**SUPPLEMENTARY MATERIAL**

**Flood Stage Forecasting using Machine-Learning Methods: a Case Study on the Parma River (Italy)**

**Table S1.** List of flood events considered in this work (ordered by descending peak level for each type of event).

| Type of event | Event | Start date (dd/mm/yyyy hh:nn) | Duration (days) | Peak level (m a.s.l.) |
|---|---|---|---|---|
| Group 1: Large floods on the Parma River | E1_1 | 08/12/2017 18:00 | 7.0 | 32.12 |
| | E1_2 | 11/10/2014 20:00 | 6.1 | 31.83 |
| | E1_3 | 24/03/2015 10:00 | 6.6 | 31.03 |
| | E1_4 | 27/02/2016 16:00 | 6.7 | 30.88 |
| Group 2: Po River floods (backwater in Colorno) | E2_1 | 12/01/2014 08:00 | 17.1 | 30.10 |
| | E2_2 | 02/01/2014 18:00 | 9.6 | 29.51 |
| | E2_3 | 04/11/2014 15:00 | 22.1 | 29.43 |
| | E2_4 | 29/01/2014 10:00 | 29.6 | 29.39 |
| | E2_5 | 15/11/2019 10:00 | 20.6 | 29.34 |
| | E2_6 | 25/12/2013 00:00 | 8.8 | 28.58 |
| | E2_7 | 20/12/2019 12:00 | 7.0 | 28.55 |
| | E2_8 | 28/02/2013 00:00 | 17.1 | 28.00 |
| | E2_9 | 15/05/2013 20:00 | 14.0 | 27.85 |
| | E2_10 | 24/11/2016 12:00 | 6.5 | 27.79 |
| | E2_11 | 28/02/2014 00:00 | 12.0 | 27.70 |
| | E2_12 | 29/10/2018 00:00 | 17.0 | 27.50 |
| | E2_13 | 27/11/2012 18:00 | 8.5 | 27.36 |
| | E2_14 | 26/11/2014 17:00 | 12.3 | 27.31 |
| | E2_15 | 03/10/2020 00:00 | 8.0 | 27.08 |
| | E2_16 | 17/04/2013 08:00 | 23.7 | 26.99 |
| Group 3: Medium floods on the Parma River | E3_1 | 09/11/2012 11:00 | 6.5 | 30.07 |
| | E3_2 | 28/03/2013 08:00 | 20.0 | 29.83 |
| | E3_3 | 05/11/2016 00:00 | 4.0 | 28.68 |
| | E3_4 | 01/02/2019 00:00 | 5.0 | 28.58 |
| | E3_5 | 03/11/2012 23:00 | 5.5 | 28.44 |
| | E3_6 | 15/03/2018 01:00 | 6.8 | 28.35 |
| | E3_7 | 26/10/2012 07:00 | 8.7 | 28.31 |
| | E3_8 | 01/02/2013 12:00 | 5.4 | 28.17 |
| | E3_9 | 10/03/2018 20:00 | 4.2 | 28.08 |
| | E3_10 | 24/05/2019 22:00 | 7.1 | 28.06 |
| | E3_11 | 20/02/2015 23:00 | 9.1 | 27.96 |
| | E3_12 | 07/02/2016 20:00 | 5.0 | 27.8 |
| Group 4: Small floods on the Parma River | E4_1 | 05/03/2016 08:00 | 6.7 | 27.68 |
| | E4_2 | 04/04/2014 00:00 | 4.0 | 27.65 |
| | E4_3 | 12/05/2019 00:00 | 5.4 | 27.55 |
| | E4_4 | 16/01/2015 08:00 | 3.3 | 27.5 |
| | E4_5 | 17/05/2019 10:00 | 7.5 | 27.44 |
| | E4_6 | 26/09/2012 09:00 | 2.7 | 27.4 |
| | E4_7 | 14/12/2012 22:00 | 4.0 | 27.36 |
| | E4_8 | 01/05/2014 23:00 | 4.6 | 27.33 |
| | E4_9 | 05/02/2017 00:00 | 4.0 | 27.19 |
| | E4_10 | 09/01/2016 20:00 | 4.0 | 27.11 |
| | E4_11 | 17/03/2013 02:00 | 11.3 | 27.01 |
| | E4_12 | 23/11/2018 18:00 | 3.0 | 26.85 |
| | E4_13 | 23/10/2013 10:00 | 3.0 | 26.81 |
| | E4_14 | 23/11/2013 00:00 | 4.0 | 26.74 |
| | E4_15 | 01/03/2020 00:00 | 3.5 | 26.73 |

**Table S2.** Random splitting of flood events into train/validation/test for each of the 20 runs (t=training; v=validation; x=testing).

| Event | Split # | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| E1_1 | x | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | x | t | x |
| E1_2 | t | x | t | t | t | t | t | t | t | t | x | t | t | t | t | t | t | t | x | t |
| E1_3 | t | t | x | x | x | t | t | t | t | t | t | t | x | x | x | t | t | t | t | t |
| E1_4 | t | t | t | t | t | x | x | x | x | x | t | x | t | t | t | x | x | t | t | t |
| E2_1 | x | t | t | v | x | v | t | t | t | t | t | t | t | t | t | t | t | x | v | v |
| E2_2 | t | x | t | x | t | t | t | t | t | t | x | t | v | t | t | v | t | x | t | x |
| E2_3 | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | v | x | t | t | t |
| E2_4 | v | v | x | t | v | x | v | x | t | x | t | x | t | v | t | v | x | x | t | x |
| E2_5 | x | t | v | t | v | t | x | v | x | x | t | t | x | t | t | t | t | v | x | x |
| E2_6 | t | t | t | v | t | t | t | t | v | v | v | t | t | t | x | t | t | t | x | t |
| E2_7 | t | x | x | t | t | v | v | t | t | v | t | x | t | t | v | x | v | t | v | t |
| E2_8 | t | t | v | t | t | t | t | t | x | t | v | t | t | t | t | t | t | t | t | t |
| E2_9 | v | v | t | v | t | t | t | t | v | t | t | x | t | x | v | t | t | t | t | t |
| E2_10 | t | t | t | x | t | t | x | v | t | t | t | v | v | x | t | t | t | t | t | t |
| E2_11 | t | v | v | x | x | t | t | x | t | t | t | t | x | x | t | t | t | t | t | t |
| E2_12 | t | t | t | t | t | t | v | t | v | v | v | t | v | v | t | x | v | v | t | v |
| E2_13 | x | t | x | t | v | v | t | x | t | t | x | t | t | t | x | t | t | t | x | t |
| E2_14 | v | x | t | t | x | x | t | t | t | t | x | v | t | t | t | t | t | t | t | t |
| E2_15 | t | t | t | t | t | x | t | v | x | x | t | v | t | v | x | t | v | t | v | v |
| E2_16 | t | t | t | t | t | t | x | t | t | t | t | t | x | t | v | x | x | v | t | t |
| E3_1 | x | t | t | t | x | v | t | t | t | t | v | t | t | t | t | t | t | x | v | t |
| E3_2 | t | x | t | x | t | t | t | t | t | t | x | t | v | t | t | v | t | v | t | v |
| E3_3 | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | v | x | t | t | t |
| E3_4 | v | v | x | t | v | x | v | x | t | x | t | x | t | v | t | t | x | x | t | x |
| E3_5 | x | t | v | t | v | t | x | v | x | x | t | t | v | t | t | t | t | v | x | x |
| E3_6 | t | t | t | t | t | t | t | t | v | v | v | t | t | t | x | t | t | t | x | t |
| E3_7 | t | x | x | t | t | t | v | t | t | v | t | x | t | t | x | x | v | t | t | t |
| E3_8 | t | t | v | t | t | x | t | t | x | t | x | t | t | t | t | t | t | t | t | t |
| E3_9 | v | v | t | v | t | t | t | t | t | t | t | v | t | x | v | t | t | t | t | t |
| E3_10 | t | t | t | v | t | t | x | v | t | t | t | t | t | v | t | t | t | t | t | t |
| E3_11 | t | t | t | x | x | v | t | x | v | t | t | v | x | x | v | t | t | t | v | v |
| E3_12 | t | t | t | t | t | t | t | t | t | t | t | t | x | t | t | x | v | t | t | t |
| E4_1 | x | t | t | t | x | t | t | t | t | t | t | t | t | t | t | t | t | x | v | t |
| E4_2 | t | x | t | x | t | t | t | t | t | t | x | t | t | t | t | v | t | v | t | v |
| E4_3 | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | t | x | t | t | t |
| E4_4 | v | t | x | t | v | x | v | x | t | x | t | x | t | v | t | t | x | x | t | x |
| E4_5 | x | t | t | t | v | t | x | t | x | x | t | t | v | t | t | t | t | v | x | x |
| E4_6 | t | t | t | t | t | t | t | t | t | t | t | t | t | t | v | t | t | t | x | t |
| E4_7 | t | v | x | t | t | v | v | t | t | v | t | x | t | t | v | v | t | t | t | t |
| E4_8 | t | t | t | t | t | t | t | t | x | t | v | t | t | t | t | t | t | t | t | t |
| E4_9 | t | t | t | v | t | t | t | t | t | t | t | v | t | x | t | t | t | t | t | t |
| E4_10 | t | t | t | v | t | t | x | t | t | t | t | v | t | v | t | t | t | t | t | t |
| E4_11 | t | v | v | x | x | t | t | x | t | t | t | t | x | x | t | t | t | t | t | t |
| E4_12 | t | t | t | t | t | t | t | t | v | v | v | t | v | t | t | x | v | t | t | v |
| E4_13 | v | t | v | t | t | v | t | v | t | t | x | t | t | t | x | t | t | t | v | t |
| E4_14 | t | x | t | t | t | x | t | v | v | t | t | t | t | t | t | t | t | t | t | t |
| E4_15 | t | t | t | t | t | t | t | t | t | t | t | t | x | t | x | x | v | t | t | t |

**Table S3.** Split #3 (example of Figure 8): comparison of ML models' performance for training, validation, and testing dataset.

| Time lag | Model | Training | | | | Validation | | | | Testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RMSE (m) | MAE (m) | CC | NSE | RMSE (m) | MAE (m) | CC | NSE | RMSE (m) | MAE (m) | CC | NSE |
| 3 h | SVR | 0.063 | 0.034 | 0.9989 | 0.9977 | 0.066 | 0.031 | 0.9989 | 0.9978 | 0.059 | 0.035 | 0.9990 | 0.9979 |
| | MLP | 0.079 | 0.041 | 0.9982 | 0.9964 | 0.078 | 0.041 | 0.9985 | 0.9969 | 0.073 | 0.043 | 0.9984 | 0.9968 |
| | LSTM | 0.070 | 0.036 | 0.9986 | 0.9972 | 0.064 | 0.034 | 0.9990 | 0.9979 | 0.059 | 0.034 | 0.9989 | 0.9979 |
| 6 h | SVR | 0.115 | 0.065 | 0.9962 | 0.9922 | 0.112 | 0.058 | 0.9968 | 0.9936 | 0.122 | 0.072 | 0.9957 | 0.9910 |
| | MLP | 0.128 | 0.073 | 0.9954 | 0.9904 | 0.133 | 0.079 | 0.9957 | 0.9910 | 0.137 | 0.083 | 0.9943 | 0.9886 |
| | LSTM | 0.121 | 0.071 | 0.9958 | 0.9914 | 0.122 | 0.072 | 0.9963 | 0.9924 | 0.125 | 0.075 | 0.9952 | 0.9904 |
| 9 h | SVR | 0.235 | 0.120 | 0.9842 | 0.9672 | 0.228 | 0.106 | 0.9870 | 0.9738 | 0.217 | 0.128 | 0.9863 | 0.9714 |
| | MLP | 0.242 | 0.133 | 0.9829 | 0.9653 | 0.241 | 0.127 | 0.9854 | 0.9706 | 0.221 | 0.141 | 0.9851 | 0.9703 |
| | LSTM | 0.239 | 0.134 | 0.9833 | 0.9662 | 0.239 | 0.133 | 0.9861 | 0.9712 | 0.223 | 0.143 | 0.9849 | 0.9698 |

**Table S4.** Split #20 (example of Figure 9): comparison of ML models' performance for training, validation, and testing dataset.

| Time lag | Model | Training | | | | Validation | | | | Testing | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RMSE (m) | MAE (m) | CC | NSE | RMSE (m) | MAE (m) | CC | NSE | RMSE (m) | MAE (m) | CC | NSE |
| 3 h | SVR | 0.072 | 0.039 | 0.9989 | 0.9978 | 0.065 | 0.031 | 0.9988 | 0.9977 | 0.071 | 0.034 | 0.9985 | 0.9969 |
| | MLP | 0.086 | 0.051 | 0.9985 | 0.9969 | 0.078 | 0.045 | 0.9984 | 0.9966 | 0.075 | 0.040 | 0.9982 | 0.9965 |
| | LSTM | 0.075 | 0.047 | 0.9989 | 0.9976 | 0.067 | 0.038 | 0.9988 | 0.9975 | 0.069 | 0.036 | 0.9986 | 0.9971 |
| 6 h | SVR | 0.146 | 0.078 | 0.9956 | 0.9909 | 0.112 | 0.057 | 0.9965 | 0.9930 | 0.131 | 0.072 | 0.9952 | 0.9892 |
| | MLP | 0.152 | 0.100 | 0.9953 | 0.9901 | 0.133 | 0.084 | 0.9952 | 0.9900 | 0.140 | 0.082 | 0.9939 | 0.9878 |
| | LSTM | 0.146 | 0.099 | 0.9959 | 0.9909 | 0.122 | 0.078 | 0.9961 | 0.9916 | 0.131 | 0.075 | 0.9947 | 0.9893 |
| 9 h | SVR | 0.259 | 0.138 | 0.9862 | 0.9714 | 0.229 | 0.106 | 0.9854 | 0.9704 | 0.238 | 0.129 | 0.9840 | 0.9645 |
| | MLP | 0.258 | 0.168 | 0.9858 | 0.9716 | 0.243 | 0.139 | 0.9835 | 0.9669 | 0.241 | 0.143 | 0.9820 | 0.9636 |
| | LSTM | 0.263 | 0.184 | 0.9864 | 0.9705 | 0.253 | 0.155 | 0.9826 | 0.9639 | 0.251 | 0.156 | 0.9807 | 0.9607 |

In the following figures (Figures S1 and S2), dashed lines indicate a ±20% error (relative to the peak level above the river bed, i.e. water depth).

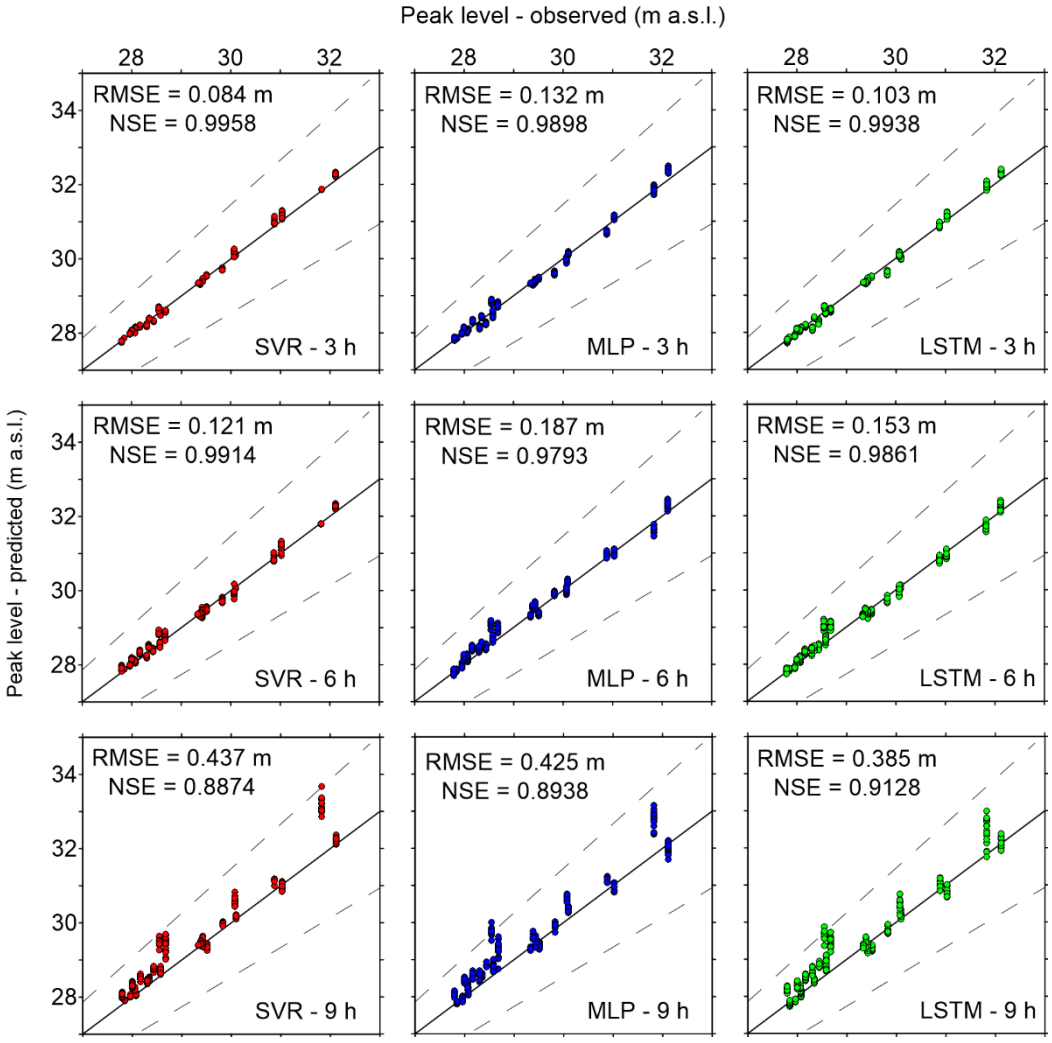


**Figure S1.** Comparison of observed and forecasted peak levels in Colorno (training dataset) for time lags of 3, 6, and 9 hours.

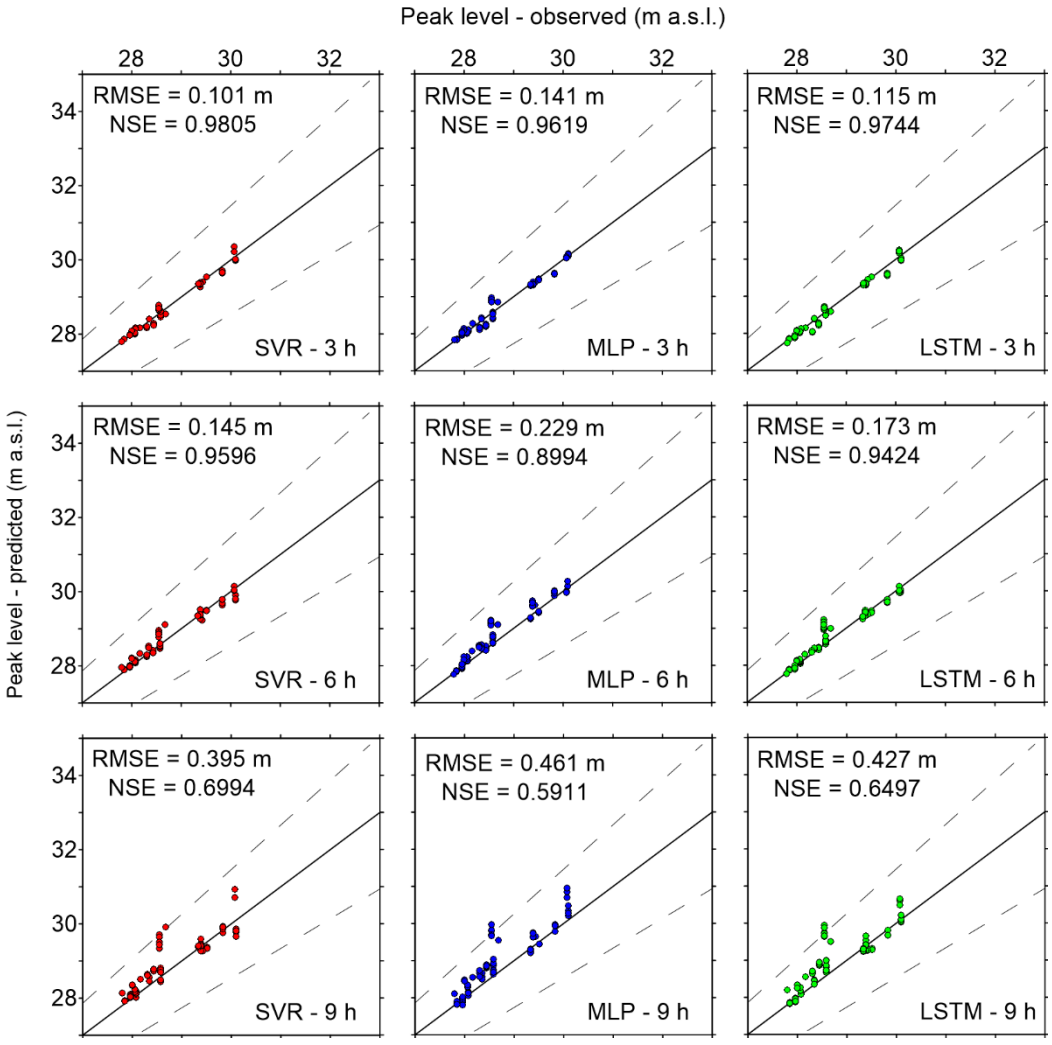


**Figure S2.** Comparison of observed and forecasted peak levels in Colorno (validation dataset) for time lags of 3, 6, and 9 hours.