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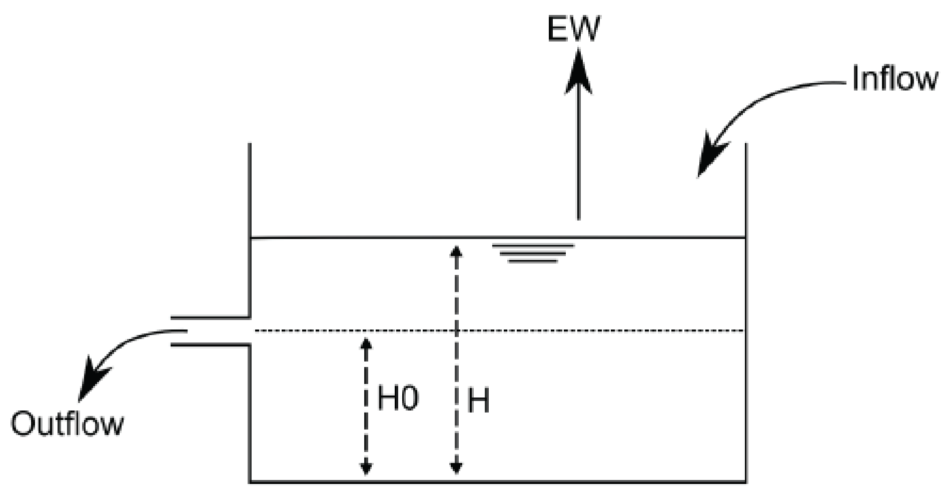
A brief feasibility study on the implementation of the Lakes routine into EFAS

Peter Salamon



EUR 23710 EN - 2008

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JRC 49533

EUR 23710 EN
ISSN 1018-5593

Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

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Abstract

In this brief feasibility study first the lake routine as implemented in LISFLOOD is presented and the required input parameters are discussed. Then, the effect of including the lakes using the Lago Maggiore, Lago di Como, Lago di Garda, Lake Leman, and Lake Constance is illustrated. It is shown, that including the lakes probably will give a better reproduction of the simulated hydrograph, but that a new calibration of the catchment parameters is required. Considering the spatial scale of EFAS, the results also suggest that only large lakes influence discharge sufficiently, so that a difference in EFAS performance is expected. Thus, two selection criteria are suggested, constraining the number of lakes to be implemented in the operational EFAS. As for most of these lakes the necessary input parameters for the lake routine are readily available its implementation into the operational EFAS appears feasible.

1. Introduction

Lakes can have a strong impact on the simulated discharge of rainfall-runoff models and thus also impact flood forecasts. The aim of this study is (a) to present the Lakes module as implemented in LISFLOOD, (b) to illustrate its effects on the modelled hydrographs and (c) to suggest a way forward on how to include the lakes into the European Flood Alert System (EFAS).

Section 2 outlines the theoretical background of the lake routine and its necessary parameters. In Section 3 we present example case studies of the effect of lakes on discharge using the Po, the Rhine and the Rhone catchment. We furthermore present a very brief sensitivity analysis. Section 3 discusses the available data and its collection for the implementation of the lake routine at a European scale. Finally, Section 4 presents the conclusions.

2. Implementation of the Lake routine in LISFLOOD

LISFLOOD is a spatially distributed, grid-based rainfall runoff and channel routing model. It simulates in a standard manner the most important hydrological processes occurring in a catchment, such as snow melt, infiltration, interception of rainfall, leaf drainage, evaporation and water uptake by vegetation, surface runoff, preferential flow, exchange of soil moisture between soil layers and drainage to the groundwater, sub-surface and groundwater flow, and flow through river channels. However, it also includes a number of additional options to model special structures within the channel network, e.g., reservoirs, polders etc. One of these additional options is the lake routine.

Lakes in LISFLOOD are simulated as points in the channel network and outflow is computed using the following simplified rating curve (e.g., *Maidment*, 1993)

$$O_{lake} = A\left(H - H_0\right)^B \qquad (1)$$

Where O_{lake} [m^3/s] is the lake outflow rate, H [m] is the water level in the lake, H_0 [m] is the water level at which lake outflow is zero, and A and B are constants. A schematic overview of all the computed in- and outgoing fluxes is presented in Fig. 1.

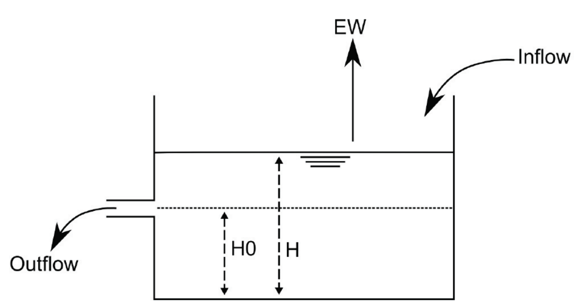

Figure 1 Schematic overview of the simulation of lakes in LISFLOOD. Here, EW is the evaporation from the lake (after *van der Knijff*, 2008).

Table 1 lists the required inputs for the lake routine. Lake location, lake surface area, mean net lake inflow, and the lake parameter A, which can be approximated using the outlet width in meters, are the parameters which can be obtained quite easily from the web pages of the concerning water authorities and/or other sources giving information about the corresponding lake (e.g. Wikipedia). Unfortunately, the water level H_0 at which the lake outflow is zero is not as easily obtained as this parameter usually does not belong to the standard set of values characterizing the hydrologic features of the lake. Nevertheless, as H and H_0 are defined both relative to the average bottom level of the lake we can approximate H_0 as follows:

$$H_0 \approx \overline{D} - \left(\overline{G} - G_{low}\right) \qquad (2)$$

where $\overline{D}$ is the average depth of the lake, $\overline{G}$ is the average water level measured at the water gauge of the outflow of the lake and G_{low} is the lowest water level measured at the gauging station. For most cases, the values required in Eq. (2) are available from the corresponding water authorities.

Table 1 Input requirements for the lake routine in LISFLOOD

Parameter description	Input format [default file name]
Lake location	Nominal PCRaster map describing the lake locations [lakes.map]
Lake surface area [m^2]	Table with the lake identifier and its corresponding surface area [lakearea.txt]
Lake level at H_0 [m]	Table with the lake identifier and the water level at which lake outflow is zero [lakeh0.txt]
Lake parameter A [-]	Table with lake identifier and parameter A [lakea.txt]
Lake parameter B [-]	Table with lake identifier and parameter B [lakeb.txt]
Mean net lake inflow [m^3/s]	PCRaster map denoting the average lake inflow for each lake location [lakeavinflow.map]

Finally, lake parameter B can vary within the range of 1.5 – 2. This parameter is the only parameter for the lake routine which cannot be related to any physical characteristics of the lake and has to be either guessed or calibrated. However, LISFLOOD currently does not provide the option to calibrate on this value. Hence, the parameter B is guessed for the examples in this report unless stated otherwise.

As lakes tend to produce a relatively slow response over time, it is important to make sure that the initial lake level is set to a more or less sensible value. Similarly to the initialisation of the lower groundwater zone, LISFLOOD has a specific option to compute the steady-state lake level and use this value as the initial lake level. For this purpose the *LakeInitialLevelValue* in the LISFLOOD settings file needs to be set to -9999. This will cause the model to calculate the steady state level using the mean net lake inflow according to

$$H_{SS} = H_0 + \left(\frac{I_l - EW_l}{A} \right)^{1/B}$$

where H_{SS} is the steady state water level [m], I_l is the mean net lake inflow [m^3/s], and EW_l is the lake evaporation [m^3/s].

A special attention needs to be paid to the lake locations. As lakes are represented as points they should be located at the outlet of lake so that all the upstream rivers discharging into the lake are also located upstream of the lake point in the model. Otherwise this could lead to erroneous output and, in the worst case, to a falling of the lake level below H_0 which in turn means that lake outflow ceases completely.

The lake routine produces one map stack and four additional time series. The map stack corresponds to the lake level at the reporting time step. The time series describe the lake inflow, lake outflow, lake evaporation and the lake level for each lake within the model domain during the simulation. Further details concerning the lake routine can be found in Annex 5 of the LISFLOOD manual (*van der Knijff*, 2008).

3. Evaluating the effect of lakes on streamflow – Some examples

In this section we will illustrate the effects of including the lake routine into the LISFLOOD simulations using Lago Maggiore, Lago di Garda, and Lago di Como in the Po catchment, Lake Constance in the Rhine catchment and Lake Leman in the Rhone catchment. All these lakes have a very considerable size and we expect strong impacts on the modelled discharges for all these catchments.

3.1 Lago Maggiore, Lago di Garda, and Lago di Como

Although many lakes exist within the Po catchment we have chosen to include only these three lakes based on their relatively large surface area, lake volume and/or their average net discharge. All of these lakes are located in the southern part of the Alps and all of them are fed by discharges from Alpine catchments. The main contributor to in- and outflow for the Lago Maggiore are the rivers Ticino and Toce. The Lago di Como has several inflows of which the most important ones are the Adda and the Mera. Lago di Como discharges into the Adda river. Finally, Lago di Garda is principally fed by the river Sarca and it discharges into the river Mincio. Table 2 lists the used parameters within the lake routine for these three lakes. All required parameters were obtained from *Fondazione Lombardia per l'Ambiente* (2004).

Table 2 Input parameters for the Lago Maggiore, Lago di Como, and Lago di Garda in the LISFLOOD lake routine

	Lago Maggiore	Lago di Como	Lago di Garda
Lake Location (according to EFAS coordinate system)	X: -34061 Y: -248941	X: 28051 Y: -237096	X: 133637 Y: 291732
Lake surface area [m^2]	213000000	145000000	368000000
H_0 [m]	170.5	149.5	128
Lake parameter A	53	30	12
Lake parameter B	1.92[a]	1.9	1.9
Av. net inflow [m^3/s]	290	161	58

[a] This value was obtained from *Bartholmes* (2004).

Simulations were performed for the period from 01/01/2004 – 12/11/2006. All simulations use the calibrated parameters sets as currently employed in the operational EFAS. However, simulations were performed using the latest LISFLOOD version.

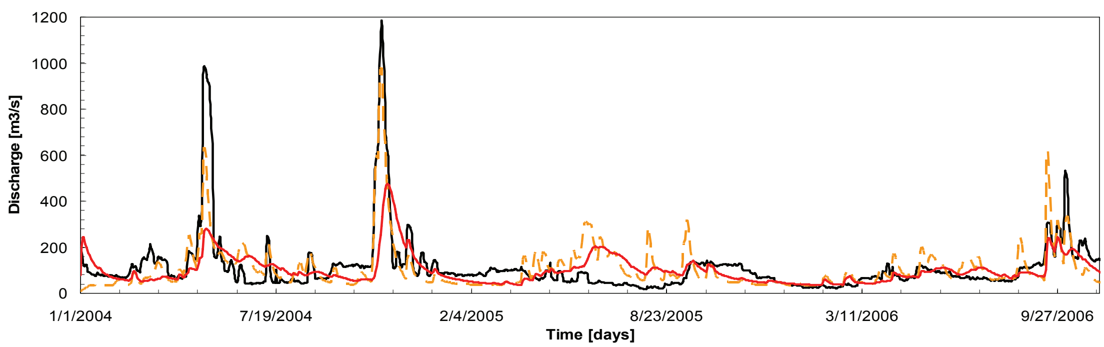

Figure 2 Hydrograph for the Vigevano gauging station at the Ticino downstream of Lago Maggiore. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

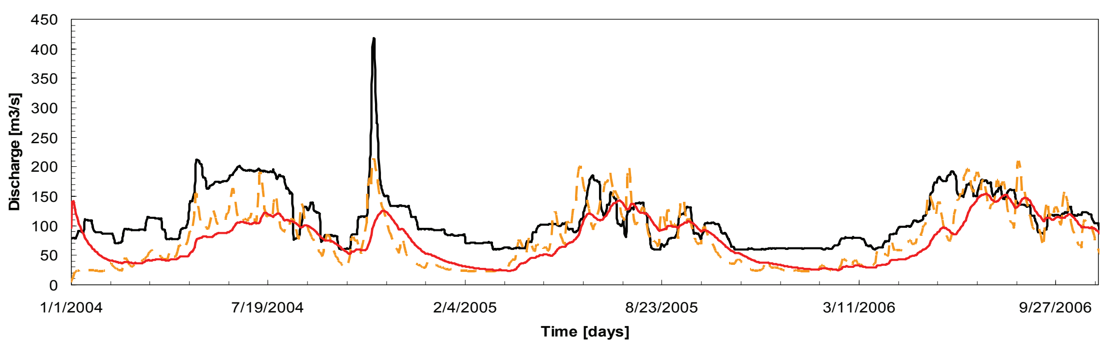

Figure 3 Hydrograph for the Santa Maria Lavello gauging station at the Adda downstream of Lago di Como. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

Figs. 2 and 3. illustrate the effect of including Lago Maggiore and Lago di Como at gauging stations located directly downstream of the lakes. What is immediately obvious from these graphs is that the presence or absence of modelling lakes within LISFLOOD is not the main factor for the unsatisfactorily reproduction of streamflow.

However, these graphs also clearly illustrate that including the lakes into a set of parameters which have been calibrated without taking into account the lakes principally does not improve results but even worsens them. Nevertheless, it is also observable especially in Figure 3 that, whereas the simulated discharge without the lake shows very pronounced responses to even minor precipitation events, the simulated discharge including the lake clearly has a smoother curve which generally corresponds better to the behaviour of the observed discharge.

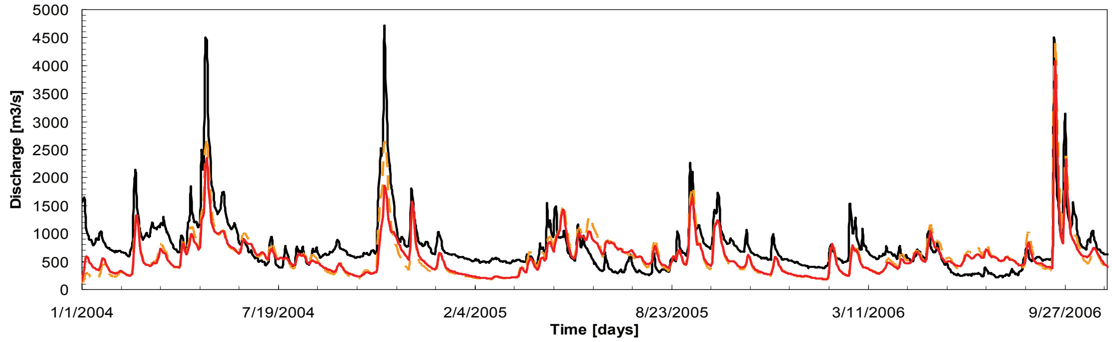

Figure 4 Hydrograph for the Cremona gauging station at the Po downstream of Lago Maggiore and Lago di Como. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

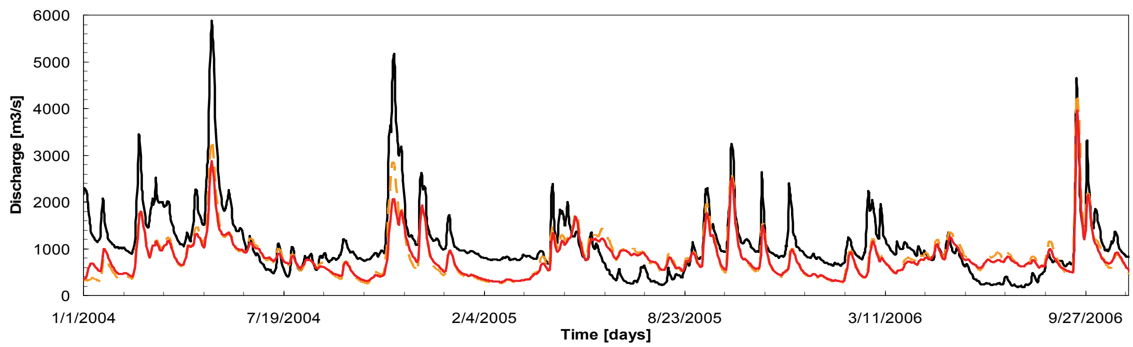

Figure 5 Hydrograph for the Pontelagoscuro gauging station at the Po downstream of Lago Maggiore, Lago di Como, and Lago di Garda. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

Figs. 4 and 5 present the observed and modeled hydrographs from two stations further downstream of the lakes. Here it becomes clear that although especially Lago Maggiore and Lago di Como have considerable average outflows their effect in the downstream Po river is almost negligible. This is certainly even more true for the Lago di Garda which has an average outflow of only 58 m^3/s.

3.2 Lake Constance

Lake Constance is one of the largest lakes in Europe and it is located within the northern pre-Alps. Three countries, (Germany, Switzerland, and Austria) share its shores turning international cooperation between these countries into a necessary tool to preserve and use its natural resources. Lake Constance is part of the upper Rhine catchment and receives its main inflow principally from alpine catchments. It is divided into an upper (the largest part) and a lower lake (the small part). Here, we consider lake Constance as one large lake, hence all lake parameters listed in Table 3 refer to the whole lake. All required parameters were obtained from *Internationale Gewässerschutzkommission für den Bodensee (IGKB)* (2004).

Table 3 Input parameters for lake Constance in the LISFLOOD lake routine

	Lake Constance	
Lake Location (according to EFAS coordinate system)	X: 12731.1	Y: -37356.1
Lake surface area [m^2]	534000000	
H_0 [m]	88.0	
Lake parameter A	150.0	
Lake parameter B	1.9	
Av. net inflow [m^3/s]	348.17	

Figs 6. and 7 present the impact of including lake Constance into LISFLOOD for a station immediately downstream of the lake (Rekingen gauging station - Fig. 6) and for a station approximately 300 km downstream of the lake (Maxau gauging station). Similarly to the hydrographs presented for the Po catchment it is obvious that without a new calibration simulated discharges actually are worse than without modeling the lake. However, the attenuated discharges when including the lake appear to describe the overall behavior of the measured discharges better than the curve without the lake. Again, the influence of lake Constance at the Maxau gauging station is minor.

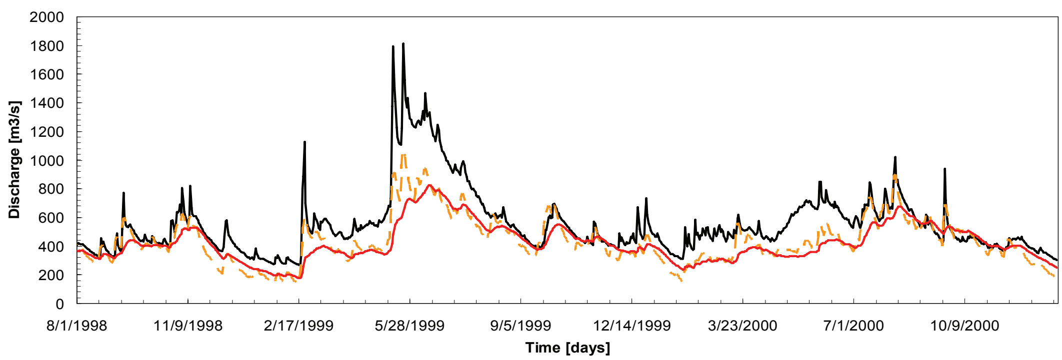

Figure 6 Hydrograph for the Rekingen gauging station at the Rhine downstream of lake Konstanz. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

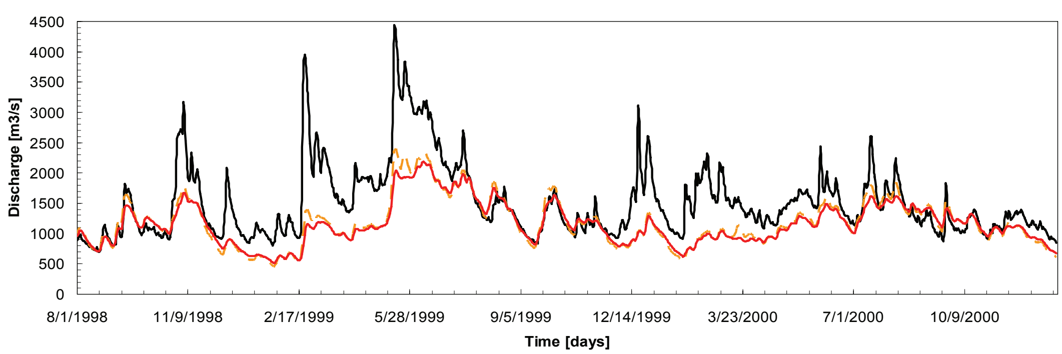

Figure 7 Hydrograph for the Maxau gauging station at the Rhine downstream of lake Konstanz. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

3.3 Lake Leman

Lake Leman is located in the north-western pre-Alps and is part of the Rhone catchment. It receives its principal inflows from the Rhone, the Dranse, the Venoge, and Aubonne. Table 4 lists the used parameters within the lake routine for lake Leman. All required parameters were obtained from the *Bundesamt fuer Umwelt, Wald und Landschaft* (1994).

Table 4 Input parameters for lake Leman in the LISFLOOD lake routine

	Lake Leman	
Lake Location (according to EFAS coordinate system)	X: -218002	Y: -191318
Lake surface area [m^2]	581300000	
H_0 [m]	150.0	
Lake parameter A	90.0	
Lake parameter B	1.9	
Av. net inflow [m^3/s]	247.0	

Figs. 8 and 9 present the simulated hydrographs with and without including lake Leman at the Pougny gauging station, located approximately 15 km downstream of the lake Leman outflow, and at the Lyon gauging station located approximately 200 km downstream of the lake outlet. The strongly fluctuating measured discharges at the Pougny station suggest a very strong and fast changing regulation as stations located closely to the outlet of a large lake should show the attenuating effect of the lake. Hence, the Pougny station is unfortunately inadequate to judge whether the inclusion of the lake would lead to an improvement, probably also after a calibration. Even the 200 km distant station of Lyon still shows the influence of the strong and fast changing regulation. Thus, a conclusion whether including the lake Leman would improve simulated discharge is not possible, as here clearly human influence is dominating river discharge strongly.

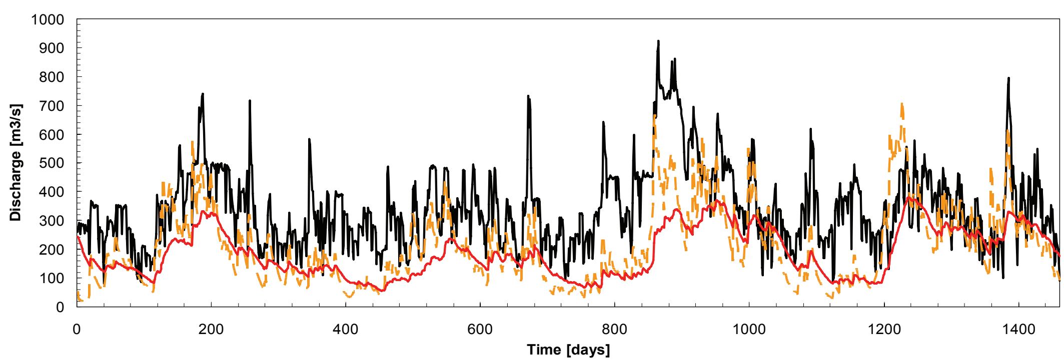

Figure 8 Hydrograph for the Pougny gauging station at the Rhone downstream of lake Leman. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

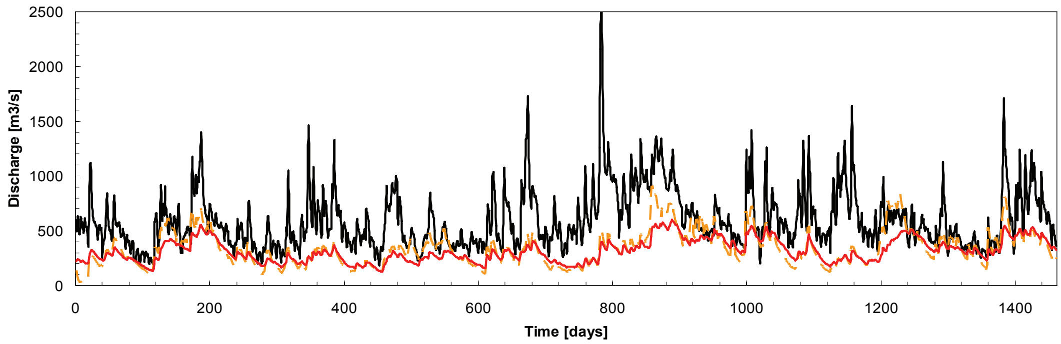

Figure 9 Hydrograph for the Lyon gauging station at the Rhone downstream of lake Leman. The black line denotes the measured discharge, whereas the orange dotted and the red solid line, show the simulated discharge without and with the lake routine, respectively.

3.4 A rough sensitivity analysis of the lake routine parameters

As mentioned in Section 2 most of the parameters required for the lake routine are physically based and can be derived from readily available standard hydrologic information about the lake and/or gauging stations located at the outlet of the lake. However, lake parameters A and B have to be estimated by the modeler. Whereas parameter A can be estimated using the outlet width of the lake, no guidance can be established for lake parameter B, except the parameter range from 1.5 – 2. Hence, in order to get a rough idea about their influence on modeled discharges simulations were performed taking extreme values for these parameters and evaluating the simulated discharges. Fig. 10 depicts the simulated discharge at the Rekingen gauging station using a value of 1.5 (orange line) and 2 (red line) for the lake parameter B. It is obvious that the choice of this parameter value has only a minor influence on simulated discharge.

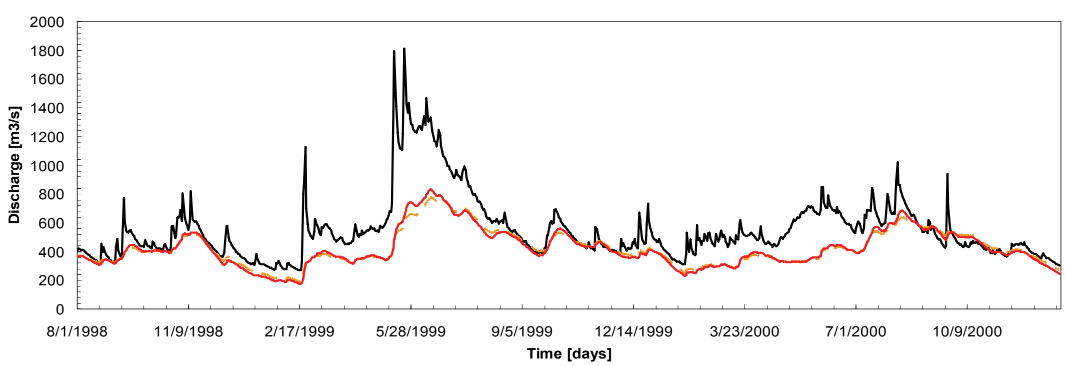

Figure 10 Hydrograph for the Rekingen gauging station at the Rhine downstream of lake Konstanz. The black line denotes the measured discharge, whereas the orange dotted line corresponds to the simulated discharge using lake parameter B = 1.5 and the red solid line using lake parameter B = 2.0, respectively.

Although lake parameter A can be approximated with the outlet width of the lake, this parameter can vary substantially, as usually the outlet of a lake is not a clearly defined point. Figure 11 shows the modelled hydrograph assuming either a value of 50 (orange line) or 200 (red line). Similarly, as was observed for lake parameter B, the sensitivity of the parameter to simulated discharge is very little.

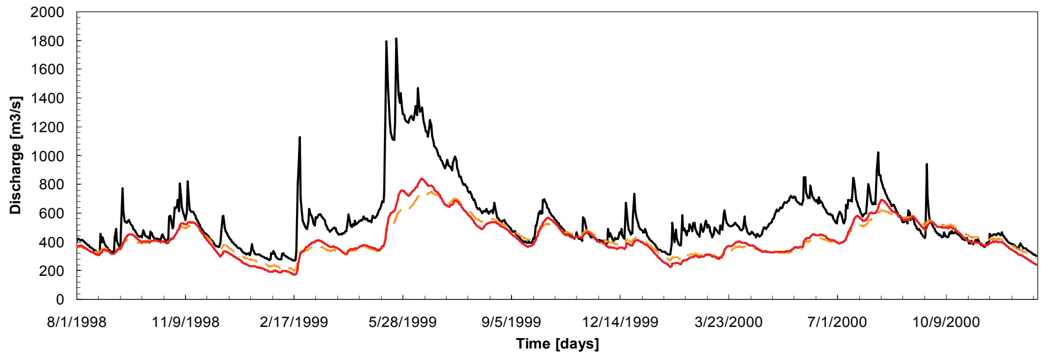

Figure 11 Hydrograph for the Rekingen gauging station at the Rhine downstream of lake Konstanz. The black line denotes the measured discharge, whereas the orange dotted line corresponds to the simulated discharge using lake parameter A = 50 and the red solid line using lake parameter A = 200, respectively.

4. Data availability and collection

In order to implement the lake routine of LISFLOOD at a European scale the necessary data required (see Section 2) needs to be available and to be collected. Considering the spatial scale of EFAS and in order to make this data collection feasible, we have decided to apply two exclusion criteria: (1) The average surface area of the lake has to be larger than 140 km^2. (2) Average discharge has to be larger than 100 m^3/s. These two criteria were selected considering the results in Section 3. For example, it could be shown that the influence of the Lago di Garda on discharge, even at a gauging station located in the proximity of the lake outlet, is relatively small, despite its very large surface area. We could also show that even for larger lakes with a significant average discharge (e.g., Lago Maggiore) its influence further downstream is not as strong as initially expected. Furthermore, most of the lakes having smaller average discharges than 100 m^3/s have an upstream catchment that is relatively small. However, in EFAS only flood alerts with an upstream area of approximately larger than 5000 km^2 are considered and thus we believe that the above listed two criteria are reasonable.

Table 5 presents a list of lakes having an average surface area larger than 140 km^2. This list was obtained using available information in the internet, mostly from Wikipedia. Except for the Scandinavian lakes, there are only a few lakes in the rest of Europe fulfilling the above conditions: Lake Peipus, Lake Leman, Lake Constance, Lake Maggiore, and, provided the average discharge is larger than 100 m^3/s, Lough Neagh, and Lough Carrib. Unfortunately, information about the average discharge of the Scandinavian lakes was not easily available. However, searching on the web pages of the corresponding authorities or directly contacting them, additional information could be obtained. For all the other lakes fulfilling the criteria most of the hydrological characteristics of the lakes are easily available.

Table 5 List of lakes located entirely or partially in the EU member states with a surface area larger than 140 km^2.

Lake Name	Country Name	Average surface area [km^2]	Average discharge > 100 m^3/s
Vänern	Sweden	5655	Yes
Saimaa	Finland	4377	?
Peipus	Estonia, Russia	3555	Yes
Vättern	Sweden	1893	?
Päijänne	Finland	1081	?
Inari	Finland	1040	?
Pielinen	Finland	894	?
Oulujärvi	Finland	887	?
Balaton	Hungary	592	No
Geneva	Switzerland, France	581	Yes
Constance	Germany, Switzerland, Austria	541	Yes
Keitele	Finland	494	?
Hjälmaren	Sweden	485	?
Kallavesi	Finland	473	?
Storsjön	Sweden	464	?
Lough Neagh	United Kingdom	388	?
Garda	Italy	370	No
Siljan	Sweden	354	?
Puula	Finland	330	?
Torneträsk	Sweden	330	?
Lokka	Finland	315	?
Neusiedl	Austria, Hungary	315	No
Höytiäinen	Finland	282	?
Võrtsjärv	Estonia	270	No
Akkajaure	Sweden	261	?
Näsijärvi	Finland	256	?
Hornavan	Sweden	252 (220–283)	?
Yli-Kitka	Finland	237	?
Suvasvesi	Finland	234	?
Kemijärvi	Finland	231	?
Juojärvi	Finland	220	?
Maggiore	Italy, Switzerland	212	Yes
Uddjaure	Sweden	210 (190–250)	?
Pyhäjärvi	Finland, Russia	207	?
Lough Corrib	Ireland	200	?
Enonvesi	Finland	197	?
Kiantajärvi	Finland	191	?
Prespa	Albania, Greece, Macedonia	190	No
Konnevesi	Finland	189	?
Bolmen	Sweden	184	?
Ströms vattudal	Sweden	183	?
Storuman	Sweden	173	?
Storavan	Sweden	172	?
Nilakka	Finland	169	?
Koitere	Finland	167	?
Stora Lulevatten	Sweden	165	?
Iisvesi	Finland	164	?
Åsnen	Sweden	159	?

Juurusvesi–Akonvesi	Finland	159	?
Pyhäjärvi	Finland	155	?
Kivijärvi	Finland	154	?
Vanajavesi	Finland	150	?
Porttipahta	Finland	149	?
Como	Italy	146	Yes
Lappajärvi	Finland	145	?
Suontee	Finland	143	?

5. Conclusions and way forward

The lake routine in LISFLOOD requires a total of 6 parameters of which most of them are physically based and relatively easy to obtain as they correspond to the standard hydrological characteristics of a lake. The two lake parameters A and B have a relatively small influence on the simulated discharge and hence a value within the given range can be assumed (lake parameter B) or the value can be reasonably estimated with the outlet width in meters. Considering the results in Section 3 and the spatial scale of EFAS only lakes with a surface area larger than 140 km ^{2} and an average discharge of larger than 100 m^3/s should be selected first.

For an implementation of the lakes into EFAS the following procedure is suggested:

- Create a list of lakes with a surface area larger than 140 km^2 and an average discharge of larger than 100 m^3/s. (see Table 5 for a start) If this is not feasible for the Scandinavian lakes, focus on the lakes located within the river basins where an Memorandum of Understanding exists.
- Collect the remaining necessary information about these lakes from the corresponding web pages of the national and/or local authorities. In cases where this is not possible contact the concerning local authority directly.
- Perform a calibration on the catchments where lakes are now included

If the newly calibrated catchments, including the lakes, show a significantly better reproduction of the observed hydrograph, more lakes should be incorporated by lowering the selection criteria.

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European Commission

EUR 23710 EN – Joint Research Centre – Institute for Environment and Sustainability
Title: A brief feasibility study on the implementation of the Lakes routine into EFAS
Author(s): Peter Salamon
Luxembourg: Office for Official Publications of the European Communities
2008 – 12 pp. – 21.0 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593

Abstract
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