VARIATIONAL DATA ASSIMILATION OF AIRSWOT AND SWOT DATA INTO THE 2D SHALLOW WATER MODEL DASSFLOW. METHOD AND TEST CASE ON GARONNE RIVER (FRANCE).

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ABSTRACT

For continental water bodies and river hydraulic studies, water level measurements are fundamental information, yet they are currently mostly provided by punctual gauging stations located on the main river channel. That is why they are sparsely distributed in space and can have gaps in their time series (e.g. sensors failures). These issues can be compensated by remote sensing data, which have considerably contributed to improve the observation and understanding of physical processes in hydrology and hydraulics in general. Satellites such as SWOT (Surface Water and Ocean Topography) would give spatially distributed information on water elevations at an unprecedented resolution. Gathering pre-mission data over specific and varied science targets is the purpose of the AirSWOT airborne campaign in order to implement and test SWOT products retrieval algorithms. A reach of the Garonne River, downstream of Toulouse (FRANCE), is a proposed study area for AirSWOT flights. This choice is motivated by previous studies already performed on this section of 100km reach of the river. Moreover, on this highly instrumented and studied portion of river many typical free surface flow modelling issue has been encountered, and this river reach represents the limit of SWOT observation capability. The 2D hydrodynamic model DassFlow especially designed for variational data assimilation will be used on this portion of the Garonne River with cartographic sensitivity analysis. An identification strategy would allow retrieving spatial roughness along the main channel, variation of the local topographic slope or else temporal evolution of the streamflow. Addressing such problems and studying horizontal and vertical river sinuosity would improve fine scale hydraulics representation and understanding, which could additionally help to improve global discharge algorithms with different scales and complexity levels.

1. INTRODUCTION

Rivers discharges and lake water storage are important components of the continental water cycle, yet their spatial and temporal variations are not subtly known. As a consequence, continental water cycle understanding in a quantitative manner is significantly narrowed by measurements limitations as for example water fluxes in wetlands or floodplains. Water elevations are crucial information for hydraulic studies and they are currently provided in most cases by gauging stations located in the main channel. These measurements are therefore punctual and scattered in space or even nonexistent for some regions of the world. Moreover, time series discontinuities can be due to floods' power often disturbing or even damaging sensors. Thus, teledection represents a powerful mean together with in situ measurement networks, and contributed to improve physical process observation in hydrology and hydraulics in general, and floods hydrodynamics in particular (Alsdorf et al., 2007). As a matter of fact, new generation of satellites can be equipped with metric resolution sensors. Water bodies elevations can be measured with nadir altimeters, and water masks corresponding to their spatial extent can be derived from optic or synthetic aperture radars data (SAR). Main limitations of the current satellite datasets lies in the revisit period : 10 to 30 days for altimeters, and their spatial resolution : for nadir altimeters rivers must be wider than 1km and their coverage presents important discontinuities (Biancamaria et al., 2010). For the years to come, several spatial missions are planed in view to observe different components of the water cycle : snow and ice cover (Cold Regions Hydrology High-resolution Observatory, CoRe-H2O mission and Deformation Ecosystem Structure and Dynamics of Ice, mission DESDynI), soil moisture (Soil Moisture Active-Passive, SMAP mission and Soil Moisture and Ocean Salinity, SMOS mission), gravity field and large-scale water movements (Gravity Recovery and Climate Experiment II, GRACE-II mission), and surface water (Surface Water and Ocean Topography, SWOT mission). Global coverage for data provided by these missions would allow analysis and direct modelling at different scales.

Given the resolution and the huge informative content of the future SWOT mission data, there is a great potential to study rivers and water bodies that remained unobservable as to apply powerful data demanding mathematical techniques for singular cases. The optimal control theory (Le Dimet and Talagrand 1986; Le Dimet 1982) provides many concrete realizations and continues to offer promising results in several fields (Bertino 2001; Ngnepieba and Hussaini 2004) for example in the fields related to geosciences. In hydrology, it allows approaching physical parameters and state variables not always accessible through measurements (Roux and Dartus 2004). Optimization methods such as minimizing an error criterion and the extended Kalman filter allow (Roux and Dartus, 2005) reconstituting river cross sections synthetic from flood plain extent data. The potential of remote sensing data to identify discharges is tested by (Roux and Dartus, 2006) who obtain Nash efficiencies superior to 0,9 for the studied hydrographs.

A variationnal data assimilation (DA) method (4D-VAR) is presented for water elevations (Castaings et al., 2005). For several tributaries of the Pearl river (China), satisfying identifications of incoming flows are performed as attested by water elevations compared to in situ measurements (Honnorat et al., 2006). Method's efficiency for static parameters identification (roughness coefficients, initial conditions) is shown trough academic test cases with a single water extent map (Lai and Monnier, 2009). This framework is successfully tested on a real flood that occurred on the Moselle river (France) with a SAR image of water extent and elevations (Hostache et al., 2010). Using the 4D-VAR method and DassFlow hydrodynamic model, discharge is identified and spatial Manning roughness sensitivity is highlighted by (Couderc et al., 2012a).

The future SWOT mission is designed to provide global maps of water elevation at an unprecedented spatial resolution, with an intrinsic pixel resolution from 2*10m to 2*60m and a vertical decimetric accuracy (Durand et al., 2010). Several authors have shown the possibilities for identifying morpho-hydraulic parameters from remote sensing and in situ measurements. When assimilating SWOT virtual observations into a the Amazon river hydraulic modelling, (Durand et al., 2008) show that bathymetric slopes can be estimated within 0.3 cm.km-1 and depths to within 56 cm (it represents 84% error reduction compared to the case without assimilation). The authors point the fact that modelling errors dominate measurement errors and so bathymetry estimates are relatively insensitive to data errors for this huge river.

Some recent studies have focused on quantifying the benefit of SWOT mission for hydrology and especially for discharge estimation. At the global scale for different orbits it is shown that errors in instantaneous discharges should be below 25% for rivers wider than 50m (Biancamaria et al., 2010). Twin experiments with Ensemble Kalman filters (EnKF) for virtual wide swath measurement assimilation are shown to reduce modelling errors due to lateral inflows on the Ohio mid-latitude river (Andreadis et al., 2007). The best results are obtained for the smallest orbits. (Biancamaria et al., 2011) show the huge decrease of spatial and temporal RMSE when assimilating virtual SWOT data for the Ob river modelling (Biancamaria et al., 2009). High latitudes will be very well sampled during one orbit repeat period. The authors have used on the Ob river ISBA model (Interactions between the Soil Biosphere-Atmosphere, CNRM, France) coupled with the 1D-2D LISFLOOD-FP (Bates and De Roo, 2000) and a smoothed Kalman filter.

This paper presents a framework for quantifying hydraulic modelling improvements brought by SWOT data and parameters that could be identified. A reach of the Garonne river (France) located between Toulouse and Malause has already been studied with a 1D thermo- hydraulic model (Larnier et al., 2010). This study zone is proposed for Air SWOT Airborne campaigns (France, 2014) and 2D fine scale hydrodynamic modelling with DassFlow and 4D-VAR DA will be performed. Variationnal data assimilation approach represents a complementary approach to Kalman filters.

2. MATERIAL AND METHODS

1.1. DassFlow

The computational code DassFlow solving shallow water equations (Honnorat et al., 2006) has especially been developed to allow variationnal data assimilation and cartographic sensitivity analysis studies. The two dimensional form of the Shallow Water Equations (SWE) with variable topography is taking into account bed shear stress in conservative form:

$$\begin{cases} \partial_t h + \nabla \cdot (h\mathbf{u}) = 0 \\ \partial_t (h\mathbf{u}) + \nabla \cdot (h\mathbf{u} \otimes \mathbf{u}) + \frac{1}{2} g \nabla h^2 = -gh \nabla z_b - g \frac{n_b^2 \|\mathbf{u}\|_2}{h^{1/3}} \mathbf{u} \end{cases} \quad (1)$$

where h is the water depth, $\mathbf{u} = [u, v]^T$ the depth averaged velocity vector the gravity acceleration, the bottom elevation (topography/bathymetry), and the Manning coefficient for the bed roughness.
With initial condition:

$$\begin{cases} h(t = 0, x, y) = h_0(x, y) \\ \mathbf{q}(t = 0, x, y) = \mathbf{q}_0(x, y) \end{cases} \quad (2)$$

Where $\mathbf{q} = h\mathbf{u}$ is the unit discharge, h_0 the initial water depth-field and q_0 the initial unit discharges field.

Finite volume discretisation and Riemann solver and several numerical schemes of order 1 and 2 are implemented (Couderc et al., 2012b).

1.2. Variationnal Data assimilation

Variationnal data assimilation relies on minimizing a cost function using the so-called adjoint model. Considering a cost function on the form :

$$J(\mathbf{k}) = \sum_i \int_0^T \left\| h(t,P_i)) - h_{obs}(t,P_i) \right\|_\Omega^2 dt + \sum_j \int_0^T \left\| \mathbf{q}(t,P_j) - \mathbf{q}_{obs}(t,P_j) \right\|_\Omega^2 dt \qquad (10)$$

Cost function formulation depends on the goals of the study and regularisation terms can be added. And introducing the adjoint variables $\widetilde{h}$ et , the adjoint equations of model (1), (2) are (Honnorat et al., 2007):

$$\begin{cases} \partial_t \tilde{h} - \mathbf{u}\cdot(\mathbf{u}\cdot\nabla)\tilde{\mathbf{q}} + gh\nabla\cdot(\tilde{\mathbf{q}}) - g\tilde{\mathbf{q}}\cdot\nabla\mathbf{z_b} + \frac{7}{3}g\frac{n^2\|\mathbf{u}\|}{h^{4/3}}\mathbf{u}\tilde{\mathbf{q}} = (h(t) - h_{obs}(t)) \\ \partial_t \tilde{\mathbf{q}} + \nabla\tilde{h} + (\mathbf{u}\cdot\nabla)\tilde{\mathbf{q}} + (\nabla\tilde{\mathbf{q}})^T\mathbf{u} - g\frac{{n_b}^2\|\mathbf{u}\|}{h^{4/3}}\tilde{\mathbf{q}} - g\frac{{n_b}^2}{h^{4/3}\|\mathbf{u}\|}(\mathbf{u}\otimes\mathbf{u})\tilde{\mathbf{q}} = 0 \end{cases} \qquad (11)$$

$$\begin{cases} \tilde{h}(t = T, x, y) = 0 \\ \tilde{\mathbf{q}}(t = T,x,y) = (0,0)^T \end{cases} \qquad (12)$$

The backward integration of this adjoint model leads to a solution $(\tilde{h}, \tilde{\mathbf{q}})$ at t = 0. Then the partial derivatives of the cost function are obtained from this solution:

$$\begin{cases} \frac{\partial J}{\partial h_0}(\mathbf{k}) = -\tilde{h}(0) \\ \frac{\partial J}{\partial \mathbf{q}_0}(\mathbf{k}) = -\tilde{\mathbf{q}}(0) \\ \frac{\partial J}{\partial z_b}(\mathbf{k}) = -\int_0^T \mathrm{div}(gh(t)\tilde{\mathbf{q}}(t))dt \\ \frac{\partial J}{\partial z_b}(\mathbf{k}) = 2gn\int_0^T \|\mathbf{u}(t)\| h(t)^{\frac{-1}{3}}\mathbf{u}(t)\tilde{\mathbf{q}}(t)dt \\ \frac{\partial J}{\partial q_{in}}(\mathbf{k}) = -\tilde{h} \end{cases} \qquad (13)$$

These partial derivates are then provided to a minimisation algorithm.

1.3. A Garonne tributary : the Lèze river (France)

A small reach of 2km long of the Lèze river a Garonne tributary near Toulouse city is studied in (Larnier et al., 2012). Throughout this study a version of DassFlow based on a HLLC solver for flux computation and a flux modification (Leveque and Georges, 2008) to obtain a well-balanced scheme. The adjoint source code was computed using the automatic differentiation tool TAPENADE developed by the the research team Tropics of the INRIA Sophia-Antipolis (website : http://www-sop.inria.fr/tropics/).). The minimisation of the cost function was performed with a constrained quasi-Newton algorithm (BGFS) using the M2QN1 routine by (Gilbert and C. Lemarechal 1989).

The discretization mesh is about 100 000 triangular elements with increasing density near the River. A 50 years return period flood that occurred in 2000 was analyzed. In order to perform twin experiments Three observation stations were selected and random noise is added to water depth computed from direct modelling (*Figure 1*).

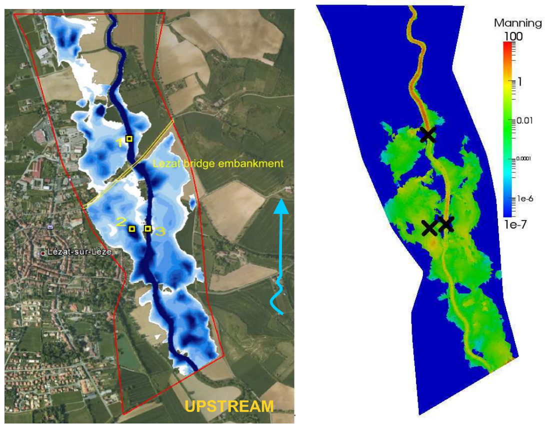


Figure 1 : (left) Solution at maximum flooding time and locations of the three (virtual) observations stations; (right) sensitivity of the water level to the Manning at 3 stations. Source (Larnier et al., 2012)

A thorough sensitivity analysis with respect to Manning coefficient is performed and key flow controls are localized (*Figure 1*). Variational method only is able to provide that kind of mapping.

For that case study, the synthetic noised discharges within the domain are used to identify inflow discharge (*Figure 2*). The identified discharge can be smoothed with an additional term on the temporal derivates in the cost function (Couderc et al., 2012b).

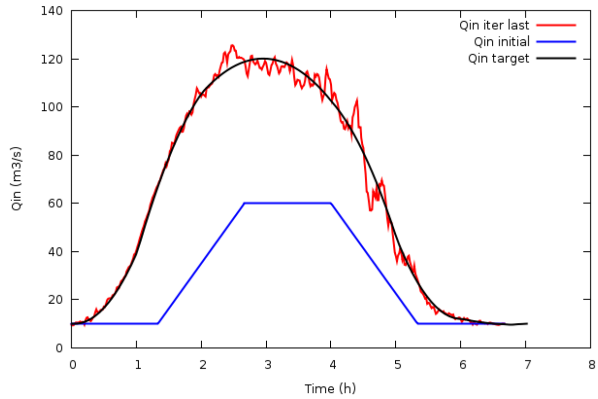
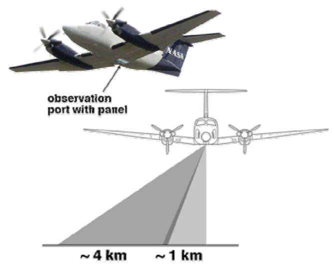


Figure 2 :Leze 2000 flood Inflow discharge identified with three synthetic noised observation stations. Source (Couderc et al., 2012b)

3. THE GARONNE RIVER BETWEEN TOULOUSE AND MALAUSE (FRANCE)

A wide swath altimeter (Ka-band radar) is currently under study by NASA (National Aeronautics and Space Administration) and CNES (Centre National d'Etudes Spatiales) for an operational SWOT launch between 2018 and 2020. AirSWOT Airborne campaigns are planed to test a Ka-band radar interferometer similar to SWOT one. A proposed study zone for AirSWOT is the Garonne river between Toulouse and Malause (*Figure 3*). This 100 km reach is well documented with 200 cross section and 25m Digital Elevation Model (D.E.M), and 20 year of various hydrometeorological data. The Garonne flow regime is very contrasted in space with huge module variations upstream to downstream, and in time with severe low flows and violent flood events.



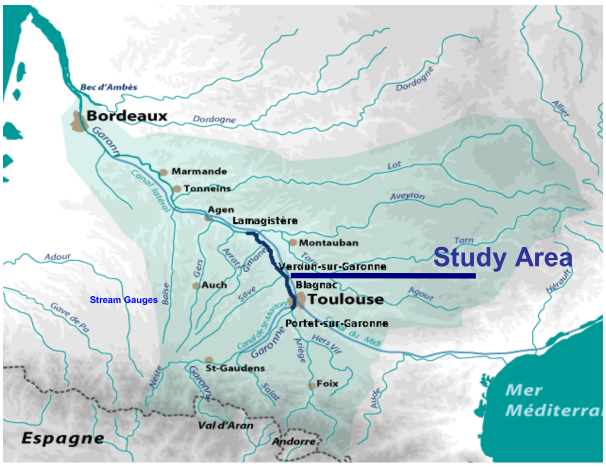


Figure 3: Garonne reach between Toulouse and Malause for AirSWOT airborne campaign

A 1D hydraulic model also calculating water temperature has already been calibrated on this reach of the Garonne *(Larnier et al., 2010)*. Satisfying water elevations and discharges are determined that way (*Figure 4* and *Figure 5*). Several typical problems of hydraulics are represented on this reach. Singular cross sections with emerging bedrock and sandbanks (*Figure 6*), complex floodplain topography can exert a strong control on river flow.

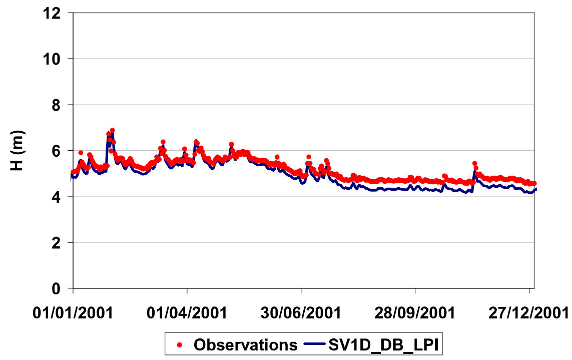


Figure 4: Water elevation at Portet sur Garonne. Source (Larnier et al., 2010)

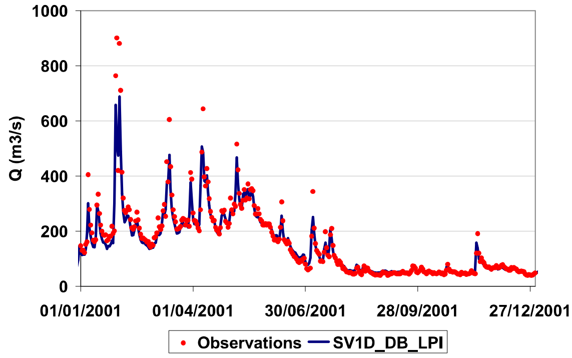


Figure 5: Discharge at Lamagistère. Source (Larnier et al., 2010)

Because of the succession of rifles and pools a model needs to correctly describe these zones producing a variety of flow velocities (critical and supercritical). (Air)SWOT data offer interesting possibilities to understand this vertical sinuosity managing energy within a river reach; to identify the main characteristics of the river but also to study these singular locations by improving cross sectional roughness representation and overbank flow dynamics.

Figure 6: Example of bedrock and sandbanks emerging in the main channel of the Garonne. (Source Google)

4. FURTHER WORK

This paper presents a framework for quantifying hydraulic modelling improvements brought by SWOT data and parameters that could be identified. A reach of the Garonne river (France) located between Toulouse and Malause has already been studied with a 1D thermo- hydraulic model (Larnier et al., 2010). This study zone is proposed for Air SWOT Airborne campaigns (France, 2014) and 2D fine scale hydrodynamic modelling with DassFlow and 4D-VAR DA will be performed. Variationnal data assimilation approach represents a complementary approach to Kalman filters but is the only one providing spatially distributed sensitivities. Moreover the dependency of data assimilation potential for identification with respect to data content along a reach will be explored.

Addressing such problems and studying horizontal end vertical river sinuosity would improve fine scale hydraulics representation and understanding, which could help to improve global discharge algorithms with different scales and complexity levels.

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