by MODCOU [*Ledoux, et al.*,  
106 1989]. The surface and river networks of SIM-France and their connectivity were created  
107 using a routine called HydroDem [*Leblois and Sauquet, 2000*] and consist of 193,861  
108 surface cells and 24,264 river cells, each river cell being a particular surface cell. The  
109 surface area covered by the river cells is 65,000 km<sup>2</sup>. The surface network uses a quad-  
110 tree structure with cell sizes of 1 km, 2 km, 4 km and 8 km. The river network has cell  
111 sizes of 1 km and 2 km. The smaller quad-tree cells are used at the conference of  
112 branches of the river network for better representation of the network connectivity and at  
113 basin boundaries for more accurate basin surface area.

114 The connectivity between river cells is given by a table that provides for each  
115 downstream river cell up to four upstream river cells. There are no loops or divergences  
116 in the river network of SIM-France. The connectivity between catchments and rivers is  
117 given by a table that provides for each surface cell a unique downstream cell where its  
118 runoff enters the river.

119 For both surface and river routing, the calculations of flow and volume of water within  
120 MODCOU are carried out using groups of cells as computing elements, therefore  
121 minimizing the amount of calculations compared to computing for all cells separately.

122 These groups of cells – or isochrone zones – are based on the notion of isochronism  
123 developed by Leblanc and Villeneuve [1978]. An isochrone is a line representing a  
124 constant time of travel to a reference point downstream. An isochrone zone is the area  
125 between two successive isochrones. This zone is represented by a set of cells which are a  
126 single computational unit in MODCOU. Both the land surface isochrones and river  
127 isochrones of MODCOU have three-hour time intervals, which means that the time of  
128 travel between the upstream-most and the downstream-most cell in a given isochrone  
129 zone is approximately three hours. All the isochrones of a given network are determined  
130 using the travel time between connected cells which is estimated based on topography  
131 and on the geometry of the quad-tree mesh. For surface cells and river cells, the travel  
132 time  $\tau_{i,j}$  between two consecutive cells  $i$  and  $j$  is calculated using the distance  
133  $d_{i,j}$  between the two cells and the slope  $s_{i,j}$ , as shown in Equation (1):

134

$$135 \quad \tau_{i,j} = \alpha \cdot \frac{d_{i,j}}{\sqrt{s_{i,j}}} \quad (1)$$

136

137 where  $\alpha$  is the inverse of a velocity. In the current version of SIM-France, a unique  
138 value of  $\alpha$  is calibrated for each major basin.

139 Figure 3 shows an example of the isochrone zones and connectivity between surface cells  
140 and river cells in MODCOU for the Ardèche River Basin. Figure 3a) shows the Ardèche  
141 River, its basin and three river gages. Figure 3b) shows the river isochrone zones of the  
142 Ardèche River. Figure 3c) shows the surface isochrone zones corresponding to the  
143 upstream-most river isochrone zone. Each surface cell belongs to a surface isochrone

144 zone, but only the isochrone zones corresponding to one river isochrone zone are shown  
145 of Figure 3c) for clarity. The units used for isochrone zones are the number of  
146 MODCOU 3-hour time steps to the outlet (here the Mediterranean). The quad-tree  
147 structure of increasing resolution can be seen at the boundary of the basin in Figure 3c).  
148 In MODCOU, the volume of water  $V^{out}$  that discharges across each isochrone line in a  
149 computation time step is calculated differently for the surface network and for the river  
150 network. For routing on the land surface, all the volume of water  $V$  available in the  
151 isochrone zone is transferred to the downstream zone, as shown in Equation (2):

152

$$153 \qquad \qquad \qquad V^{out} = V \qquad \qquad \qquad (2)$$

154

155 For routing in the river network,  $V^{out}$  is proportional to the volume of water  $V$  available  
156 within the isochrone zone as shown in Equation (3):

157

$$158 \qquad \qquad \qquad V^{out} = \beta \cdot V \qquad \qquad \qquad (3)$$

159

160 where  $\beta \in [0,1]$  is manually calibrated and usually set constant for large basins. Equation  
161 (3) can be viewed as the linear reservoir equation associated with a first-order explicit  
162 development of the continuity equation. The variation of volume related to lateral inflow  
163 and groundwater inflow of water are added to the volume  $V$  before calculating  $V^{out}$ . In  
164 SIM-France,  $\beta$  has four possible values: 0.5, 0.7, 0.8 and 0.9 as shown in Figure 4.

165 Equation (3) is applied to isochrone zones. Hence, the volume of water within each  
166 isochrone zone needs be partitioned among its several river cells before computation of  
167 the river-aquifer exchanges. This interaction depends on the aquifer head, on the river  
168 head – assumed constant – and on the volume of water in the river cell when the river  
169 infiltrates water into the aquifer. The partitioning of water volume among all cells of an  
170 isochrone zone is done using a weighted average of the total amount of water reflecting  
171 the spatial distribution of lateral inflow in each isochrone zone.

172 This formulation has several inconsistencies, especially when the junction between two  
173 streams lies in the interior of an isochrone zone. This can have a consequence in river-  
174 aquifer interactions, but also in the computation of river flow. Furthermore, using only  
175 one set of isochrones in each basin can lead to two gages being located in one isochrone  
176 zone, in which case the flow computed by MODCOU has to match the flow at two  
177 different gaging stations. In order to avoid such inconsistencies, MODCOU uses a  
178 unique set of isochrone zones for each gage, such that each gage is the downstream-most  
179 river cell in its isochrone zone. Therefore, several flow calculations can be performed for  
180 a given cell, if the given cell belongs to several isochrone zones, which is inefficient and  
181 requires time consuming processing work in case of change of number or locations or  
182 river gages. The work done herein aims at simplifying the river modeling done within  
183 SIM-France.

## 184 **2.2. RAPID**

185 RAPID [David, *et al.*, 2011] is a river network model that uses a matrix-based version of  
186 the Muskingum routing scheme to calculate discharge simultaneously through a river  
187 network. RAPID was first applied to the Guadalupe and San Antonio River Basins in

188 Texas using a vector-based river network extracted from a geographic information  
189 system dataset called NHDPlus [USEPA and USGS, 2007]. The governing equation used  
190 in RAPID is the following:

191

$$192 \quad (\mathbf{I} - \mathbf{C}_1 \cdot \mathbf{N}) \cdot \mathbf{Q}(t + \Delta t) = \mathbf{C}_1 \cdot \mathbf{Q}^e(t) + \mathbf{C}_2 \cdot (\mathbf{N} \cdot \mathbf{Q}(t) + \mathbf{Q}^e(t)) + \mathbf{C}_3 \cdot \mathbf{Q}(t) \quad (4)$$

193

194 where  $t$  is time and  $\Delta t$  is the river routing time step. The bolded notation is used for  
195 vectors and matrices. All matrices are square.  $\mathbf{I}$  is the identity matrix.  $\mathbf{N}$  is the river  
196 network connectivity matrix which has a value of one in element  $N_{i,j}$  if reach  $j$  flows  
197 into reach  $i$  and zero elsewhere.  $\mathbf{C}_1$ ,  $\mathbf{C}_2$  and  $\mathbf{C}_3$  are parameter matrices which depend on  
198 Muskingum  $k$ ,  $x$  and time step  $\Delta t$ .  $\mathbf{Q}(t)$  is a vector of outflows from river reaches,  
199 and  $\mathbf{Q}^e(t)$  is a vector of lateral inflows to these reaches from land surface runoff or  
200 groundwater inflow. The number of river quad-tree cells – here 24,264 – is used for  
201 dimension of all vectors and matrices, each element of the vectors corresponding to one  
202 river cell.

203 Provided with a vector of lateral inflows  $\mathbf{Q}^e(t)$ , RAPID calculates the flow and volume  
204 of water in all reaches of a river network, therefore allowing coupling of a river network  
205 to most land surface models and groundwater models. A different value for the  
206 parameters  $k$  and  $x$  of the Muskingum method can be assigned for each river quad-tree  
207 cell, and RAPID uses two vectors  $\mathbf{k}$  and  $\mathbf{x}$  as input which are used to compute the values  
208 of the matrices  $\mathbf{C}_1$ ,  $\mathbf{C}_2$  and  $\mathbf{C}_3$ . However, before routing with RAPID, horizontal surface

209 and subsurface routing is needed to transport runoff from a land surface cell to its  
 210 corresponding river cell. In the present study, this surface and subsurface routing is done  
 211 by MODCOU and RAPID replaces only the river modeling of MODCOU.  
 212 The connectivity information that already exists between the river cells in the SIM-  
 213 France river network is used to create the network connectivity matrix  $\mathbf{N}$  needed by  
 214 RAPID and described in David et al. [2011].  
 215 RAPID uses an automated parameter estimation procedure which, given lateral inflow  
 216  $\mathbf{Q}^e$  everywhere in the river network, and gage measurements at some locations,  
 217 determines a best set of parameters based on a square error cost function. As in David et  
 218 al. [2011], the search for optimal vectors of parameters  $\mathbf{k}$  and  $\mathbf{x}$  is made by determining  
 219 two multiplying factors  $\lambda_k$  and  $\lambda_x$  such that:

220

$$221 \quad \forall j \in [1, 24264] \quad k_j^\rho = \lambda_k \cdot \frac{L_j}{c^0} \quad , \quad x_j^\rho = \lambda_x \cdot 0.1 \quad (5)$$

222

223 where  $j$  is the index of a quad-tree river cell,  $k_j^\rho$  and  $x_j^\rho$  are its Muskingum parameters,  
 224  $L_j$  is the flow distance within a river cell and  $c^0 = 1km \cdot h^{-1} = 0.28m \cdot s^{-1}$  is a reference  
 225 celerity for the flow wave. The parameters  $k_j^\rho$  and  $x_j^\rho$  are the same developed in As in  
 226 David et al. [2011] and are referred to as  $\rho$  parameters in the following. In this study, the  
 227 size of the side of each quad-tree river cell was used as an approximation of its flow  
 228 distance. The value of  $\lambda_x$  is bounded by the interval  $[0, 5]$  since the Muskingum method  
 229 is stable only for  $x \in [0.0, 0.5]$ , as shown in Cunge [1969]. The two scalars  $\lambda_k$  and  $\lambda_x$  are

230 determined such that the corresponding vectors  $\mathbf{k}$  and  $\mathbf{x}$  minimize the value of an  
231 optimization criteria, or cost function. At the end of the optimization procedure, one  
232 couple  $(\lambda_k, \lambda_x)$  is determined for a given part of the network. The values of  $\lambda_k$  and  $\lambda_x$  can  
233 be determined for the entire study domain, or for sub-basins. If a sub-basin is located  
234 downstream of another sub-basin, observations at a gaging station are used to provide the  
235 upstream flow. Therefore, the delineation of sub-basins has to be consistent with the  
236 location of available gage measurements.

237 The optimization procedure uses a line-search algorithm called the Nelder-Mead method  
238 [*Nelder and Mead*, 1965] to determine the two scalars  $\lambda_k$  and  $\lambda_x$ .

239 The use of RAPID within SIM-France allows for flow and volume calculation at each  
240 river cell, the river-aquifer interactions are computed more properly, and RAPID allows  
241 for the ready inclusion of additional river gages to be used for calibration.

242

### 243 **3. Application of RAPID in France**

#### 244 **3.1. Optimization of RAPID parameters**

245 This section focuses on the optimization of RAPID parameters with various options used  
246 for  $k_j$  and  $x_j$ , for the optimization cost function and for the spatial variability of the  
247 optimization. In order to simplify the optimization procedure and to ensure its  
248 repeatability, the parameter estimation of RAPID was run uncoupled from SIM-France.  
249 Lateral and groundwater inflow to the river network were obtained from a simulation  
250 using the standard version of SIM-France (without RAPID) augmented with improved  
251 physics of the land surface parameterization of ISBA developed in Quintana-Seguí et al.  
252 [2009]. Daily gage measurements from the French HYDRO database [SCHAPI, 2008]  
253 were used for the parameter estimation as well as for comparison with daily-averaged  
254 flow calculations .

255 The period of interest of the present study is August 1<sup>st</sup> 1995 to July 31<sup>st</sup> 2005. However,  
256 the parameter estimation was performed using five months of the first winter (November  
257 1<sup>st</sup> 1995 to March 31<sup>st</sup> 1996). As part of the first year (1995-1996) was used for  
258 calibration, separate statistical results are presented for 1995-1996 and 1995-2005.

259 RAPID is run using a 30-minute time step and forced with 3-hourly lateral inflow  
260 volumes; daily averages of computed discharge are compared with daily observations at  
261 gage locations. There are 907 stations within the river network of SIM-France but only  
262 493 of these have daily measurements every day during the first year (August 1<sup>st</sup> 1995 to  
263 July 31<sup>st</sup> 1996). Amongst the 493 available stations, the best 291 were utilized for  
264 optimization of RAPID parameters. The criterion used for the selection of the 291 best

265 stations is a Nash efficiency [Nash and Sutcliffe, 1970] better than 0.5 in the existing  
266 SIM-France model (without RAPID) over 1995-1996. This selection excludes the gages  
267 that are affected either by dams or by water diversions, and thus avoids unrealistic model  
268 parameters due to anthropogenic modifications of river flow. Therefore, the proposed  
269 routing scheme is optimized at locations where the previous routing scheme already  
270 performed well.

271 The optimization is first performed on all rivers of the domain, therefore obtaining unique  
272 values of  $\lambda_k$  and  $\lambda_x$  for all 24,264 river quad-tree cells. However, such an optimization  
273 may not capture the variability between river basins and within sub-basins, due to the  
274 various slopes or soil types. Therefore, the optimization procedure was also run  
275 independently within the seven main river basins of France shown in Figure 5a) and  
276 within the twenty sub-basins shown in Figure 5b).

277 In order to limit the effect of the initial state of the system at the beginning of the  
278 optimization procedure, the initial flows on 01 November 1995 were estimated using a  
279 simple run of RAPID. This estimation was obtained through running the routing model  
280 from 01 August to 31 October 1995 with uniform values of  $\lambda_k$  and  $\lambda_x$  over the study  
281 domain and initial flows  $0 \text{ m}^3/\text{s}$  for all river cells on 01 August 1995.

282 The results of a parameter estimation procedure depend slightly on the initial guess for  
283 the parameters. Therefore, three different sets of initial guesses for  $\lambda_k$  and  $\lambda_x$  were used:  
284  $(\lambda_k, \lambda_x) = (2, 3)$ ,  $(\lambda_k, \lambda_x) = (4, 1)$  or  $(\lambda_k, \lambda_x) = (1, 1)$ . The numerical values of these three  
285 sets have no particular meaning and serve to start the optimization with a different initial  
286 value for  $\mathbf{k}$  and  $\mathbf{x}$ . Each set of initial guesses leads to slightly different results for the

287 optimal  $\lambda_k$  and  $\lambda_x$ . Out of the three sets of optimal  $\lambda_k$  and  $\lambda_x$  that are determined for  
288 each sub-basin, only the best is kept. This selection is based on the set of parameters that  
289 leads to the smallest value of the optimization cost function.

290 Once the optimization procedure was completed, RAPID was run with SIM-France over  
291 a 10-year period, from August 1995 to July 2005. This section focuses on the first year  
292 while the next section studies the ten-year run. In order to compare the overall  
293 performance of both routing models on the river network, the Nash efficiency and the  
294 root mean square error (RMSE) were calculated for each of the 493 gaging stations over  
295 1995-1996. These criteria are sorted and comparisons between the computations of  
296 MODCOU and those of RAPID are shown in Figure 6. The two graphs in Figure 6 do  
297 not allow comparing both models at each gaging station since the criteria are sorted, but  
298 they depict the overall relative performance of both models. Table 1 shows the average  
299 Nash efficiencies and RMSEs obtained by the original version of SIM-France and with  
300 RAPID using various optimization procedures. During 1995-1996, 382 stations have a  
301 positive efficiency using the standard version of SIM-France. The averages presented in  
302 Table 1 show the best 382 values for both efficiency and RMSE, but similar patterns are  
303 found for all 493 values or the best 291 values.

304 In its original formulation, the criterion used in the optimization of RAPID is based on a  
305 square error cost function  $\phi_1$ . This function is the sum of the square errors between daily  
306 measurements  $Q_i^s(t)$  and daily-averaged  $\overline{Q}_i(t)$  flow computations for several river  
307 gaging stations  $i$  and for everyday of a given period of time  $[t_o, t_f]$ , as shown in  
308 Equation (6).

309

310

$$\phi_1(\mathbf{k}, \mathbf{x}) = \sum_{t=t_o}^{t=t_f} \sum_{i=1}^{i=291} \left[ \frac{\overline{Q}_i(t) - Q_i^g(t)}{f} \right]^2 \quad (6)$$

311

312 where the summation is made daily and at river cells with active gaging stations only.  $t_o$

313 and  $t_f$  are respectively the first day and last day used for the calculation of  $\phi_1$ .

314  $i \in [1, 291]$  is the index for gaging stations. The model parameter vectors  $\mathbf{k}$  and  $\mathbf{x}$  are

315 kept constant within the temporal interval  $[t_o, t_f]$ , and the cost function is calculated

316 several times with different sets of parameters during the optimization procedure.  $f$  is a

317 scalar that allows  $\phi_1$  to be of the order of magnitude of  $10^1$  which is helpful for automated

318 optimization procedures. One can notice that, in  $\phi_1$ , a given fractional error (5% error

319 between modeled and measured flow for example) for two stations with different orders

320 of magnitude for river flow influences the cost function differently. A small fractional

321 error on a gaging station with a large flow penalizes the cost function more than the same

322 fractional error on a gaging station with small flow. The Nash efficiency  $E$  is highly

323 influenced by the difference between the model computation and the mean average flow,

324 as shown in Equation (7):

325

326

$$E = 1 - \frac{\sum_{t=t_o}^{t=t_f} [Q_i^g(t) - \overline{Q}_i(t)]^2}{\sum_{t=t_o}^{t=t_f} [Q_i^g(t) - \langle Q_i^g \rangle]^2} \quad (7)$$

327

328 where  $\langle Q_i^g \rangle$  is the average daily flow observed at the gaging station  $i$  over a long the  
 329 interval  $[t_o, t_f]$ . Therefore, the use of  $\phi_1$  penalizes the Nash efficiency. In order to avoid  
 330 that the order of magnitude of flow at each gaging station influences their weight in the  
 331 cost function, a new cost function  $\phi_2$  is created, as shown in Equation (8):

332

$$333 \quad \phi_2(\mathbf{k}, \mathbf{x}) = \sum_{t=t_o}^{t=t_f} \sum_{i=1}^{i=291} \left[ \frac{\overline{Q}_i(t) - Q_i^g(t)}{\langle Q_i^g \rangle} \right]^2 \quad (8)$$

334

335 The new cost function  $\phi_2$  results in the improvements shown in Table 1 and Figure 6  
 336 where the Nash efficiencies and RMSEs obtained with RAPID using  $\phi_2$  are better than  
 337 with  $\phi_1$ . Overall, the Nash efficiencies and the RMSEs in RAPID are comparable while  
 338 not as good as those obtained with the routing scheme of the original SIM-France.  
 339 Therefore, the choice of the cost function is crucial to determining a set of optimal  
 340 parameters.

341 In order to estimate the effect of more spatial variability in the optimization of RAPID  
342 parameters, the parameter estimation was done on different basins and sub-basins. Figure  
343 7 shows the sorted Nash efficiencies and RMSEs obtained with three degrees of spatial  
344 variability using  $\phi_2$  as the cost function. These spatial variabilities include “France”  
345 which has uniform parameters over the whole domain, “basins” for the 7 river basins of  
346 Figure 5a) (Adour, Garonne, Loire, Seine, Meuse, Rhône and Hérault) and “sub-basins”  
347 where the major river basins have been divided into 20 sub-basins as shown in Figure  
348 5b). The increase in spatial variability of parameters improves the efficiency while the  
349 RMSE remains almost constant, but the improvement in efficiency is limited compared to  
350 that triggered by a change in the cost function. The values of parameters  $\lambda_k$  and  $\lambda_x$   
351 obtained with the parameter estimation procedure using the second cost function are  
352 shown in Table 2.

353 The number of gaging stations in a basin can be divided by the number of river cells in  
354 the basin to calculate an observability ratio  $O$ , as done in Table 2. This ratio ranges from  
355  $O = 22$  on the Ardèche River to  $O = 1307$  downstream of the Seine River, showing a wide  
356 spread in density of observations. The Seine River, of great interest to the French  
357 community, has a higher resolution and therefore more river cells in SIM-France than any  
358 other basin – all the river cells are of size 1 km – which explains the lower observability  
359 ratio. Unrealistically low results are obtained for  $\lambda_k$  in the downstream part of the Seine  
360 River and for the Ardèche River Basin. The former can be explained by a limited amount  
361 of stations used for optimization in the downstream part of the Seine River Basin (only  
362 one station). The latter may be due to either the basin being too small, or to the

363 observation ratio being too high and therefore over constraining the optimization  
 364 procedure. The observability ratio is therefore a driver for the quality of the optimization.  
 365 These unrealistic values for  $\lambda_k$  may partly explain why the improvement between  
 366 optimization for 7 basins and for 20 sub-basins is very limited. As expected, the  
 367 optimization procedure converges to the largest values of the parameter  $\lambda_k$  for the Seine  
 368 and Loire rivers which are the slowest rivers. For each of the 7 major basins, the value of  
 369  $\lambda_k$  is bounded by the value of  $\lambda_k$  for each of their corresponding sub-basins. Also, one  
 370 can notice that upstream parts of a basin are usually faster (lower  $\lambda_k$ ) than downstream  
 371 parts as can be seen for the upstream part of the Loire Basin, and for the Allier Basin  
 372 which are located in high topography areas. This shows that – as expected – topography  
 373 plays an important role in the travel time of flow waves. This motivates a final  
 374 experiment where RAPID model parameters are estimated based on topography as shown  
 375 in Equation (9).

376

$$\forall j \in [1, 24264] \quad k_j^\sigma = \lambda_k \cdot \alpha \cdot \frac{d_{i,j}}{\sqrt{s_{i,j}}} \quad , \quad x_j^\sigma = \lambda_x \cdot 0.1 \quad (9)$$

378

379 This formulation of  $k_j^\sigma$  is adapted from Equation (1) which is used to determine the  
 380 location of isochrone zones. In the following, the parameters  $k_j^\sigma$  and  $x_j^\sigma$  of Equation (9)  
 381 are referred to as  $\sigma$  parameters. Table 1 shows the average efficiencies and RMSEs  
 382 obtained with  $\sigma$  parameters using  $\phi_1$  and  $\phi_2$  uniformly over France, and with

383  $\sigma$  parameters over the 7 major basins using  $\phi_2$ . Figure 8 shows the sorted efficiencies  
384 and RMSEs obtained with  $\sigma$  parameters using  $\phi_1$  and  $\phi_2$  uniformly over France. From  
385 Table 1 and Figure 8 one can conclude that regardless of the optimization cost function  
386 used,  $\sigma$  parameters allow to obtain better results than  $\rho$  parameters. Therefore, taking  
387 topography into account in the travel time of the flow wave is advantageous. Similarly,  
388 regardless of the parameters used and of the spatial resolution of the optimization,  
389 optimizing using  $\phi_2$  allows obtaining better average results than with  $\phi_1$ . The average  
390 results obtained using  $\sigma$  parameters and  $\phi_2$  are comparable (slightly better) than those  
391 obtained by the original routing module of SIM-France. One should note however, that  
392 the best stations with MODCOU are better than the best with RAPID, while the worse  
393 stations in MODCOU are worse than the worst in RAPID. This suggests a flattening of  
394 the curves most likely due to equal treatment of all stations in the  $\phi_2$  cost function.  
395 Finally, regardless of the cost function used in optimization or the set of parameters  
396 ( $\sigma$  and  $\rho$ ) basin and sub-basin optimizations have a limited effect on overall  
397 performance of RAPID. This suggests that at the spatial scale of France as it is modeled  
398 in SIM-France, there is little inter-basin and intra-basin variability of river routing  
399 parameters.

### 400 **3.3. Comparison of routing schemes over 10 years**

401 Over 1995-2005, only 3 gaging stations have a full daily record. Therefore, results  
402 presented in this section are using stations with gaps in observations; efficiency and  
403 RMSE are calculated only at times when measurements are available. A threshold of  
404 70% of daily measurements available over 1995-2005 leads to selecting 493 gaging

405 stations. These stations differ slightly from the ones used in 1995-1996. Out of the 493  
406 stations that have full daily record in 1995-1996, 436 stations are included in the 1995-  
407 2005 period. Similarly, out of the best 291 stations that have full daily record in 1995-  
408 1996, 261 are included in 1995-2005. During 1995-2005, 427 out of the 493 stations  
409 have a positive efficiency using the standard version of SIM-France. Table 1 shows  
410 average statistics for 1995-2005 for the best 427 values for both efficiency and RMSE,  
411 but similar patterns are found for all 493 values. The conclusions drawn in Section 3.2.  
412 regarding the sets of parameters, the cost functions and the spatial resolution of the  
413 optimization are still valid for the ten-year simulation. However, one should note that  
414 over ten years, MODCOU performs slightly better than RAPID using the best set of  
415 options. This may be explained by the slightly different stations used for the 5-month  
416 optimization and for the ten-year study. However, five months of the first year seem to  
417 be sufficient to capture RAPID parameters and allow comparable performance between  
418 MODCOU and RAPID over ten years. Figure 9 shows the sorted efficiencies and  
419 RMSEs obtained with MODCOU and with RAPID with  $\sigma$  parameters optimized  
420 uniformly over France using  $\phi_2$ . Globally the two models perform comparably although,  
421 similarly to 1995-1996 results, the best stations are degraded and some stations with low  
422 but positive efficiency are improved. Figure 10 shows observations and modeled  
423 hydrographs during 1995-1996 and 1995-2005 for the Meuse River at Stenay (the  
424 location of this station is shown in Figure 11) in which MODCOU and RAPID are almost  
425 indiscernible. One should note, however, that in all the hydrographs plotted (not shown)  
426 the timing of events differs slightly between the two models, none of which being

427 consistently better than the other regardless of the optimization options as expected from  
428 results shown in Table 1 and Figure 9.

429 Figure 11 shows a spatial comparison of efficiencies obtained over France.

430 Improvements and degradations of statistical results between MODCOU and RAPID  
431 have no particular spatial patterns. Overall, the discharge simulated by MODCOU and  
432 RAPID are similar in RMSE and Nash efficiency. This similarity can be explained by  
433 the strong dependence of discharge calculations on the lateral inflow forcing which is the  
434 same for both river routing schemes. Furthermore, the routing equations used in  
435 MODCOU and RAPID are comparable (the linear reservoir equation in SIM-France is a  
436 simplified Muskingum equation, given  $x=0$ ). The addition of RAPID to SIM-France can  
437 be regarded as advantageous since RAPID provides with flow and volume of water in all  
438 the cells of the river network and provides flexibility in the number and location of river  
439 gages, which was not the case in the original version of SIM-France.

### 440 **3.2. Influence of dams on river flow**

441 RAPID does not have a specific physical model for treatment of dams. However, the  
442 model is designed such that observations at gaging stations can easily be substituted for  
443 upstream flow. This capability is not available in the routing scheme of MODCOU and  
444 is useful for a gaging station located at the outlet of a dam because the flows discharging  
445 from man-made infrastructures reflect human decisions. In France, the quality of flow  
446 calculations of the Rhône River (at Beaucaire) is influenced by the dam at the outlet of  
447 Lake Geneva. Figure 12 demonstrates the influence of forcing with observations at  
448 Pougny (downstream of the dam) on the calculation of flow at the outlet of the Rhône  
449 River Basin. The gaging station a Pougny is the outlet of the “Rhône upstream” basin in

450 Figure 5b) and is also shown on Figure 11. The first year (August 1<sup>st</sup> 1995 – July 31<sup>st</sup>  
451 1996) was used and RAPID was run uncoupled from MODCOU. Forcing with  
452 observations at Lake Geneva increases the Nash Efficiency from 0.49 to 0.62 at  
453 Beaucaire, the outlet of the Rhône basin.  
454

455 **4. Conclusions**

456 The river routing in SIM-France is done by MODCOU which uses groups of cells called  
457 isochrone zones for its computations and does not directly compute flow and volume of  
458 water for each cell of its quad-tree river network. The use of isochrones limits the  
459 flexibility in the number and location of river gages. The work in this paper presents the  
460 replacement of the river routing module in MODCOU by the river network model called  
461 RAPID. Information on the network connectivity between the quad-tree river cells of  
462 SIM-France is readily available in tables that relate upstream and downstream cells.  
463 These tables can be used directly to create the network matrix of RAPID. A ten-year  
464 study of river flow in Metropolitan France is presented comparing RAPID and the  
465 routing module of MODCOU. An automated procedure for determining optimal model  
466 parameters is available in RAPID and various options for the estimation of the  
467 parameters are investigated. Sub-basin optimization increases model performance but its  
468 influence is much smaller than the choice of the cost function. A cost function was  
469 developed that normalizes the square-error between observations at each river gage and  
470 RAPID computations by the average flow at the gage. This cost function is found to  
471 globally improve the Nash efficiency of computed flow in all gages. We suggest that this  
472 is due to the average flow having an influence on the computation of the Nash efficiency.  
473 Therefore, the use of an appropriate criterion for quantifying the quality of river flow as  
474 the cost function for the optimization procedure helps the betterment of model  
475 computations. Also, flow wave celerities included in the temporal parameter of the  
476 Muskingum method benefit from taking into account topography when compared to a  
477 simple constant celerity formulation. Overall, the computation obtained with the addition

478 of RAPID are comparable to those of the original river routing module in SIM-France.  
479 We consider the addition of RAPID as advantageous since flow and volume of water is  
480 directly computed for each cell of the quad-tree river network. The formulation of  
481 RAPID allows for easily substituting observed flows for the upstream calculated flow,  
482 which is advantageous when considering a man-made infrastructure as was shown for the  
483 Rhône River.  
484

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498

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591

592

593 Table 1 Average efficiencies and average root mean square errors for MODCOU and for RAPID with 7 different sets of  
 594 parameters. Best 382 values for 1995-1996 and best 427 values for 1995-2005.

Vector of parameters used in optimization	Optimization cost function	Spatial optimization	Model	1995-1996		1995-2005	
				Best 382 values		Best 427 values	
				Average efficiency	Average RMSE	Average efficiency	Average RMSE
N/A	N/A	N/A	MODCOU	0.617	8.37	0.650	12.67
$\rho$	$\phi_1$	France	RAPID	0.581	8.85	0.614	13.64
$\rho$	$\phi_2$	France	RAPID	0.611	8.39	0.638	13.07
$\rho$	$\phi_2$	7 basins	RAPID	0.615	8.40	0.640	13.06
$\rho$	$\phi_2$	20 sub-basins	RAPID	0.615	8.38	0.637	13.04
$\sigma$	$\phi_1$	France	RAPID	0.602	8.63	0.632	13.25
$\sigma$	$\phi_2$	France	RAPID	0.620	8.37	0.647	12.91
$\sigma$	$\phi_2$	7 basins	RAPID	0.624	8.32	0.646	12.92

595

596 Table 2 Results of optimization procedure using  $\rho$  parameters and the  $\phi_2$  cost function

Basin	Sub-basin	Number of river cells	Number of stations	Observability ratio	Optimized $\lambda_k$	Optimized $\lambda_x$	Basin	Sub-basin	Number of river cells	Number of stations	Observability ratio	Optimized $\lambda_k$	Optimized $\lambda_x$
France	all basin	24264	291	83.4	0.366	0.237	Loire	Loire downstream	1763	25	70.5	0.436	0.091
Adour	all basin	666	9	74.0	0.375	0.313	Seine	all basin	5115	41	124.8	0.531	0.234
Garonne	all basin	2985	58	51.5	0.294	0.009	Seine	Seine upstream	2919	30	97.3	0.579	0.145
Garonne	Garonne upstream	558	5	111.6	0.160	0.420	Seine	Oise	889	10	88.9	0.469	3.766
Garonne	Tarn	356	8	44.5	0.152	0.674	Seine	Seine downstream	1307	1	1307.0	0.031	4.984
Garonne	Lot	369	10	36.9	0.394	0.113	Meuse	all basin	832	3	277.3	0.383	0.059
Garonne	Dordogne	431	12	35.9	0.356	0.056	Rhône	all basin	3426	51	67.2	0.256	0.118
Garonne	Garonne downstream	1271	23	55.3	0.375	0.313	Rhône	Saône	1043	32	32.6	0.236	0.007
Loire	all basin	4138	88	47.0	0.414	0.197	Rhône	Ardèche	66	3	22.0	0.000	0.156
Loire	Vienne	706	20	35.3	0.386	0.145	Rhône	Rhône upstream	279	1	279.0	0.500	4.750
Loire	Allier	458	17	26.9	0.308	2.670	Rhône	Rhône downstream	2038	15	135.9	0.403	0.076
Loire	Loire upstream	541	12	45.1	0.391	0.305	Hérault	Hérault	101	3	33.7	0.375	4.813
Loire	Loir	670	14	47.9	0.453	0.273							

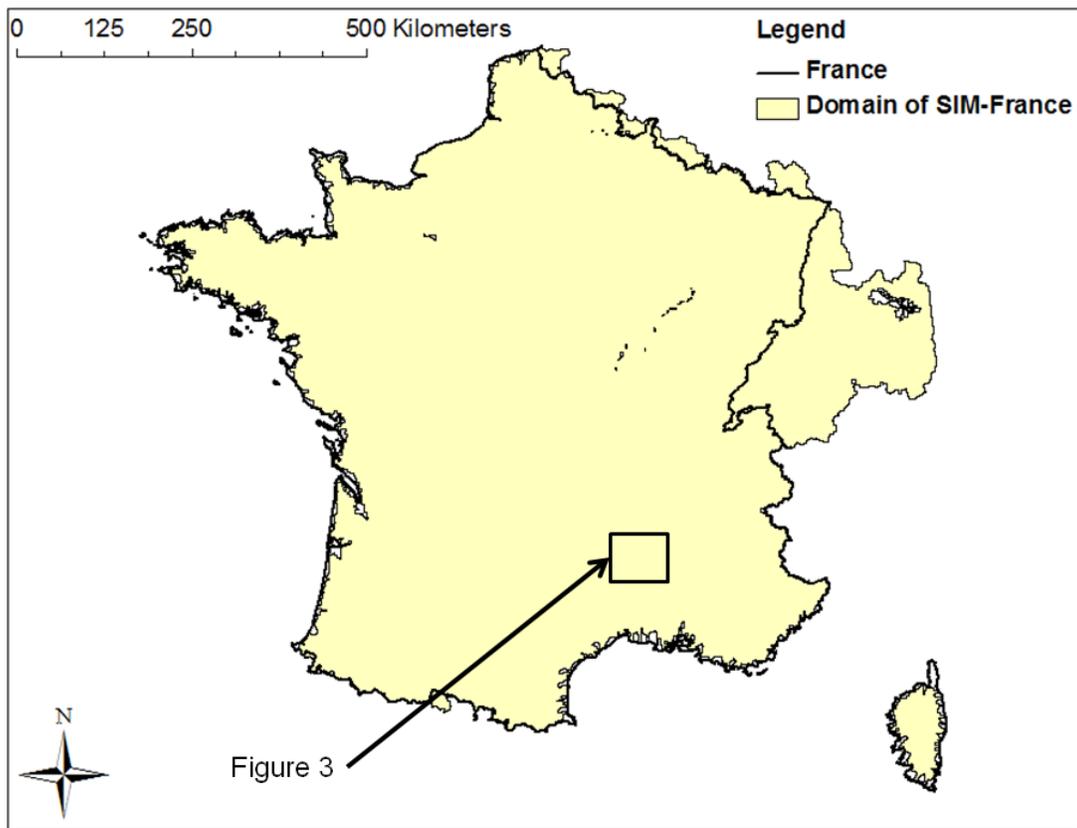
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598 **Captions to illustrations**

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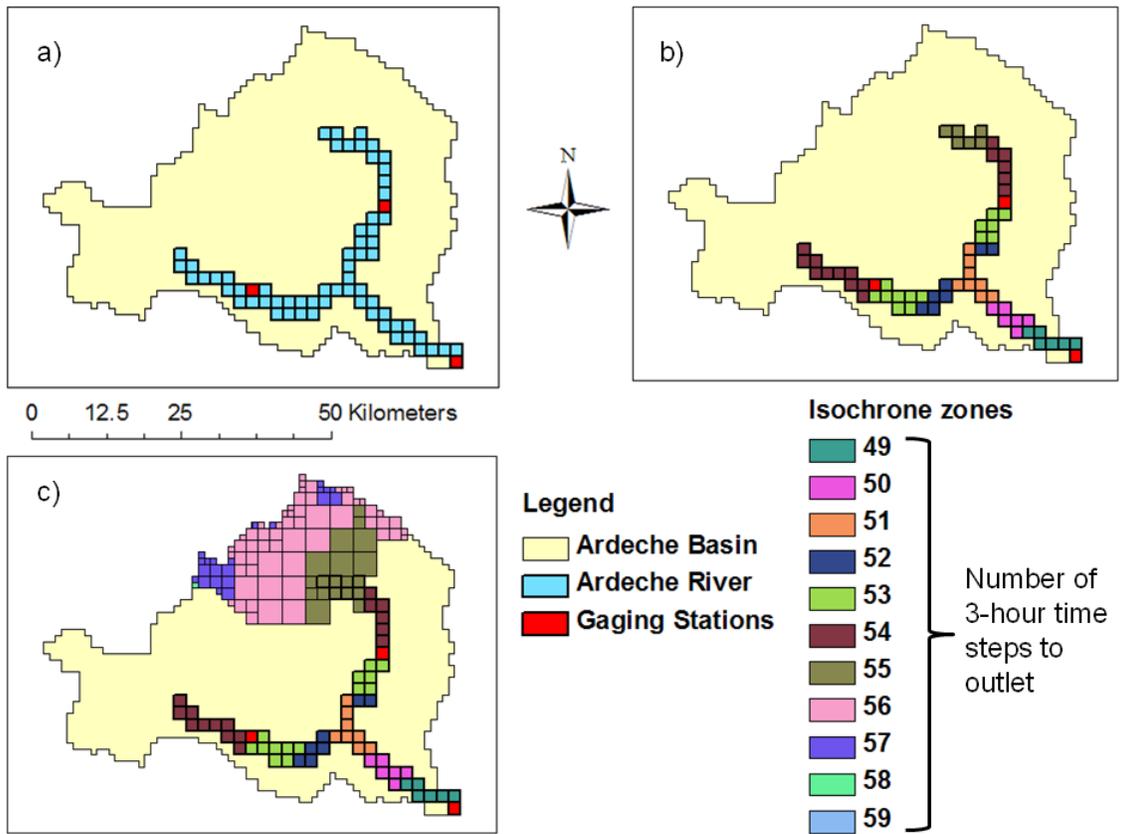




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606 Figure 2 France and computational domain of SIM-France

607

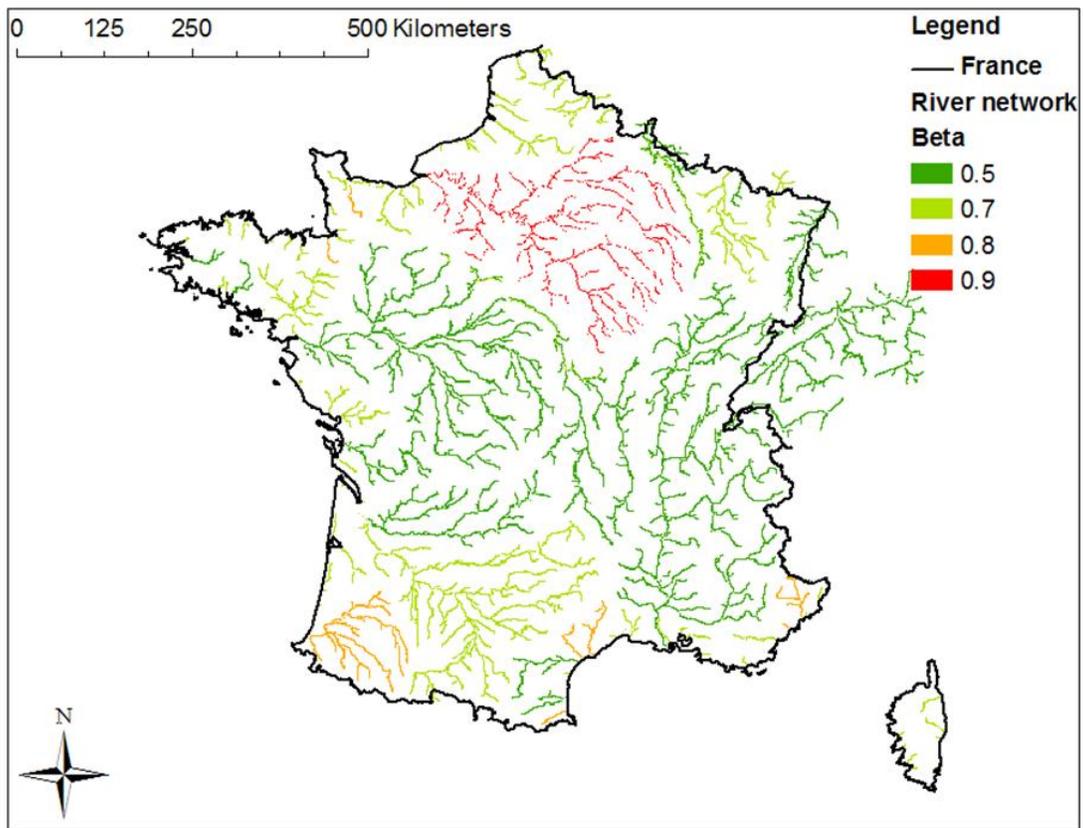


608

609 Figure 3 Surface and river isochrone zones in Ardèche Basin in MODCOU within

610 SIM-France

611

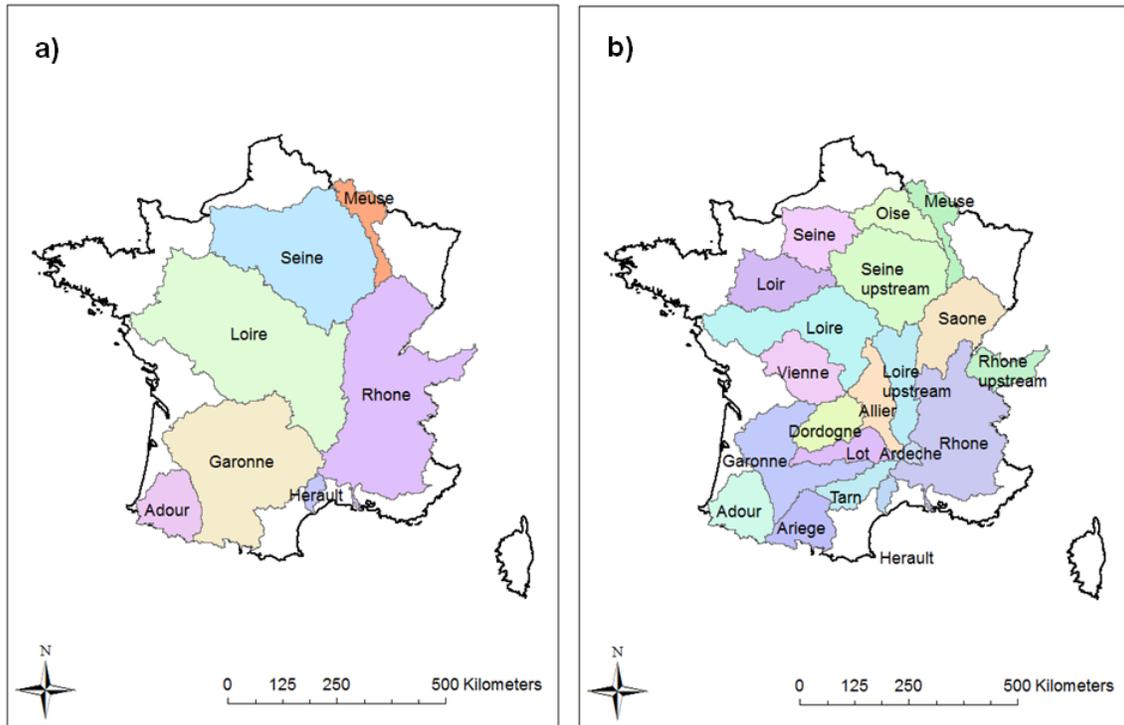


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613 Figure 4 Map of the parameter  $\beta$  used for river routing in MODCOU within SIM-

614 France

615

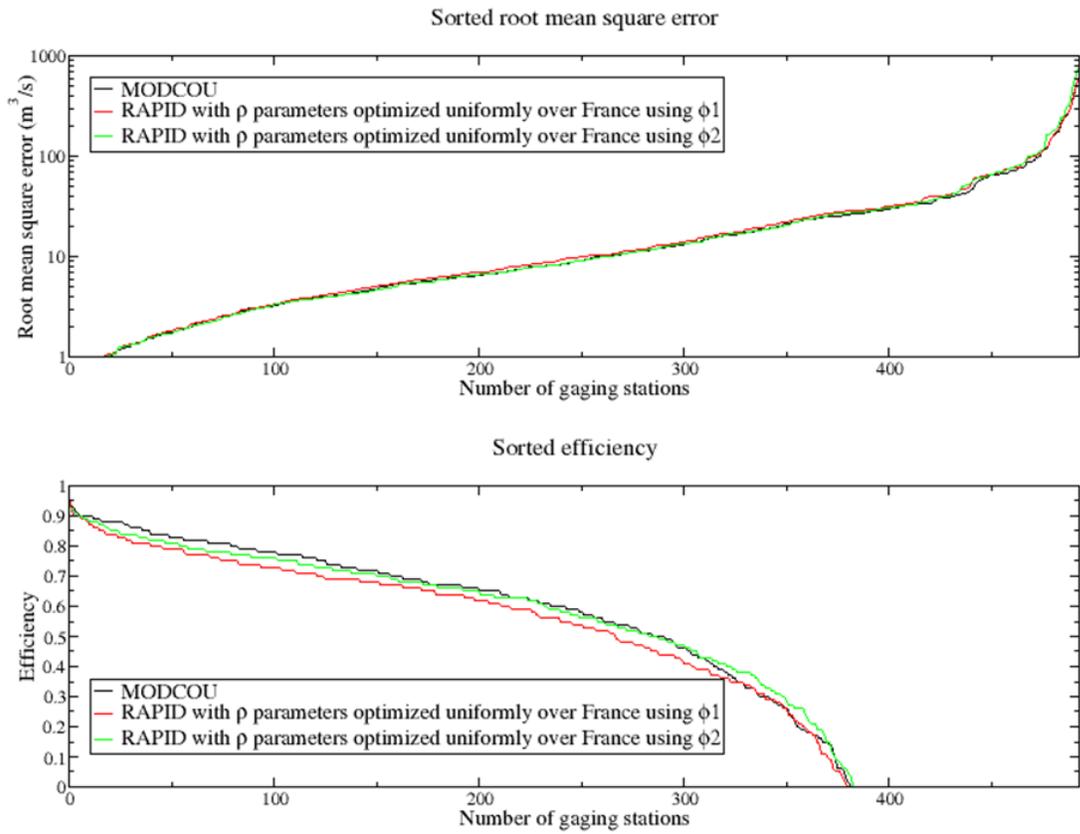


616

617 Figure 5 Basins treated independently during optimization of RAPID parameters in

618 SIM-France. a) Seven major river basins. b) Twenty sub-basins

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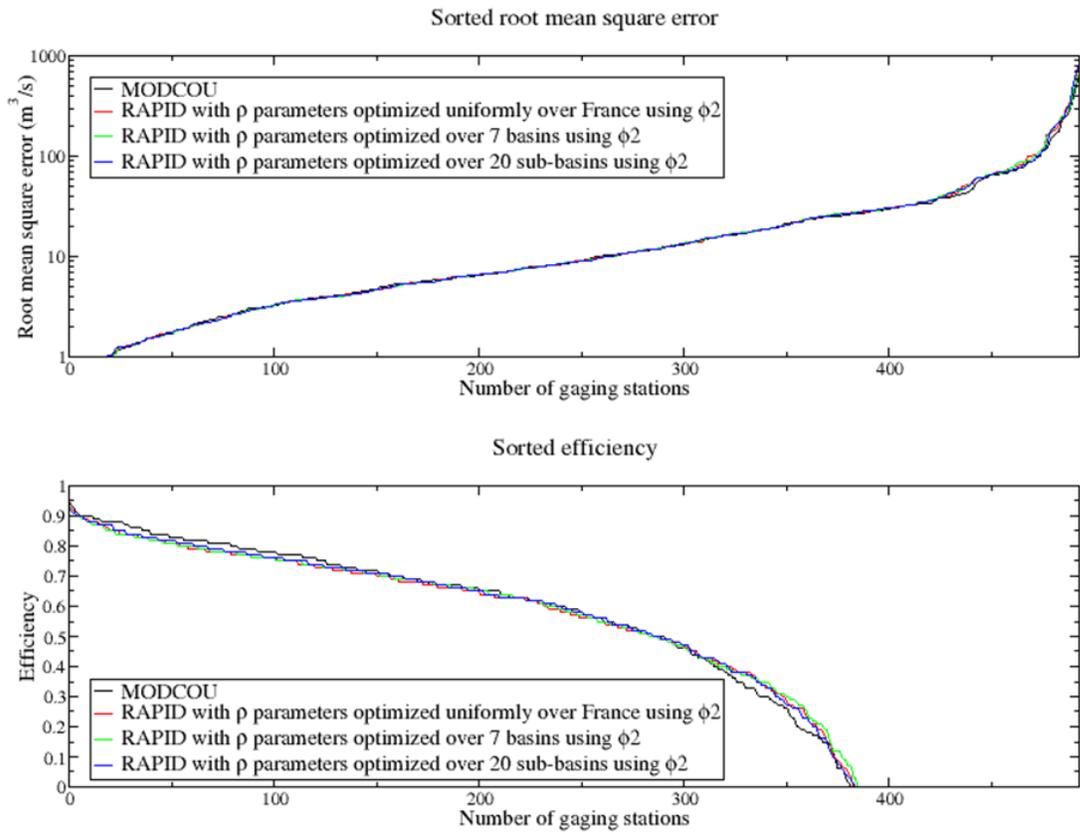
621 Figure 6 Comparison of sorted RMSEs and efficiencies for the year 1995-1996

622 between MODCOU and RAPID with  $\rho$  parameters optimized uniformly over France

623 using the original cost function  $\phi_1$  and using the new cost function  $\phi_2$

624

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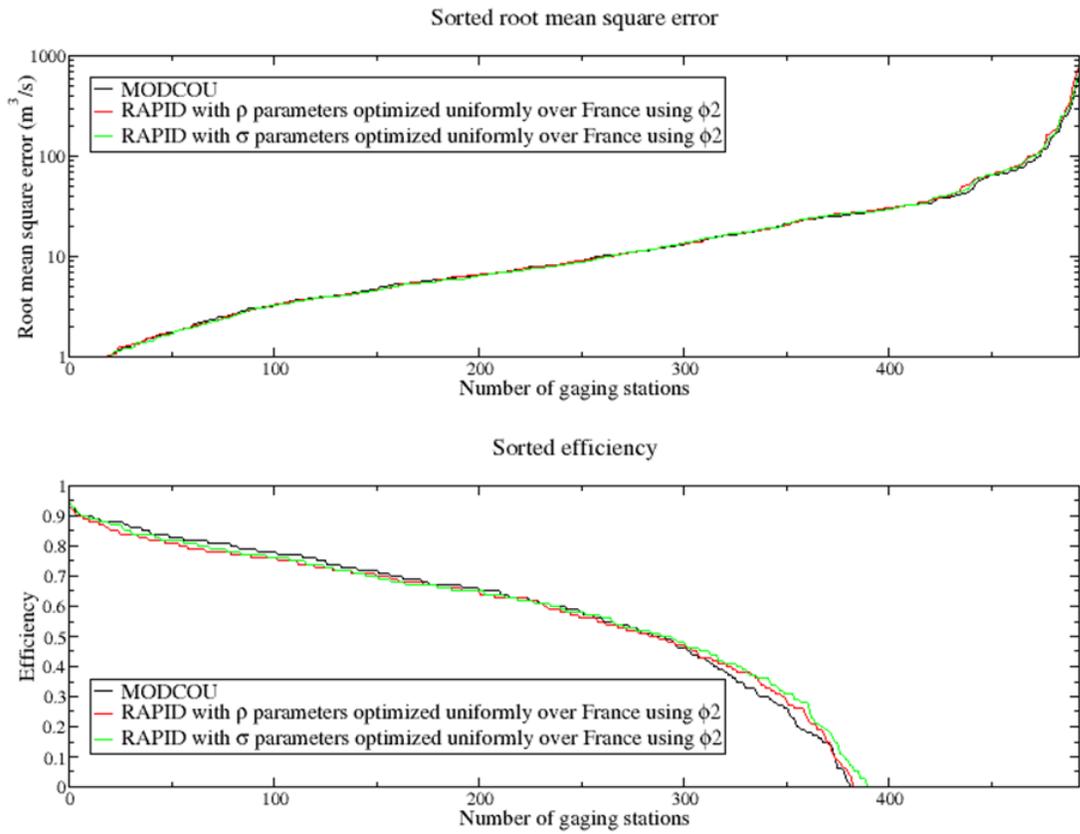


626

627 Figure 7 Effect of sub-basin optimization for RAPID on RMSEs and efficiencies

628 for the year 1995-1996 with  $\rho$  parameters using the new cost function  $\phi_2$

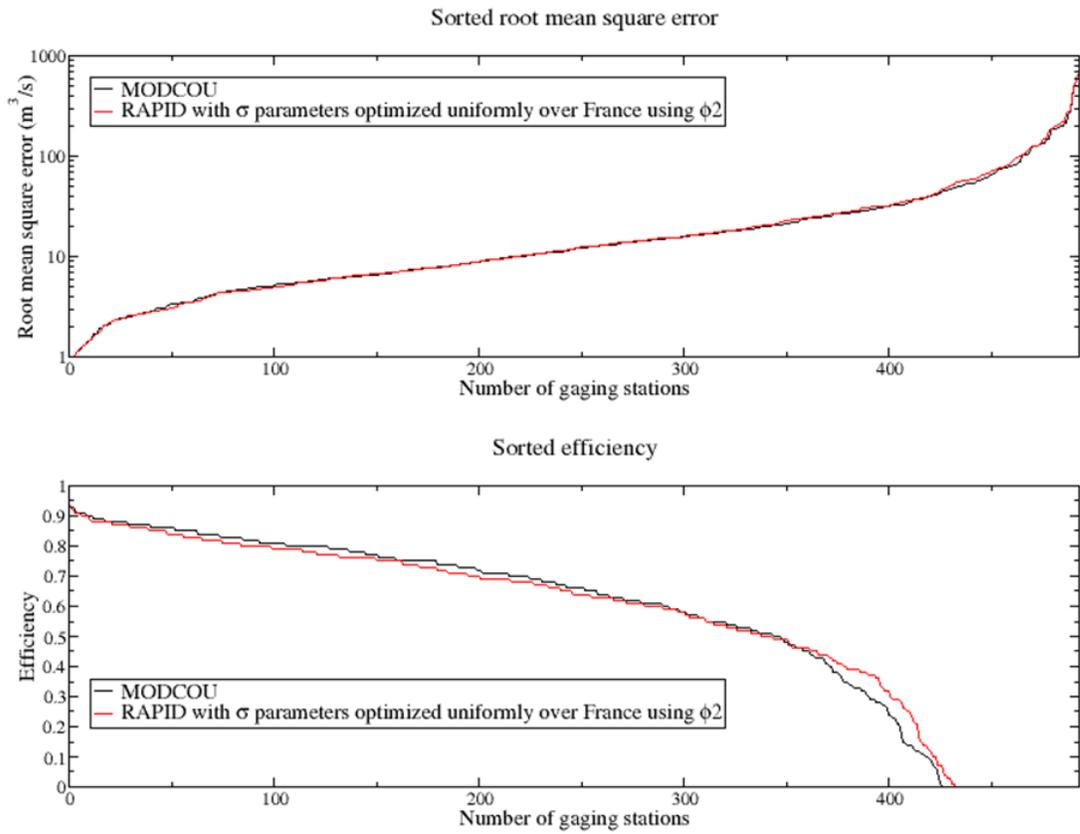
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630

631 Figure 8 Effect of set of parameters  $\rho$  and  $\sigma$  for RAPID on RMSEs and efficiencies

632 for the year 1995-1996 using the new cost function  $\phi_2$  uniformly over France

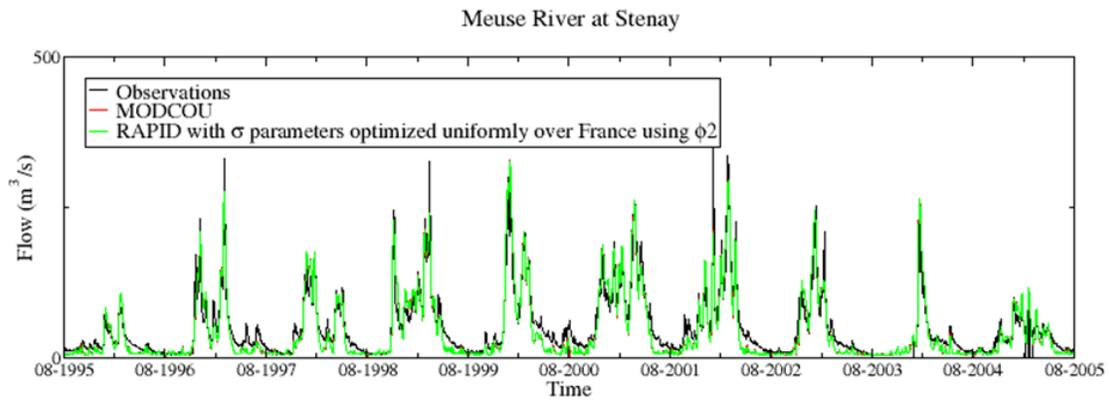
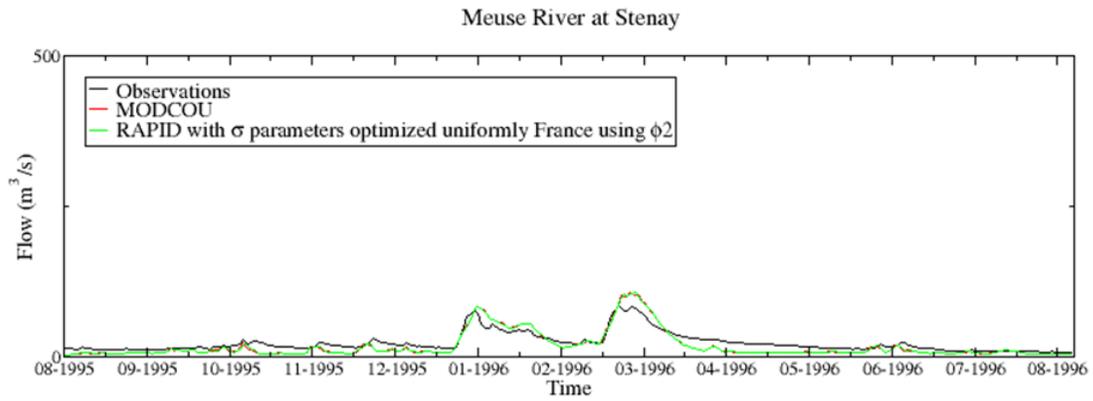


633

634 Figure 9 Comparison of sorted RMSEs and efficiencies for the years 1995-2005

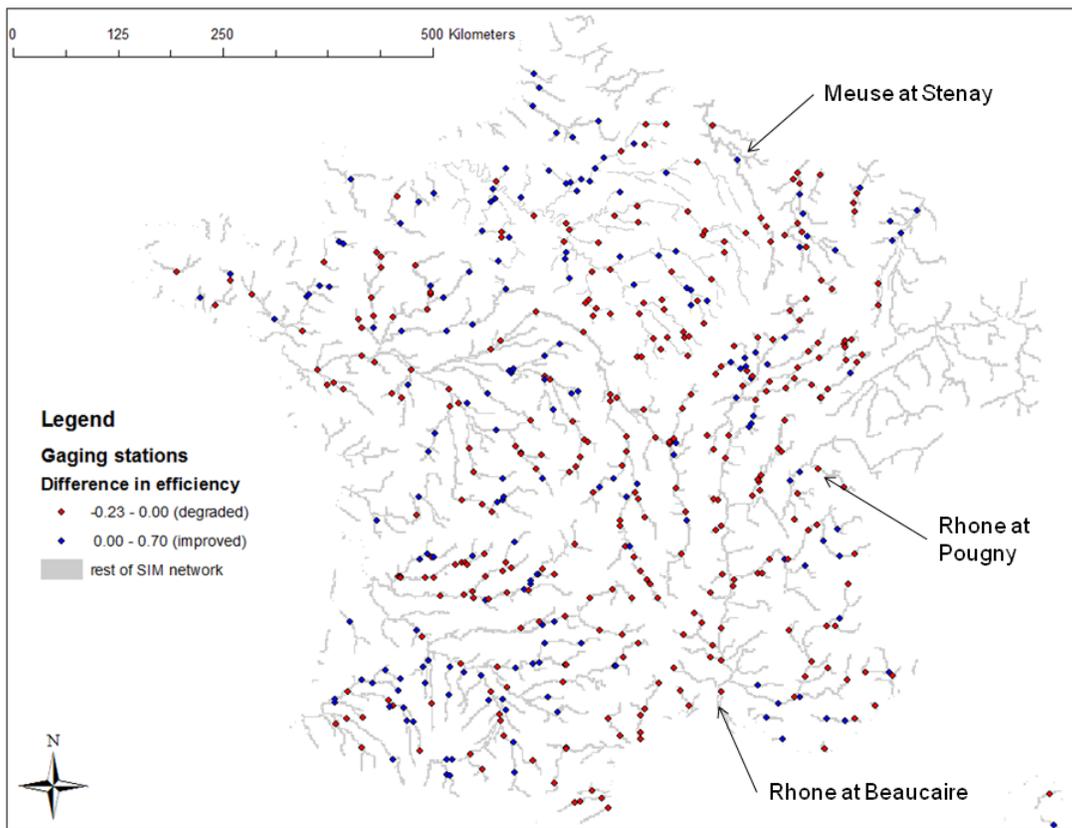
635 between MODCOU and RAPID with  $\sigma$  parameters optimized uniformly over France

636 using the new cost function  $\phi_2$



637

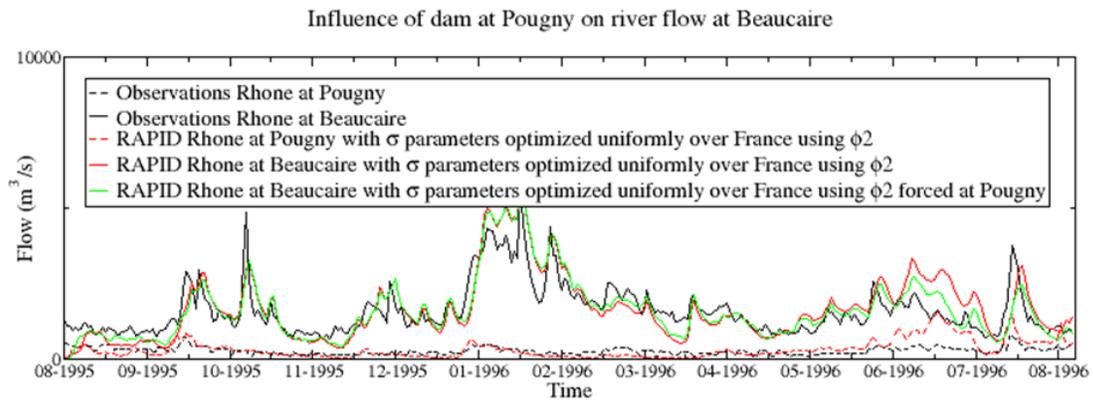
638 Figure 10 Comparison of 1995-1996 and 1995-2005 hydrographs for the Meuse  
 639 River at Stenay obtained by MODCOU and RAPID with  $\sigma$  parameters optimized  
 640 uniformly over France using the new cost function  $\phi_2$



641

642 Figure 11 Spatial difference of efficiencies obtained for the years 1995-2005  
 643 between RAPID using  $\sigma$  parameters optimized uniformly over France using the new cost  
 644 function  $\phi_2$  and MODCOU

645



646

647 Figure 12 Comparison of RAPID discharge calculation at the outlet of the Rhône

648 River (at Beaucaire) with and without forcing at the outlet of Lake Geneva (at Pougny).