The stream power variation in a GIS environment as an index to evaluate the most ’sensitive’ points of a river

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ABSTRACT

The note deals with the problem of measurement and variability, along the fluvial reaches of a hydrographic network, of the stream power, understood according to the definition originally provided by Bagnold (1966) “The available power supply, or time rate of energy supply, to unit lenght of a stream is clearly the time rate of liberation in kinetic form of the liquid’s potential energy as it descends the gravity slope S”. In formula: $\Omega = \rho\ g\ Q\ S$
where: Ω = stream power per unit of flow length (W/m) $\rho\ g$ = density x gravity acceleration = specific weight of the fluid (kg/m3) Q = liquid discharge (m3/s) S = slope of the considered reach (m/m)
Recent digital elevation models allow the calculation of channel gradient and consequently stream power with a finer spatial resolution, opening promising and novel opportunities to investigate river geomorphical processes and forms. The work carried out consisted in defining and implementing a methodological approach that could be automated within a geographic information system and that meets two requirements: 1) use input data that is easy to find as DEM at a low resolution; 2) estimate, in the best possible way and on the basis of the available data, the stream power and its variability along the considered stream. In particular, the methodological approach has been implemented in the GIS environment (GRASS Gis, Qgis), and it has been applied to a sample basin, highlighting its variability along the streams of a higher order (in practice the main stream and its most important tributaries). The sudden and more substantial variations of stream power were then related to the processes acting in the fluvial system. This approach has made it possible to highlight how the erosion, solid transport and sedimentation phenomena occurring along the fluvial reaches (and the geomorphological and geological-applicative problems that these involve, especially in anthropized areas), are correlated precisely to abrupt variations (increase/decrease) of the ”power” available. Hence the idea that automated and standardized screening of stream power variability along a stream can be used as a preliminary diagnostic element to identify the most ”sensitive” points of the same, on which to concentrate subsequent investigations (field checks, to verify the causes), aimed at mitigating the risk due to the dynamics of the riverbed.

INTRODUCTION

The term *Fluvial dynamics* is generally used with reference to water flow, sediment movement, and to bedforms resulting from the interaction between flow and sediment transport in alluvial channels.

Stream Power is a very significant quantity in sediment transport studies. Stream Power represents the rate of doing work (in transporting water and sediment). It is commonly expressed either as stream power per unit length (Ω) or power per unit bed area (ω). Bagnold (1966) denotes the stream power as:

$$\Omega = \rho \cdot g \cdot Q \cdot S \tag{1}$$

where: Ω = stream power per unit of flow length (W/m) $\rho\ g$ = density x gravity acceleration = specific weight of the fluid (kg/m^3) Q = liquid discharge (m^3/s) S = slope of the considered reach (m/m)

Stream Power (SP) represents the rate of energy dissipation through friction and work, with the bed and the banks, per unit length of a stream. The SP has been widely used to assess the sediment transport and, in general, the channel pattern evolution in a river (Bagnold, 1977; Nanson and Croke, 1992; Ferguson, 2005; Comiti and Mao, 2012; Knighton, 1999). Extensive use of Geographic Information System (GIS) and the geographical data available (frequently provided as open data) allow a local determination of SP in any section of a river. The two parameters most affected by uncertainty in their determinations are flow discharge and slope. The flow discharge is a parameter difficult to calculate as it depends of several aspects as upstream area basin, basin permeability, rainfall, etc.. and by the rainfall-discharge model. Modern digital elevation models (DEMs) allow the quantification of slope channel at high resolution, exploration of SP variability along the full length of a river Barker et al. (2009); Bizzi and Lerner (2015), and offer the opportunity to use SP as a stream assessment tool Vocal Ferencevic and Ashmore (2012).

This work uses a GIS approach to define the local value of SP combining the hydrological approach to determine the flow discharge as exposed by Casagrande et al. (2013) and the slope derived from DEM raster. As presented in the equation 1 the transport capacity of a stream is a direct function of flow discharge and local slope and for such reason the correct determination of the slope is crucial for a correct stream assessment.

The proposed approach have been applied to the river Topino in Umbria region (central Italy).

Study area

One of the most important river that across the Umbria region in central Italy is the Topino River, a tributary of Tiber River. This river belongs to the hydrographic basin of Topino-Marroggia 1 that incorporate two different basins: the basin of Marroggia-Teverone-Timia and the basin of Topino River s.s. (www.bonificaumbra.it).

From a geological point of view (Cencetti, 1993), the River Topino basin is set almost entirely on the Miocene terrigenous deposits of the ”Marnoso-Arenacea” Formation (Umbrian-Marchean Series), consisting of an alternation of marls and sandstones in variable proportions. In its middle valley, however, the river receives the contributions of tributaries that, on the right and left hydrographic, are born from the carbonate reliefs of M. Subasio (to the west) and the Foligno Mountains (to the east). The last reach of the Topino forms a wide alluvial fan at its outlet in the Umbrian Valley (Foligno-Spoleto plain) which represents the eastern ”branch” of the Ancient Tiberine Lake, filled in the Pliocene and Pleistocene by clastic sediments in lacustrine and fluvio-lacustrine facies (conglomerates, sands and clays).

1 METHODS

The procedure here proposed has the aim to define the value of the SP along any cross section of a river using a GIS procedure as simple and accurate as possible and based on the available data especially for the determination of the local slope.

1.1 Peak flow discharge

The estimated maximum expected peak flow in a particular cross-section of a riverbed, for a given return period, is a problem difficult to solve, due to the great number of involved factors. In Italy, the Basin Authority of River Tiber performed a method in order to evaluate the peak flows in the watersheds within the Tiber Basin di Bacino del Fiume Tevere (1996). This study used data from 165 gauge stations, distributed within the Basin, and It proposed a methodology that combines the results of regional precipitation analysis of duration from 1 to 24 hours with the Curve Number method (Soil Conservation Center, 1972), which allows to quantify the volume of net rainfall. This procedure has been implemented in a GIS system, creating a series of GRASS GIS scripts that, by applying the proposed procedure, determines the peak flow rate for each point of the hydrographic network.

1.2 Slope determination

The slope determination is a crucial aspect for the SP evaluation along a reach. A Digital Elevation Model (DEM) represents the starting point to derive the slope map. In GIS the slope maps are obtained using moving window (3x3 in many cases) following the main method available in GIS software as EVANS (1972) or Zevenbergen and Thorne (1987).

In this work the DEM provided by the European **Copernicus Project** called *European Digital Elevation Model (EU-DEM), version 1.1*. This DEM has a planar resolution of 25 m with a vertical accuracy of 2.9 m as assessed in https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem. Especially when it is necessary to calculate the slope for fluvial stretches, the normal proposed

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approaches are no longer valid Hengl and Reuter (2008). In fact, for the given *eu-dem* it appears that the *minimum evaluable slope* is of the order of:

$$\Delta S = \frac{\varepsilon}{cellsize} = \frac{2.9}{25} \approx 0.11$$

Where ε is the vertical accuracy.

Therefore the minimum evaluable slope is several orders of magnitude bigger then the slope that that the river presents in floodplain that is around 0.001. For such reason in this paper the local slope is not calculated by the mean of the moving window using the classical GIS approach rather calculating the slope as the ration between the elevation drop and the real length of the reach. In particular for any cross section is considered a reach of 20 times the mean-width of riverbed where the cross section is in the middle (10 times upstream and 10 times downstream).

2 RESULTS AND DISCUSSION

This work envisaged the use of the GRASS GIS for the calculation, first of all, of the precise flow values relating to 72 points identified along the Topino River, from the confluence of Caldognola Creek, approximately near the town of Nocera Umbra (Nocera Scalo), up to the entrance of the river near Foligno, as shown in the figure 2 . These points have been identified in the river hydrographic network of the river under study and are each one of a distance equal to about 20 times the width of the riverbed. Subsequently, we proceeded to determine the slope values (S) of the channel. Therefore the river have been splitted into 71 reaches sections; the relative slope value has been defined for each of them. Once the necessary data (mean flow and relative slope of each section) were collected, the equation1 proposed by Bagnold (1966) was applied. The discharge values corresponding to 72 cross sections are showed in table 1, range between a minimum value of 304.92 m^3/s and a maximum value of 929.7 m^3/s.

n.punto	Q (m3/s)	n.punto	Q (m3/s)	n.punto	Q (m3/s)	n.punto	Q (m3/s)
0	304,92	21	517,61	43	644,26	64	925,27
1	476,89	22	518,38	44	643,52	65	928,36
2	476,89	23	518,64	45	642,84	66	928,41
3	476,78	24	517,72	46	643,04	67	934,83
4	478,06	26	556,81	47	641,97	68	927,2
5	480,11	27	557,66	48	642,13	69	926,58
6	470,73	28	556,96	49	643,02	70	925,99
7	468,96	29	557,66	50	643,64	71	924,51
8	468,78	30	558,06	51	643,33	72	929,7
9	468,61	31	557,51	52	652,83		
10	474,95	32	557,79	53	653,73		
11	474,66	33	557,7	54	654,08		
12	474,07	34	557,13	55	653,42		
13	473,32	35	561,66	56	652,88		
14	472,85	36	560,95	57	652,29		
15	472,26	37	561,21	58	652,94		
16	471,98	38	560,24	59	652,12		
17	471,1	39	641,56	60	652,9		
18	470,77	40	637,86	61	652,73		
19	485,97	41	644,96	62	651,81		
20	511,94	42	643,86	63	650,98		

Table 1. Values for the peak flow corresponding to the 72 cross sections along the Topino River.

As showed in figure 3, by plotting the identification number of the reach with the respective SP value, some evident peaks are observed:

- The first peak have a SP value of 300477.8 W/m^2, corresponding to the reach number 5. This section is also the one characterized by greater slope (6.4%).
- The second peak presents a stream power value of 223900.6 W/m^2, corresponding to the reach number 26.

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- The third peak has a stream power value of 263767 W/m^2, corresponding to the reach number 37.
- The fourth peak presents a stream power value of 296577.4 W/m^2, corresponding to the reach number 43.
- The fifth peak presents a stream power value of 282906.4 W/m^2, corresponding to the reach number 46.
- The sixth peak presents a stream power value of 288100.4 W/m^2, corresponding to the number 52
- The seventh peak presents a stream power value of 218971.2 W/m^2, corresponding to reach number 67.
- In reaches ranging from number 6 to number 25 and from 29 to 35, the calculated SP values do not differ much. The image (figure 4) shows the trend of the SP values calculated in each reach.

3 DISCUSSION

Analyzing the trend of the SP shown in the figure 4, it appears that there are 7 peaks along the studied river.

As an example, the reach 5 was taken analyzed near the village Vittiano (Pg), characterized by the maximum value of the SP (300477.8 W/m). Even the slope results to have the maximum value compared to all the other reaches (6.4%). This denotes the strong influence that the slope parameter causes on the SP value. The following figure 5 shows the reach studied where appears the strong correlation between the SP and the local channel meandering morphology . The external banks of the riverbed, characterized by a bigger water velocity, shows erosional phenomena; for such reason it is placed a bank defense works.

Other reaches to analyze are 13 and 21. Both are characterized by very low SP values (32496.8 W/m for 13 and 15131.2 W/m for 21). The SP values are noticeably lower than the average of the other reaches although they have a discharge values comparable to the previous reaches: this is due to the significantly lower slope values (equal to 0.007 (0.7%) for section 13 and 0,003 for section 21). As shown in Figure XX, the presence of rotational/translational slope close to the riverbed, could justify the strong reduction of the channel slope and consequently of the SP value.

4 CONCLUSIONS

The paper uses the equation related to the stream power, proposed by Bagnold (1966), was examined, analyzing the variation of its values along a given water course and how they can be related to the geomorphological structure of the riverbed and river processes. The stream power represents the dissipation of the potential energy per unit of channel length and it is obtained by the product of the flow rate (m^3/s), the slope of the channel (m/m), the density (kg/m^3) and the gravitational acceleration (m/s^2). It is therefore expressed in W/m and can be considered as a measure of the main driving forces acting within a channel, influencing the ability of a waterway to transport sediments.

River Topino was chosen as a case study, considering the portion that extends from the confluence with Caldognola Creek, close to the town of Nocera Umbra (Nocera Scalo), until its entrance into the town of Foligno.

The variations of SP appeared to be strongly correlated to the shape of the channel and to the processes of erosion/deposition, and how its value can be a cause or consequence of instability phenomena. In some reaches, a strong correlation between the SP values and the channel morphology was observed, especially in correspondence with landslides located close to the riverbed or that involves directly the riverbed (landslide dam). In reaches where the SP value is very high, are present erosion/instability phenomena; the latter, in turn, are often placed upstream or close to reaches characterized by lower SP values (low slopes).

The work shows how the determination of the SP values can provide useful indications on river dynamics processes. It is clear that a large-scale analysis within a river basin could indicate, in a preventive and forecasting way, the areas most ”sensitive” to changes, as they are potentially subject to instability phenomena caused by the fluvial dynamics.

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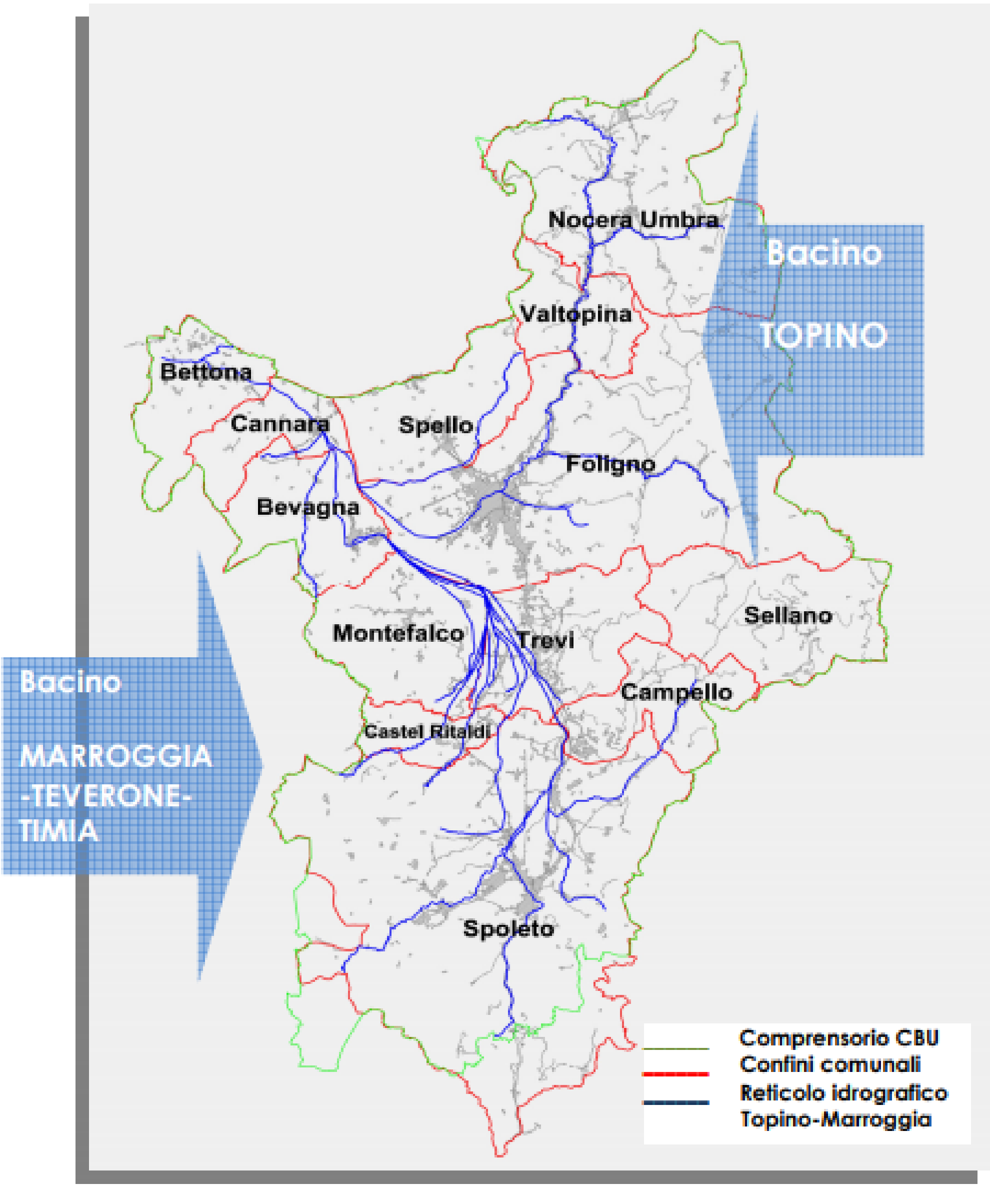

Figure 1. Hydrographic basin of Topino-Maroggia river, divided in Maroggia-Teverone-Timia Basin and Topino basin (source www.bonificaumbra.it).

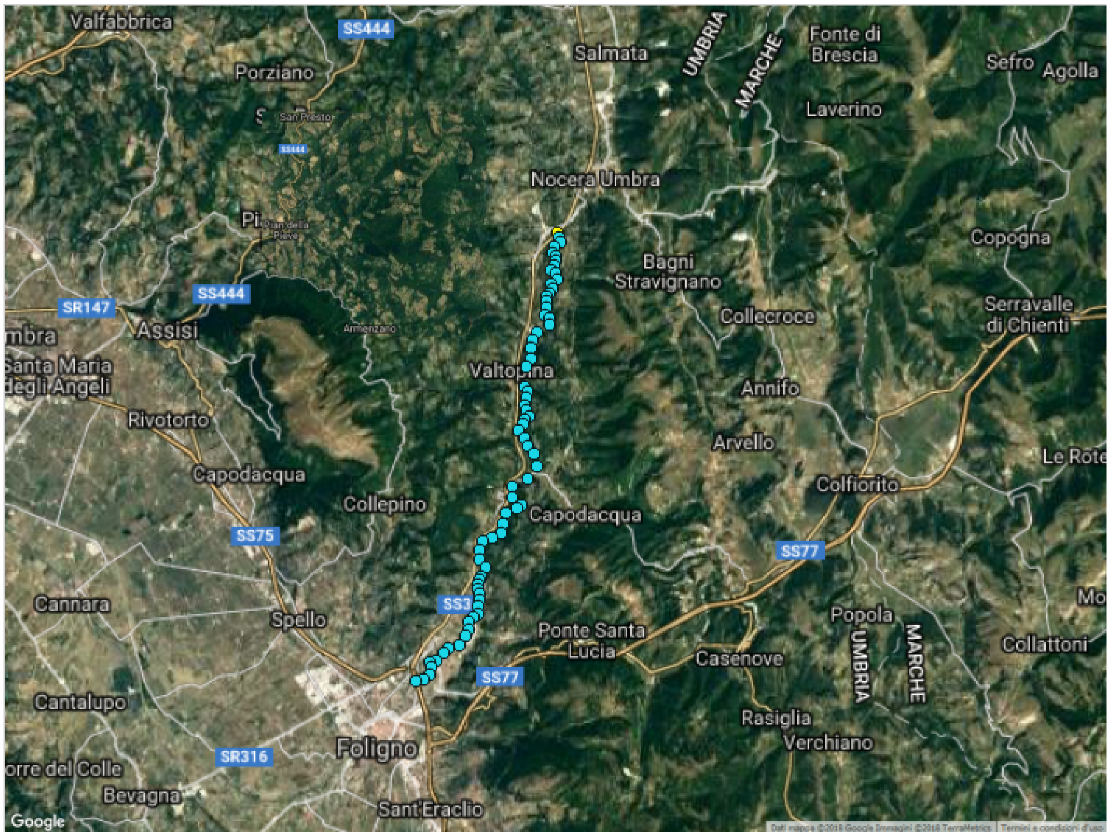

Figure 2. Identification of points along the studied reach of Topino River (from Google Hybrid)

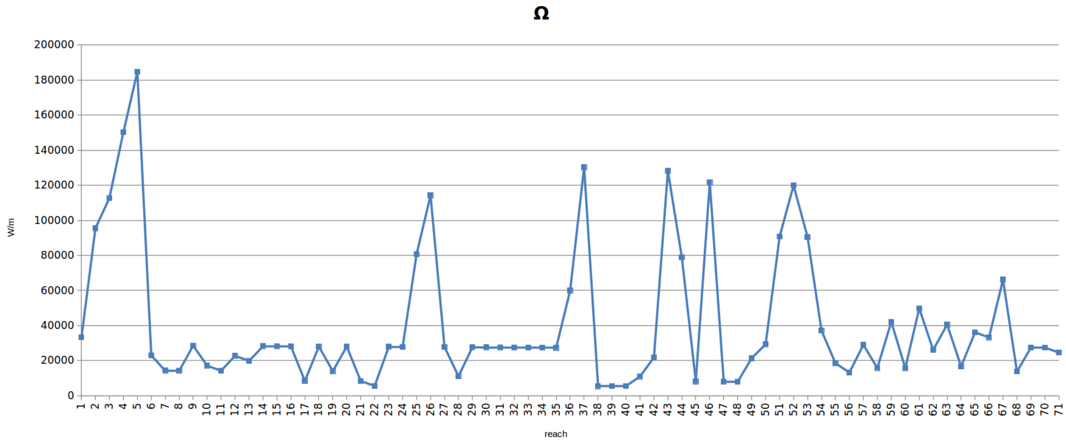

Figure 3. linear representation for the Stream Power values along the reach of the Topino river.

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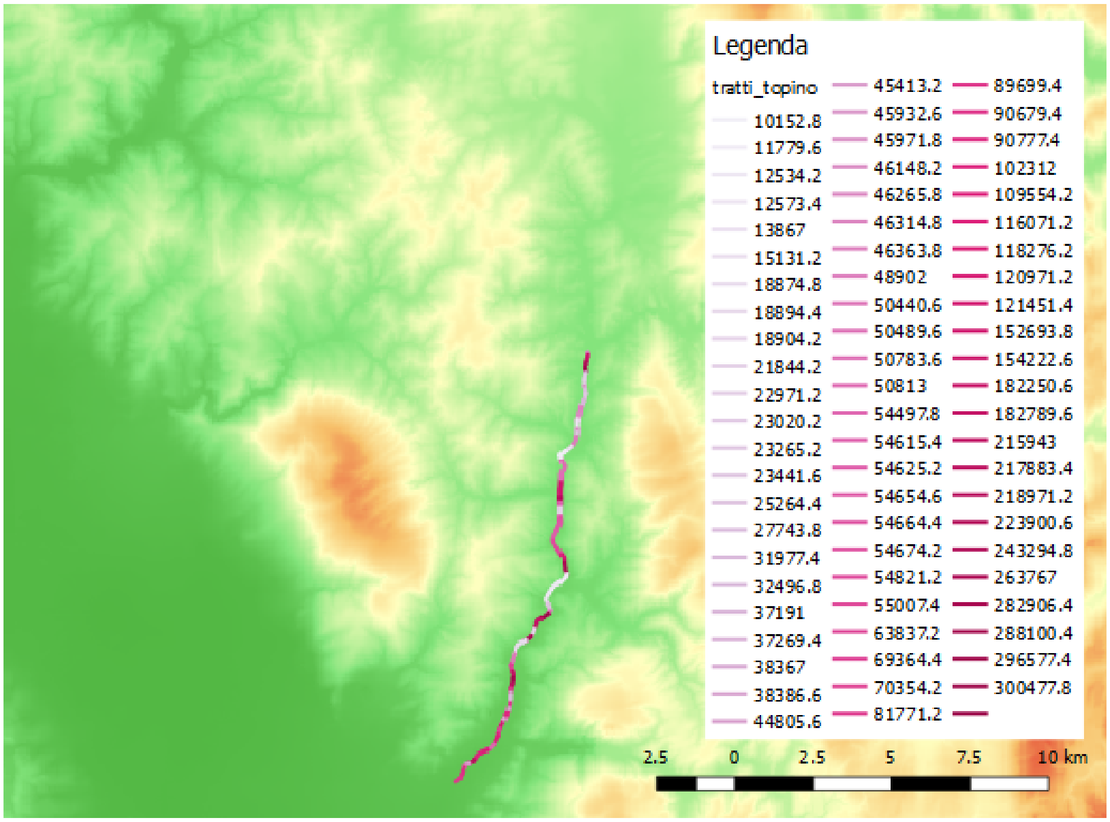

Figure 4. Distribution of the SP values along the reaches of the F. Topino studied. The clearest features are those characterized by a lower SP value, while those characterized by a more intense purple color are those where a the SP is higher.

Figure 5. Aerial photo of the reach 5 - Topino River

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