Full title

BASELINE TO EVALUATE OFF-SITE SUSPENDED SEDIMENT-RELATED MINING EFFECTS IN THE ALTO TAJO NATURAL PARK, SPAIN

Short title

SSC BASELINE TO EVALUATE OFF-SITE EFFECTS OF MINING

Ignacio Zapico[1,2,*], Jonathan B. Laronne[3], Cristina Martín-Moreno[2], José F. Martín-Duque[1,2], Ana Ortega[2], Lázaro Sánchez-Castillo[4]

1 Geoscience Institute, IGEO (CSIC, UCM), 28040 Madrid, Spain

2 Geodynamics Department, Complutense University, 28040 Madrid, Spain

3 Department of Geography and Environmental Development, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

[4] Department of Geologic Engineering, Polytechnic University of Madrid, Madrid 28003, Spain

*Corresponding author: E-mail: izapico@ucm.es

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ldr.2605

ABSTRACT

Mining is a human activity with considerable environmental impact. To evaluate such impacts, international laws require undertaking local studies based on direct sampling to establish baseline conditions of parameters modified by human activities. Mining takes place near the Alto Tajo Natural Park, where a suspended sediment concentration (SSC) baseline is required to determine whether mining affects water quality. To this end we have monitored the Tajo River and its tributary the Tajuelo following Before-After Control-Impact (BACI) techniques, recommended by Australian and New Zealand laws, requiring a specific method based on continuous monitoring and sampling to enable evaluation of SSCs. An SSC baseline has been defined at stations situated upstream of the mining area and compared with those downstream. The highest detected SSC upstream of the Tajuelo mines was 24 g l^{-1} whereas the highest simultaneous downstream value was 391 g l^{-1}, more than one order of magnitude higher than the supposed baseline (24 g l^{-1}). Additionally, this value is 1000 times more than the average concentration of 25 mg l^{-1}, used by the European Union until 2015, to guarantee the quality of salmonid waters. Following a BACI approach, a statistically significant SSC impact has been identified. The mined areas are the only source that can explain this increase. This is the first instance that such an increase and baseline have been found using this method. BACI is a simple and reliable method recommended for studying degraded areas rather than an irrelevant, fixed standard as included in most international laws.

KEY-WORDS: suspended sediment, BACI, mining activity, baseline, Natural Park

INTRODUCTION

Opencast mining impacts all ecosystem components: substrata, topography, hydrology, soil, vegetation, fauna, atmosphere and landscape (Soulard *et al.*, 2015; Tarolli & Sofia, 2016) and at mine sites there are on-site effects. In addition, mining activity can also have downstream off-site effects. Among these, the water quality impact associated with sediment discharged from mines to the fluvial system is one of the most detrimental (Martín-Moreno *et al.*, 2016; McIntyre *et al.*, 2016). Changes in sediment fluxes have been shown to have detrimental ecological effects on fish populations and their ecosystems, such as reduction in visibility and oxygen availability, temperature rise, breathing difficulties and damages in spawning beds (Robertson *et al.*, 2006; Kjelland *et al*., 2015). Any and all these impacts can dramatically decrease fish and other organism populations. Furthermore, the increase in anthropogenic sediments can also damage the fluvial network in terms of infrastructures, such as roads and bridges or reduce the water capacity of reservoirs (Batalla & Vericat, 2011) and modify fluvial system dynamics, such as the deposition of bars and the dramatic increase in flooding (Pickup, 2008).

To evaluate whether mining off-site effects occur with respect to sediment dynamics, baseline parameters require definition. Once these baselines have been properly established, they can be used to compare before and after-mining impacts. This comparison can be undertaken through the so-called BACI (Before-After Control-Impact) technique (Smith, 2006).

Such control data are demanded by the European Commission (Directive 2006/44/CE) as well as by other public institutions worldwide, such as the United States Environmental Protection Agency (U.S. EPA, 2003a). Only the Australian and the New Zealand Environment and Conservation Council (ANZECC, 2000) law points out a specific method to monitor SSC impacts based on the BACI approach. Many additional studies highlight the need to undertake relevant measurements on this topic (Macklin *et al.*, 2006; Collins *et al*., 2011; Nordstrom, 2015). These studies point out that baseline values have to be defined at the most local scale of the river. In mined areas, baseline definition has been studied widely in association with hydro-chemical properties (Yanguo *et al.*, 2002; Oyarzun *et al.*, 2011). Only few publications exist as far as a sediment transport baseline is concerned (Pentz & Kostaschuk, 1999; Chalov, 2014; Messina & Biggs, 2016). One of these is that on the Ngarradj catchment (Australia), for which a baseline of several parameters including Suspended Sediment Concentration (SSC) (Evans *et al.*, 2004) and for bed-material grain size (Saynor *et al.*, 2006) were defined. Both of these parameters are important to determine whether the sediment from mined areas modifies the sediment dynamics of the rivers in the Ngarradj catchment.

Other studies and relevant laws defined sediment-related baselines using a threshold value (U.S. EPA, 2003b). This is problematic because natural-fluvial sediment transport dynamics are complex and highly variable depending on a variety of parameters such as rainfall depth and duration, maximum rainfall intensity, peak flow, runoff occurrence and available sediment sources (Walling *et al.*, 2001; Alexandrov *et al.*, 2003; Rovira & Batalla, 2006; Nadal-Romero *et al.*, 2008; Regües & Nadal-Romero, 2013). Therefore, it is necessary to have a wide range of SSC values, representative of the different fluvial conditions, to provide a relevant baseline dataset.

Studies of suspended sediment have been undertaken worldwide. Some have monitored rivers taking into account the high variability of SSC during several hydrological years (Walling *et al.*, 2001; García-Ruiz *et al.*, 2008; López-Tarazón *et al.*, 2009). These have been accomplished to determine the total budget of catchments where human activity is significant, neither to establish a baseline nor to apply a BACI approach.

Our study seeks to be such a local study based on monitoring SSC in the kaolin mining area located near the Alto Tajo Natural Park (ATNP), Central Spain, by using BACI procedures. These are the most appropriate methods to study impacts described in an international law. We use the BACI with an aim, to improve a very narrow interpretation (fixing a limit of 25 mg l^{-1}) of the European law (Directive 2006/44/EC). The ideal manner to establish an SSC baseline to determine a likely impact due to mining activity would have been to measure each pair of stations, upstream and downstream of the disturbed area, before mining started and during its operation. This is impossible when mining began previously, as it did in the Alto Tajo in 1965 and holds for most mining areas worldwide, for which a pre-mining historic database is lacking. Another reliable method to establish an SSC baseline could have been the simultaneous monitoring of other catchments without mines but with features similar to those of the impacted streams. This is also impossible in our study area. We therefore chose a third recommended option: to install stations upstream and downstream of the potential mined sediment sources (Smith, 2006).

The principal aims of this study are: (i) defining the SSC baseline for forested areas (such as the temperate Mediterranean Tajuelo stream and the Tajo River) that receive water from mining areas; and (ii) evaluating if there is an impact in SSC associated with runoff derived from the mining areas. To accomplish these objectives an SSC Monitoring Network has been erected to record relevant data. Our hypothesis is that following a BACI approach, it is possible to determine the SSC effect of mined areas.

MATERIAL AND METHODS

Study Area

Alto Tajo Natural Park (ATNP) and mining area

The ATNP is located in East-Central Spain (Fig. 1). This protected area was established in 2000 by a regional law (DOCM, 2000) due to its outstanding biodiversity and particularly its high quality aquatic ecosystems. The ATNP area (105,721 ha) is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones) underlain by sandy sediments, in which the Tajo River has incised a canyon system longer than 100 km and up to 400 m in depth (Carcavilla *et al.*, 2011). The sandy sediments contain the kaolin (Arenas de Utrillas Formation) exploited in several mines (Olmo & Álvaro, 1989; González Amuchastegui, 1993). Several kaolin mines very near the ATNP are located in the upper reaches of the stepped slopes. This activity began in 1965.

The most common soils are calcaric cambisols, mollic leptosols and rendzic leptosols on top of the mesas, and carbonate colluvia with calcaric cambisols on the slopes (IUSS Working Group WRB, 2007). The vegetation is representative of Mediterranean continental environments, with communities dominated by *Juniperus thurifera*, *Pinus nigra* subsp. *salzmanii* and *Quercus faginea* (MARM, 1997–2006).

The climate is temperate Mediterranean with dry and mild summers (Csb, according to Köppen 1918) and with a continental influence. Mean annual precipitation is 783 mm and mean annual temperature is 10 °C (AEMET, 2013). Seasonally, this area is characterized by long and cold winters with snow being common, and short and dry summers. The spring and fall are usually wet. The rainfall erosivity factor, R (equivalent to the R factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

Tajuelo catchment

The Tajuelo is one of the tributaries of the Tajo River (Fig. 1). With a 30 km^2 watershed area, the stream flows along 9 km at an average slope of 4% from an altitude of 1397 m above sea level (a.s.l) to the confluence with the Tajo River at 1033 m a.s.l. The bedrock of the upper part of the watershed is composed of limestones and dolostones, whereas the lower part is underlain by sandy sediments containing the mined kaolin (Weald and Utrillas Formation). This perennial stream has no gauging station; therefore, historic hydrologic data are unavailable. The only existing information is that measured during our monitoring activity between 2011 and 2013. For this period, stage rises typically occur in spring and fall with a recorded 33.9 m^3 s^{-1} maximum water discharge. Minimum flows (~0.06 m^3 s^{-1}) occur in summer.

The only village in the Tajuelo catchment is the small (0.08 km^2 with a population of 131) Poveda de la Sierra. Two mines are hydrologically connected to the Tajuelo. The María José mine (0.55 km^2) is active since 1965 and has sediment ponds that store the bedload eroded and transported within the mine, decanting most of the suspended sediment. The Nuria (0.62 km^2) mine is inactive since 2007, having neither ponds nor effective reclamation. In addition, there is one area at the confluence of the María José and the Nuria mines, with traditional reclamation (outslope-benches) directly connected to the fluvial network.

The studied Tajo River reach

The stretch of the studied Tajo River is located between Poveda and Peñalen bridges (Fig.1). The length of this stretch is 5.5 km with an average slope of 0.4%. Due to its low slope, its bankfull width (10 m) and its very low sinuosity, it is classified as pattern 2 (Schumm, 1981). Here carbonate precipitation is very common forming small tufa barriers. The nearest gauging station with historic discharge data (1945-2015) is the “3001 Peralejos de las Truchas”, located 15 km upstream of the upper sampling location on the Tajo. For this period the respective average mean and maximum annual discharges were 3.1 and 15.5 m^3 s^{-1} and the maximum water discharge was 258 m^3 s^{-1} (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. Comm., 2015).

Methods

We have only focused on SSC, not on bedload nor on solution because: (i) the mines are required to maintain sediment ponds that store all the bedload eroded from within the mines, and also for decanting at least some of the suspended sediment; (ii) the abandoned mines have to be restored in a manner that produces mostly sediment similar to the natural forested landscapes of the surroundings; and (iii) the dissolved component has minor geomorphic and hydrologic relevance in the area.

Sampling design: monitoring network and BACI techniques

Two recording stations were installed in each river, four in total (Fig. 1): two stations upstream of the mining areas (UTJ: Upper Tajuelo, UTA: Upper Tajo) and two downstream of them (DTJ: Downstream Tajuelo, DTA: Downstream Tajo). The data from the upstream stations were used to define the baseline. The BACI methodology requires a baseline: a database of instantaneous water samples used to establish trigger values: if these are surpassed, authorities or companies can investigate unacceptable values and to decide how to avoid this condition. We thus focused on instantaneous values rather than mine-related before-after sediment yields. Yields are useful to quantify the entire impact of a given activity, but not to generate data for alarms. The downstream stations were compared with the upstream ones to quantify the impact of mining areas. BACI techniques are based on spatial comparison of pairs of samples taken in rivers at “the same time” before and after receiving water from the mined areas. Its aim is not to study the sediment dynamics of a catchment with respect to human activities, but to quantify the impact of one specific present activity in a given river reach. It requires an identical and contemporaneous sampling methodology.

Field equipment, monitoring and lab procedures

Rainfall was measured by two recording tipping-bucket rain gauges (Davis *Rain Collector II*) installed in the area (Fig. 1). Water level (discharge) and SSC were monitored during the 2012-2013 and 2013-2014 hydrological years (1 October – 30 September). Water depth in the Tajuelo was recorded every 10 min by a pressure sensor (Global Water WL16) at DTJ (Fig. 1). Water level data were transformed to discharge by a stage-discharge rating curve. Discharge was determined by the product of average velocity (electromagnetic current meter, Flo-Mate 2000 of Hach) and cross sectional wetted area (Whiting, 2003). As the pressure sensor broke down during 15/03/2014-02/07/2014, we made use of rain gauge and weekly field reports as well as continuous discharge from the nearby Merdero Catchment to define to which event and each sample belonged. The Merdero catchment area is a half of the Tajuelo's, but their runoff response is quite similar in terms of number and relative size of flow events. The possible differences were corrected with the weekly field data. For the Tajo we used data recorded by the Tajo Water Authorities at the ‘AR02 *Tajo en la Rocha*’ gauging station (Confederación Hidrográfica del Tajo, pers. comm., 2015), located 9 km downstream of DTA. We also used two pressure sensors (Mini-Diver at UTA and Rugged Level Troll 100 at DTA) corrected for barometric pressure (Rugged BaroTroll).

SSC was determined by direct sampling at each station using two different methods: (i) manual sampling by the depth-integrating approach (Hicks & Gomez, 2005) and (ii) automatic sampling with siphon samplers (Graczyk *et al.*, 2000) - bottles situated at different fixed heights on a channel bank high enough above the bed to exclude bedload entry (Fig. 1). Cross section and depth integration calibration were not undertaken because they are not required in the BACI. Imperative for this study was the guarantee that the samples were contemporaneously taken by the same method and cross sectional sampling position.

The four stations were visited weekly and sampled by depth integrating while bottles of the siphon samplers were replaced when necessary. Most of the manual samples were self-evidently collected during base flow. Those from the siphon samplers represent rising stages. Altogether 403 samples are available (Table 1). For each of the streams there was no correspondence in the number of samples taken upstream and downstream due to several factors:

i) At times the number of samples filled in siphon samplers were unequal (e.g., location may have had one bottle more or less than the other due to the varying water heights at each location);
ii) some siphon samplers were lost because a bottle was torn from the sampler by fast flows;
iii) at times stream conditions prevented undertaking manual depth integration sampling in one of the stations but not in the other.

Approximately 0.5 L of water was sampled and dried in the laboratory to determine the SSC.

Data analysis

Each sample was identified by time, date, location and stage (base flow, rising limb or recession). Siphon samples were related to continuously logging water stage and stage sensors. Although in each stream we use water discharge data measured by different stage sensors, the number of events recorded by them are identical as required by the BACI technique.

In order to define the baseline, the SSC database for stations UTA and UTJ were processed to calculate maximum, minimum and average values with regard to stage and season. Had the number of samples been much larger a differentiation based on sampling methodology could have been made. However, these calculations were made for SSC data derived from both depth integration and siphon samples. Using the BACI technique, we assume that the SSC data measured in upstream stations represent water without runoff from mining areas. These were compared to SSC data derived from stations located downstream of mining areas. For each stream we constructed a paired SSC database of contemporaneous UTA-UTJ and DTJ-DTA; the pairs were either only from depth integration or only form siphon sampling techniques. A student t-test was applied to each set (as common in other BACI studies – see Smith, 2006) assuming as null hypothesis that the mean difference between each data pair is 0 and, therefore, no SSC increase occurs due to mining. Each of the two compared samples derive from the same stream, hence they are paired. In these cases, the technique is known as BACIP, Before-After Control-Impact Paired (Wheater & Cook, 2005; Smith, 2006).

RESULTS

Water discharge

During the monitoring period there were 37 flow events of which 20 occurred in the first year and 17 in the second. In the Tajuelo mean discharge was 0.6 m^3 s^{-1} during the first year for which data are available. In the Tajo the mean water discharge was 9.6 and 6.8 m^3 s^{-1} during the first and second years, respectively. Maximum instantaneous discharges for these years were 33.8 and 70.5 m^3 s^{-1} for the Tajuelo and Tajo River, respectively. Run-off volume for the Tajo was 303.7 hm^3 the first year and 232.6 hm^3 the second. For the Tajuelo the first year runoff volume was 29.4 hm^3. Fig. 2 shows hydrographs for the Tajuelo stream and the Tajo River.

This study lasted two years. To what extent is it representative of past years? The respective mean and maximum instantaneous water discharges during the study period were 3.4 and 74.6 m^3 s^{-1} as recorded at the ’3001 Peralejos de las Truchas’ gauging station (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. comm., 2015). Fig. 3 shows a comparison of the peak discharge of the study period with the historic database of peak discharges. The latter is available for the Tajo River station 3001 located upstream of our study area. The maximum instantaneous water discharge in our study period is almost identical to the long-term maximum instantaneous water discharge. Therefore, we deduce that our results are representative.

Comparison of SSC at upstream vs downstream stations

We acquired samples from 24 events; 15 from the first year and 9 from the second. Twelve rises (4 from the first year and 8 from the second) were too small to be sampled because water level rise was insufficient to fill the bottles. One event was not sampled as personnel were unavailable. In total, 105 pairs of samples for the Tajuelo and 50 for the Tajo were collected. DTA samples are available only for the second hydrological year. All UTA samples were used to define the baseline and only second year samples were used to the UTA-DTA comparison.

Four stations have similar values of SSC up to the third quartile (Table 2). In contrast, the maximum values differ markedly, especially downstream of the mining areas. Upstream of the mining areas the maximum registered SSCs are similar: 24.4 g l^{-1} in the Tajuelo and 26.2 g l^{-1} in the Tajo. In contrast, the maximum SSC downstream of the mining areas was 52.4 g l^{-1} in the Tajo and 391 g l^{-1} in the Tajuelo. Fig. 4 shows a comparison among the highest values of SSC sampled in the rising limb of flow events that occurred during the study period, including only 15 - those for which samples were available in both stations.

Maximum SSC values registered in each pair of stations for a single event (see Table 3) are a16-fold increase in event 15 on the Tajuelo and a 38-fold increase in event 27 on the Tajo. These increases are statistically supported by applying a student t-test according to the BACIP technique to each data series. For the Tajuelo there is a significant difference ($p < 0.01$) between the samples taken at UTJ and at DTJ at the 99% confidence level. Similarly, in the Tajo ($p < 0.01$) there is a significant difference between the UTA and DTA samples at the 92% confidence level. Table 3 also shows SSC for one of the events with insignificant rises.

Baselines for the Tajo River and the Tajuelo Stream

The upstream stations are very similar with regard to mean, coefficient variation and maximum values of SSC (Table 2). The SSC baseline is defined for the Tajuelo and the Tajo by values summarized in Table 4. Maximum values occur on the rising limb of winter-spring events; the lowest in summer base flow. Summer rainfall events were insufficiently intense or lengthy to produce water level rises in either stream.

DISCUSSION

The BACI approach

There are few studies (Walling & Fang, 2003; Messina & Biggs, 2016) where mining impact on SSC has been measured. Some of them were undertaken by establishing annual sediment loads for a whole catchment. They show that total sediment loads continuously increase for the entire catchment, but no evidence is available as to where mining run-off is produced. Few other studies (Balamurugan 1991; Chalov, 2014) compared the annual sediment load following the before-after mining impact scheme, thereby identifying the impact using SSC-Q or NTU-SSC rating curves. These analyses allow identification of an SSC impact, but they do not establish trigger values to allow comparison with future mining run-off. There is only one study available where BACI was applied to study mining activity over SSC (Evans *et al.*, 2004), though no effect was found by comparing paired samples.

The BACI approach is a simple method whose aim is not only to study an impact from a specific river location by comparing contemporaneously paired samples, but also to determine local trigger values. It is simple though it does not replace wide studies of sediment dynamics and yields. Instead, it is a useful and realistic tool that can be easily applied by water authorities and mining companies to establish the effect of mining runoff, taking into account that in most of the cases the data are urgently needed. Despite its simplicity, it has hitherto been required only by Australian and New Zealand authorities. All other countries have laws and regulations that do not clearly take into account the high natural variability of SSC.

Effect of mining areas on SSC

The potential effect of mining areas on downstream values of SSC is based on all the events with the exception of 12 events having insignificant small rises. Table 3 includes data for one of those insignificant events (number 30) with no interstation increase in SSC.

A comparison between the max SSCs in the Tajuelo and Tajo with those in other environments is shown in Table 5. The other examples are rivers in Mediterranean areas draining different land uses: forested, abandoned cultivated areas, agricultural fields or those draining badlands. Moreover Table 5 shows rivers draining catchments with mining activity. The maximum SSC values of UTJ and UTA are similar to the maximum SSC values measured in Mediterranean catchments typical of abandoned agricultural and forested areas, for instance the Arnás catchment (Lana-Renault & Regüés, 2009). The maximum SSC in the DTJ is similar to that measured in other Mediterranean catchments with badlands, such as Isábena (López-Tarazón *et al.*, 2009), Araguás (Nadal-Romero *et al.*, 2008) or Ca l'Isard (Soler *et al.*, 2008). It is also as high as concentrations measured in rivers draining mining areas (Pentz & Kostaschuk, 1999; Chalov, 2014).

Explaining the increase between both pairs of stations is complicated owing to the fact that there are several potential sediment sources that can explain the difference in SSC between stations located upstream and downstream of mining areas. The Tajuelo catchment contains five such potential sources: the village and related activities, gullies, agriculture, mines and the rest of the catchment (Fig. 5 and Table 6). By far the largest area (95%) contributing sediments is that of forests and abandoned agricultural lands recolonized by vegetation or reforested. For Mediterranean areas these tend to produce comparatively low values of maximum SSC in the range 1-16 g l^{-1} (Table 5). The area of the Poveda village comprises 0.33% of the Tajuelo Catchment. There is no active construction in the village nor are there indications of gullying or channel widening downstream of the village, from which we deduce that its contribution to catchment sediment is negligible. There is a single prominent gulley above the village – the Poveda Gully – and few very minor gullied areas in its vicinity. The total gullied area encompasses less than 0.01% of the Tajuelo Catchment. Very small gullied areas can be responsible for high increases in SSC. For example, the Mediterranean Isábena catchment has a badland system representing merely 0.83% of the catchment, but is the likely source responsible for a maximum SSC of 350 g l^{-1} (see Table 5). However, the Poveda gullied system is 100 times smaller in its area relative to that of the entire catchment. As relevant, the Isábena badlands are marls producing very high SSCs (Laronne & Shen, 1982; Mathys *et al.*, 2003; López-Tarazón *et al.*, 2009) and fine-sediment loads, whereas the Utrillas sands contribute only low concentrations of suspended sediment and almost all the sedimentary load is transported as sandy bedload (Lucia *et al.,* 2013). The kaolin mines cover 3.87% of the Tajuelo catchment (five times more than the fraction of catchment which the badlands cover in the Isábena Catchment). Due to the extractive activity, materials prone to be eroded – primarily clay-sized kaolin - are exposed and some of these areas are hydrologically connected to the fluvial network. Finally, there are a few active agriculture areas in the west of the Tajo catchment upstream of UTJ. Due to its size (0.73%), it is improbable that these are responsible for SSC values similar to those in the Tajuelo. For instance, in the Enxoé catchment (Ramos *et al.* 2015), where active agriculture covers at least 87% of the basin, the maximum SSC was 3.5 g l^{-1}. More relevantly, these few agricultural areas cannot explain the very large SSC increase between UTJ and DTJ, because they occur over the entire upper Tajo basin. Hence, the sediment from those agricultural areas is present in UTJ samples, the station used to define the baseline.

SSC baseline for the Tajo and Tajuelo Rivers

This study is based on direct sampling at different river locations. Most of the data derive from baseflow and rising stages and only few from recessions. The number of samples has been sufficient to provide a robust value for low, high and average values of SSC considering that the BACI approach identifies SSC impacts associated with specific local rather than idealized values. Nevertheless, to more fully describe the natural fluvial system and the extent of influence, if any, of the mines on SSC, a fuller sampling program is required. This would best include automatic sampling with continuously measured high-range SSC sensors (López-Tarazón *et al.*, 2009). Furthermore, this study and most others concentrate on suspended sediment, whereas natural landscapes and mines also produce bedload sediments, not to mention a wide gamut of dissolved constituents. Hence, a baseline should ideally be extended to include not merely suspended sediment concentrations but also chemical sampling and analyses (Oyarzun *et al.*, 2011) and bed-material grain size (Saynor *et al.,* 2006).

Another important issue is how to interpret and to apply a baseline database (such as that of Table 4), specifically when an impact is being produced and an action or decision is required with respect to the mine areas. The Australian and New Zealand water quality guidelines (WQG) provide some guidance through what they term 'trigger values' that, if exceeded, an impact has occurred and an action is required by the authorities. WQG recommend trigger values equal to the 80th, 98th or 99.7th percentiles (e.g., Evans *et al.*, 2004) for each studied parameter. However, no clear explanation is given as to which among these percentiles should be used.

The situation is further complicated by the need that trigger value criteria are agreed by all stakeholders. Thus, defining a reliable baseline and trigger value without knowing the previous conditions with respect to the activity to be evaluated, or other aspects such as the difference in the geological setting within a watershed, is a task with a high degree of uncertainty as shown in Table 4. The natural background baseflow values of SSC in the Alto Tajo upstream of the mines are in the range 0.25-0.35 g l^{-1} and should be considered when trigger values have to be adopted, for instance concerning the effects of mines on SSC.

In this respect, the EU Directive 2006/44/EC suggests a maximum concentration of 25 mg l^{-1} for salmonid waters. Although this law states the possibility of no compliance because of exceptional weather or geographical conditions (and this second factor could be applicable here), this concentration has been frequently invoked for this region as a trigger or threshold value. Such an interpretation seems to be very narrow and unrealistic, due to the fact that upstream of mined areas, we measured an SSC baseflow 10 times (0.25-0.35 g l^{-1}) above that level, and an SSC at peak flow 1000 times above this invoked concentration of 25 mg l^{-1}. Summing up, our measurements clarify that the recognition by the EU Directive 2006/44/EC that this parameter can be derogated "because of exceptional weather or special geographical conditions”, and also that “floods are liable to cause particularly high concentrations” may be a pattern rather than an exception. Indeed, it seems more than likely that a similar situation will happen at most sites where direct measurements would be taken. This strengthens the realization that observed values measured continuously in the field are the only meaningful physical values for discussion as SSC baseline, considering its variation with discharge. The clearly insufficient EU Directive 2006/44/EC, and with a narrow interpretation, was used in the Alto Tajo Park until 11 September 2015, when the 817/2015 (BOE, 2015) Spanish law was decreed. This new law does not refer to SSC, merely mentioning hydromorphologic elements that should be monitored bi-annually by using the so-called riparian forest quality index (QBR).

Accurately identifying sediment sources requires continuous monitoring of all the principal sediment sources, both natural (e.g., natural gullies) and anthropogenic (e.g., mine areas). The local authorities in the Alto Tajo Natural Park are attempting to prevent possible mining impacts by fostering two measurements: (i) maintained sediment pond systems for all the active and inactive mining areas; and (ii) replacing traditional restoration methods with others based on reconstructing geomorphically stable surfaces that can manage the discharge, erosion and sediment transport as the natural surfaces surrounding the mines (Martín Duque *et al.*, 2010).

CONCLUSIONS

The local monitoring of the Tajuelo and Tajo rivers in the Alto Tajo Natural Park mining area leads us to conclude as follows: i) This is one of the few locally studies where both an SSC baseline has been defined and the BACI technique have been applied for a mining area; ii) Based on the BACI analysis we conclude that the mined area affects SSC. This effect changes the typical SSC dynamics of a forested catchment with abandoned agriculture to that more similar of badlands; iii) The BACI approach is a simple and reliable method to determine mining, or other human impacts on SSC. It can be used by water authorities or mining companies rather than the all-European 25 mg l^{-1} suggested standard; iv) Determining the precise contribution of the different sediment sources to this change in SSC is complex, because the sources, and the influence of the different geological setting between the upper and lower part of the watershed are manifold and should also be evaluated. Hence, monitoring should be extended toward each source. Moreover, water quality as well as bedload transport should be studied, because they can also be affected by mining.

ACKNOWLEDGEMENTS

This study was funded by: (i) Research Project CGL2010-21754-C02-01 (Spanish Ministry of Science and Technology, and Ministry of Economy); (ii) the Department of Agriculture and Environment of Castile – La Mancha through its so-called “Fondos Verdes” (Green Funding); (iii) the research contract 249/2015 between CAOBAR and UCM; (iv) the Ecological Restoration Network REMEDINAL-3 of the Madrid Community (S2013/MAE-2719); (v) the Spanish National Research Council (CSIC) for Ph.D. Grant JAE-Predoc to IZA. We thank Ana Lucía Vela, the Zapico-Alonso family, Guillermo Pinto, Ana Sánchez, Eduardo Taulero, Jan van Minnen, Saskia Keesstra, Nuria Fernández, Carlos de Andrés, Angel Martín, Sara Nyssen, María Tejedor, Carmen Tomé and the staff rangers of the ATNP. Very special thanks to José Manuel Nicolau, a member of our team of research at the Alto Tajo, to Andrés Díez lending his sensor, to Valle López, for her cartographic contribution, to Clara Lorca and David Gutiérrez for their help in Figure 5 and to Laura Donadeo for her bibliographic help; to the Managers of the Alto Tajo Natural Park (Ángel Vela, Raquel Ibáñez, Rafael Ruiz and José Antonio Lozano) and to Ángel Moya and Jesús González for their constant support. Vodafone Spain S.A.U. and Catch The Data for providing communication of our sensors. The Confederación Hidrográfica del Tajo provided gauging data. We thank the reviewers and the editor for the manifold constructive suggestions.

REFERENCES

AEMET. 2013. Agencia Estatal de Meteorología. (Spanish Meteorological Agency). http://www.aemet.es/es/portada [accessed December 2013].

Alexandrov Y, Laronne JB, Reid I. 2003. Suspended sediment concentration and its variation with water discharge in a dryland ephemeral channel, northern Negev, Israel. *Journal of Arid Environment* **53**: 73–84. DOI:10.1006/jare.2002.1020.

Australian and New Zealand Environment and Conservation Council (ANZECC), 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality Volume 1, The Guidelines. Agricultural and Resources Management Council of Australia and New Zealand (ARMCANZ). Canbera, ACT Australia.

Balamurugun G. 1991. Tin mining and sediment supply in Peninsular Malaysia with special reference to the Kelang River basin. *The Environmentalist* **11**: 281– 291. DOI: 10.1007/BF01266561.

Batalla JR, Vericat D. 2011. A Review of Sediment Quantity Issues: Examples from the River Ebro and Adjacent Basins (Northeastern Spain). *Integrated Environmental Assessment and Management* **7**: 256-268. DOI: 10.1002/ieam.126.

BOE, 2015. Law 817/2015, 11th September, Boletín Oficial del Estado, N. 219: 80582-80677.

Buchanan PA, Morgan TL. 2012. Summary of suspended-sediment concentration data, San Francisco Bay, California, water year 2009. U*.S. Geological Survey Data Series* **744**: 1-26.

Carcavilla L, Ruiz R, Rodríguez E. 2011. Guía geológica del Parque Natural del Alto Tajo. Instituto Geológico y Minero de España, Madrid.

Chalov SR, 2014. Effects of placer mining on suspended sediment budget: case study of north of Russia's Kamchatka Peninsula. *Hydrological Sciences Journal* **59**: 1081–1094. DOI:10.1080/02626667.2014.903330.

CEDEX. 2015. Centro de Estudios y Experimentación de obras públicas. http://ceh-flumen64.cedex.es/anuarioaforos/afo/estaf-codigo.asp [accessed December 2015].

Collins AL, Naden PS, Sear DA, Jones JI, Foster IDL, Morrow K. 2011. Sediment targets for informing river catchment management: international experience and prospects. *Hydrological Processes* **25**: 2112–2129. DOI: 10.1002/hyp.7965.

European Union. Directive 2006/44/EC on the quality of fresh waters needing protection or improvement in order to support fish life, 6 September 2006.

DOCM, 2000. Law 1/2000, 6th April, Diario Oficial de Castilla-La Mancha DOCM, Vol. **43**: 4413–4424.

DOCM, 1999. Order 204/1999, 21th January, Diario Oficial Castilla-La Mancha DOCM, Vol. **61**: 6473-6544.

Evans KG, Moliere DR, Saynor MJ, Erskine WD, Bellio MG. 2004. Baseline suspended-sediment, solute, EC and turbidity characteristics for the Ngarradj catchment, Northern Territory, and the impact of mine construction. *Supervising Scientist Report* **179**, Supervising Scientist, Darwin NT.

García-Ruiz JM, Regües D, Alvera B, Lana-Renault N, Serrano-Muela P, Nadal-Romero E, Navas A, Latrón J, Martí-Bono C, Arnáez J. 2008. Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. *Journal of Hydrology* **356**: 245-260. DOI:10.1016/j.jhydrol.2008.04.013.

González Amuchastegui MJ. 1993. Geomorfología del Alto Tajo en el sector de Molina de Aragón. PhD Dissertation, Autónoma University, Madrid.

Graczyk DJ, Roberston DM, Rose WJ, Steuer JJ. 2000. Comparison of water-quality samples collected by Siphon samplers and automatic samplers in Wisconsin. *U.S. Geological Survey*, Fact Sheet FS-067-00

Hicks DM, Gomez B. 2005. Sediment Transport. In: Kondolf GM, Piégay, H. (Eds.), Tools in Fluvial Geomorphology. John Wiley & Sons, Ltd: 425-461. DOI: 10.1002/0470868333.ch15.

ICONA. 1988. Agresividad de la lluvia en España. MAPA: Madrid.

IUSS Working group WRB. 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO, Rome.

Kjelland ME, Woodley CM, Swannack TM, Smith DL. 2015. A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. *Environment Systems and Decisions* **35**: 334-350. DOI: 10.1007/s10669-015-9557-2.

Köppen W, 1918. Klassifikation der Klimatenach Temperatur, *Niederschlag und Jahreslauf. Petermanns Mitt* **64**: 193–203.

Lana-Renault N, Regüés D, 2009. Seasonal patterns of suspended sediment transport in an abandoned farmland catchment in the Central Spanish Pyrenees. Earth *Surface Process and Landforms* **34:** 1291-1301. DOI: 10.1002/esp.1825

López-Tarazón JA, Batalla RJ, Vericat D, Francke T. 2009. Suspended sediment transport in a highly erodible catchment: The River Isábena (Southern Pyrenees). *Geomorphology* **109**: 210-221. DOI:10.1016/j.geomorph.2009.03.003.

Laronne JB, Shen HW. 1982. The effect of erosion on solute pickup from Mancos Shale hillslopes. *Journal of Hydrology* **59**: 189-207. DOI:10.1016/0022-1694(82)90011-7.

Lucía A, Recking A, Martín-Duque JF, Storz-Peretz Y, Laronne JB. 2013. Continuous monitoring of bedload discharge in a small, steep sandy channel. *Journal of Hydrology* **497**: 37-50. DOI:10.1016/j.jhydrol.2013.05.034.

Macklin MG, Brewer PA, Hudson-Edwards KA, Bird G, Coulthard TJ, Dennis IA, Lechler, PJ, Miller JR, Turner JN. 2006. A geomorphological approach to the management of rivers contaminated by metal mining. *Geomorphology* **79**: 423-447. DOI:10.1016/j.geomorph.2006.06.024.

MARM, 1997−2006. Mapa Forestal de España 1:50,000. Hoja 433 Atienza. Ministerio de Medio Ambiente, Medio Rural y Marino.

Martín-Duque JF, Sanz MA, Bodoque JM, Lucía A, Martín-Moreno C. 2010. Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes. *Earth Surface Processes and Landf*orms **35**: 531–548. DOI: 10.1002/esp.1950.

Martín-Moreno C, Martín Duque JF, Nicolau Ibarra JM, Hernando Rodríguez N, Sanz Santos MA, Sánchez Castillo L. 2016. Effects of topography and surface soil cover on erosion for mining reclamation: The experimental spoil heap at El Machorro Mine (Central Spain). Land Degradation & Development **27**: 145-159. DOI: 10.1002/ldr.2232.

Mathys N, Brochot S, Meunier M, Richard D. 2003. Erosion quantification in the small marly experimental catchments of Draix (Alpes de Haute Provence, France), calibration of the ETC rainfall-runoff-erosion model. *Catena* **50**: 527-548. DOI:10.1016/S0341-8162(02)00122-4.

McIntyre N, Bulovic N, Cane I, McKenna P. 2016. A multi-disciplinary approach to understanding the impacts of mines on traditional uses of water in Northern Mongolia. *Science of The Total Environment* **557-558**: 404-414. DOI:10.1016/j.scitotenv.2016.03.092.

Messina AM, Biggs TW. 2016. Contributions of human activities to suspended sediment yield during storm from a small, steep, tropical watershed. *Journal of Hydrology* **538**: 726-742. DOI:10.1016/j.jhydrol.2016.03.053.

Nadal-Romero E, Latron J, Martí-Bono C, Regüés D. 2008. Temporal distribution of suspended sediment transport in a humid Mediterranean badland area: the Araguás catchment, Central Pyrenees. *Geomorphology* **97**: 601–610. DOI:10.1016/j.geomorph.2007.09.009.

Nordstrom DK. 2015. Baseline and premining geochemical characterization of mined sites. *Applied Geochemistry* **57**: 17-34. DOI:10.1016/j.apgeochem.2014.12.010.

Olmo P, Álvaro M., 1989. Mapa Geológico de España 1:50,000, 2ª Serie (MAGNA), Peralejos de las Truchas (539) IGME, Servicio de Publicaciones: Madrid.

Oyarzun R, Lillo J, López-García JA, Esbrí JM, Cubas P, Llanos W, Higueras P. 2011. The Mazarrón Pb–(Ag)–Zn mining district (SE Spain) as a source of heavy metal contamination in a semiarid realm: Geochemical data from mine wastes, soils, and stream sediments. *Journal of Geochemical Exploration* **109**: 113-124. DOI:10.1016/j.gexplo.2010.04.009.

Pentz SB, Kostaschuk RA. 1999. Effect of placer mining on suspended sediment in reaches of sensitive fish habitat. *Environmental Geology* **37**: 78-89. DOI: 10.1007/s002540050363.

Pickup G. 2008. Floodplain inundation modeling and forecasting for the Middle Fly River. pp 291-318 in: Barrie Bolton (editor), The Fly River, Papua New Guinea: Environmental Studies in an Impacted Tropical River System. Developments in Earth and Environmental Sciences **9**, Elsevier. DOI: 10.1016/S1571-9197(08)00408-4.

Ramos TB, Gonçalves MC, Branco MA, Brito D, Rodrigues S, Sánchez-Pérez J, Sauvage S, Prazeres Â, Martins JC, Fernandes ML, Pires FP. 2015. Sediment and nutrient dynamics during storm events in the Enxoé temporary river, southern Portugal. *Catena* **127**: 177-190. DOI:10.1016/j.catena.2015.01.001.

Regüés D, Nadal-Romero E. 2013. Uncertainty in the evaluation of sediment yield from badland areas: Suspended sediment transport estimated in the Araguás catchment (central Spanish Pyrenees). *Catena* **106**: 93-100. DOI:10.1016/j.catena.2012.05.006.

Robertson MJ, Scruton DA, Gregory RS, Clarke KD. 2006. Effects of suspended sediment on freshwater fish and fish habitat. *Canadian Technical Report of Fisheries and Aquatic Habitats* **2644**.

Rovira A, Batalla RJ. 2006. Temporal distribution of suspended sediment transport in a Mediterranean basin: the Lower Tordera (NE Spain). *Geomorphology* **79**: 58–7. DOI:10.1016/j.geomorph.2005.09.016.

Saynor MJ, Erskine WD, Evans KG. 2006. Bed-material grain size changes in the Ngarradj Creek catchment between 1998 and 2003. *Supervising Scientist Report* **188**, Supervising Scientist, Darwin NT.

Schumm SA. 1981. Evolution and response of the fluvial system, sedimentologic implications. *Society of Economic, Paleontologists and Mineralogists. Special Publication* **31**: 19-29.

Smith EP. 2006. BACI Design. Encyclopedia of Environmetrics. John Wiley & Sons, Ltd. DOI:10.1002/9780470057339.vab001.pub2

Soler M, Latrón J, Gallart F, 2008. Relationships between suspended sediment concentrations and discharge in two small research basins in a mountainous Mediterranean area (Vallcebre, Eastern Pyrenees). *Geomorphology* **98**: 143-152. DOI:10.1016/j.geomorph.2007.02.032.

Soulard CE, Acevedo W, Stehman SV, Parker OP. 2015. Mapping Extent and Change in Surface Mines Within the United States for 2001 to 2006. *Land Degradation and Development* **27**: 248-257. DOI:10.1002/ldr.2412.

Tarolli P, Sofia G. 2016. Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology* **255**: 140-161. DOI:10.1016/j.geomorph.2015.12.007.

U.S. EPA 2003a. Developing water quality criteria for suspended and bedded sediments (SABS). *Office of Water*. August. 58 pp.

U.S. EPA 2003b. Strategy for Water Quality Standards and Criteria: Setting Priorities to Strengthen the Foundation for Protecting and Restoring the Nation's Waters. *Office of Water* (*4305T*). August. EPA-823-R-03-010.

Walling DE, Collins AL, Sichingabula HM, Leeks GJL. 2001. Integrated assessment of catchment suspended sediment budgets: A Zambian example. *Land Degradation & Development* **12**: 387-415. DOI: 10.1002/ldr.461.

Walling DE, Fang D. 2003. Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change* **39**: 111–126. DOI:10.1016/S0921-8181(03)00020-1.

Wheater CP, Cook PA. 2005. Using statistics to understand the environment. Routledge, London.

Whiting PJ. 2003. Flow Measurement and Characterization. In: Kondolf GM, Piégay H (Eds.), Tools in Fluvial Geomorphology. John Wiley & Sons, Ltd, pp. 323-346. DOI:10.1002/0470868333.ch12.

Yanguo T, Shijun N, Xianguo T, Chengjiang Z, Yuxiao M. 2002. Geochemical baseline and trace metal pollution of soil in Panzhihua mining area. *Chinese Journal of Geochemistry* **21**: 274-281. DOI:10.1007/BF02831093.

Zabaleta A, Martínez M, Uriarte JA, Antigüedad I. 2007. Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque Country. *Catena* **71**: 179–190. DOI:10.1016/j.catena.2006.06.007.

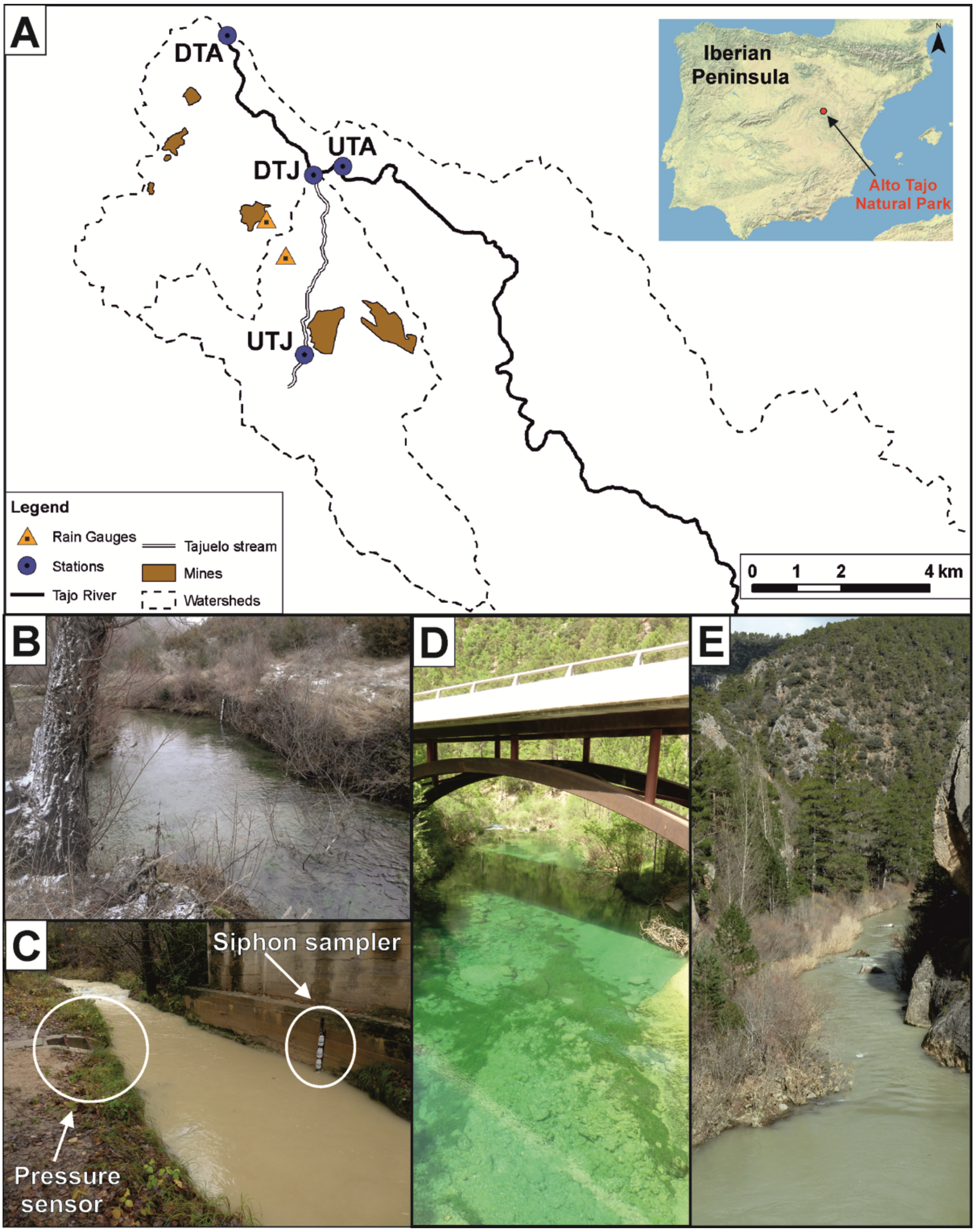

Figure 1. A: The SSC monitoring network in the Tajo River and Tajuelo stream. B: The Tajuelo upstream of the mining area (UTJ), C: The Tajuelo downstream of the mining area (DTJ), D: The Tajo upstream of the mining area (UTA), E: The Tajo downstream of the mining area (DTA).

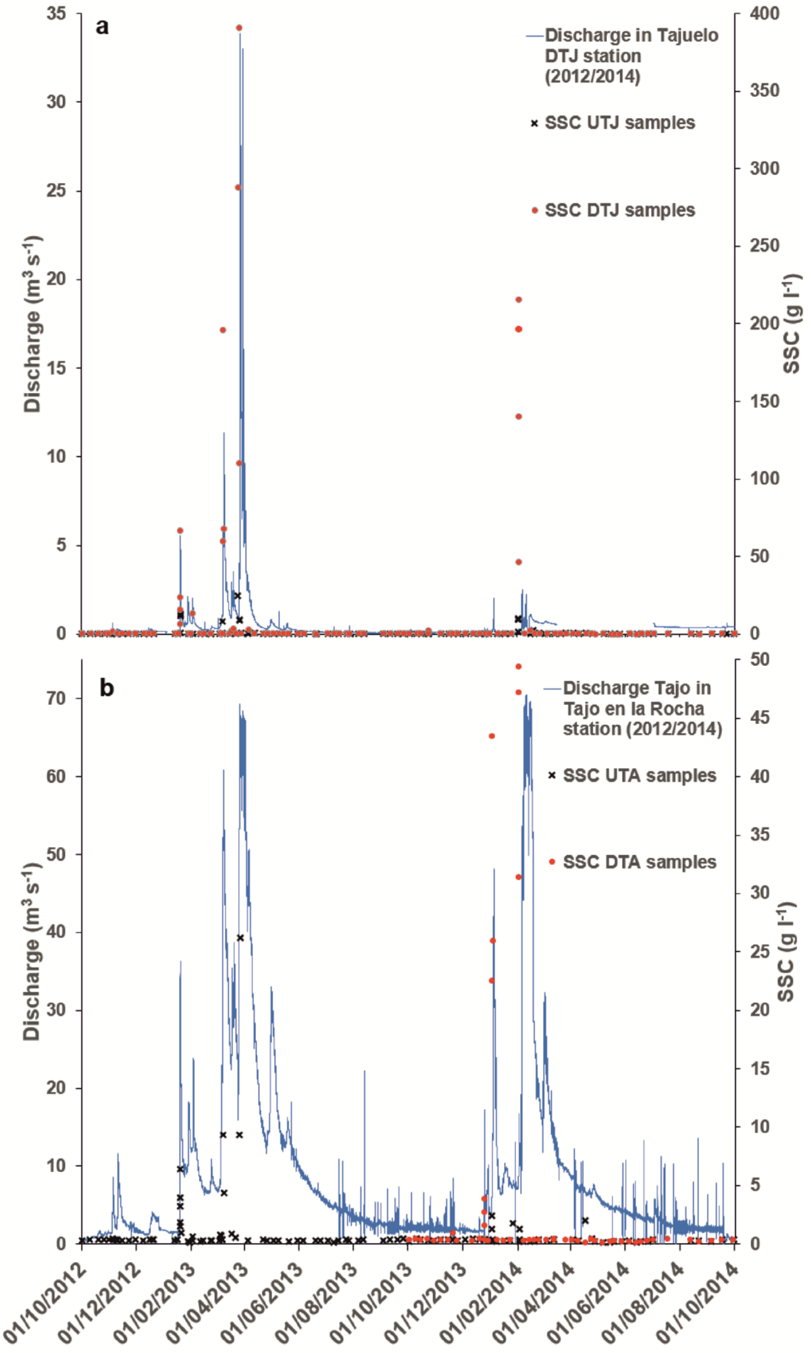

Figure 2. Hydrograph and SSC for the Tajo (a) and the Tajuelo (b) during the 2012-2013 and 2013-2014 hydrological years. DTA samples are available for the Tajo only for the second hydrological year. All UTA samples were used to define the baseline and only the second year samples were used to undertake the UTA-DTA comparison. Due to lack of Tajuelo discharge data for the period 15/03/2014-02/07/2014, the timing of samples on rain gauge and discharge data were determined from the nearby Merdero stream.

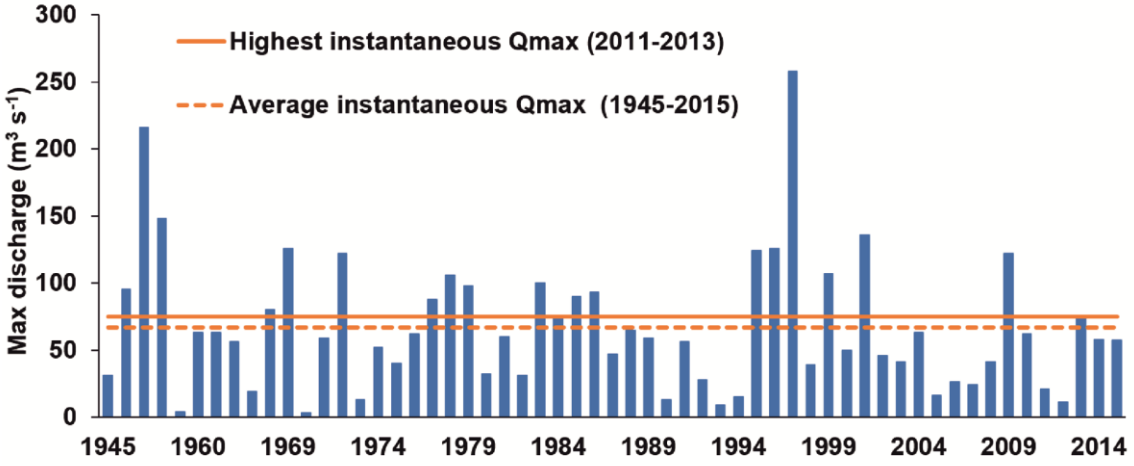

Figure 3. Maximum instantaneous water discharge for the 1945-2015 data series at the “3001 Peralejos de las Truchas" gauging station (CEDEX, 2015; Confederación Hidrográfica del Tajo, pers. comm., 2015). The horizontal lines are the highest instantaneous discharge: the full line refers to the period recorded during the study period and the dashed line to the mean for 1945-2015.

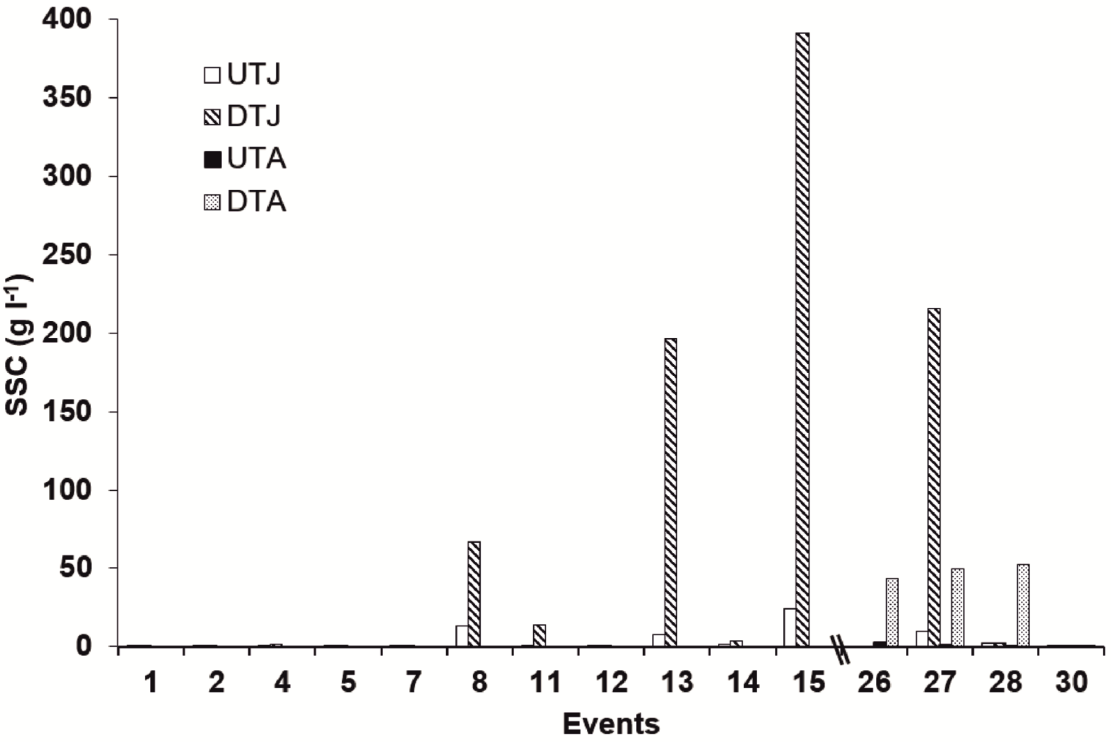

Figure 4. Comparison among the highest values of SSC sampled in rising limbs during the 2012-2013 and 2013-2014 hydrological years.

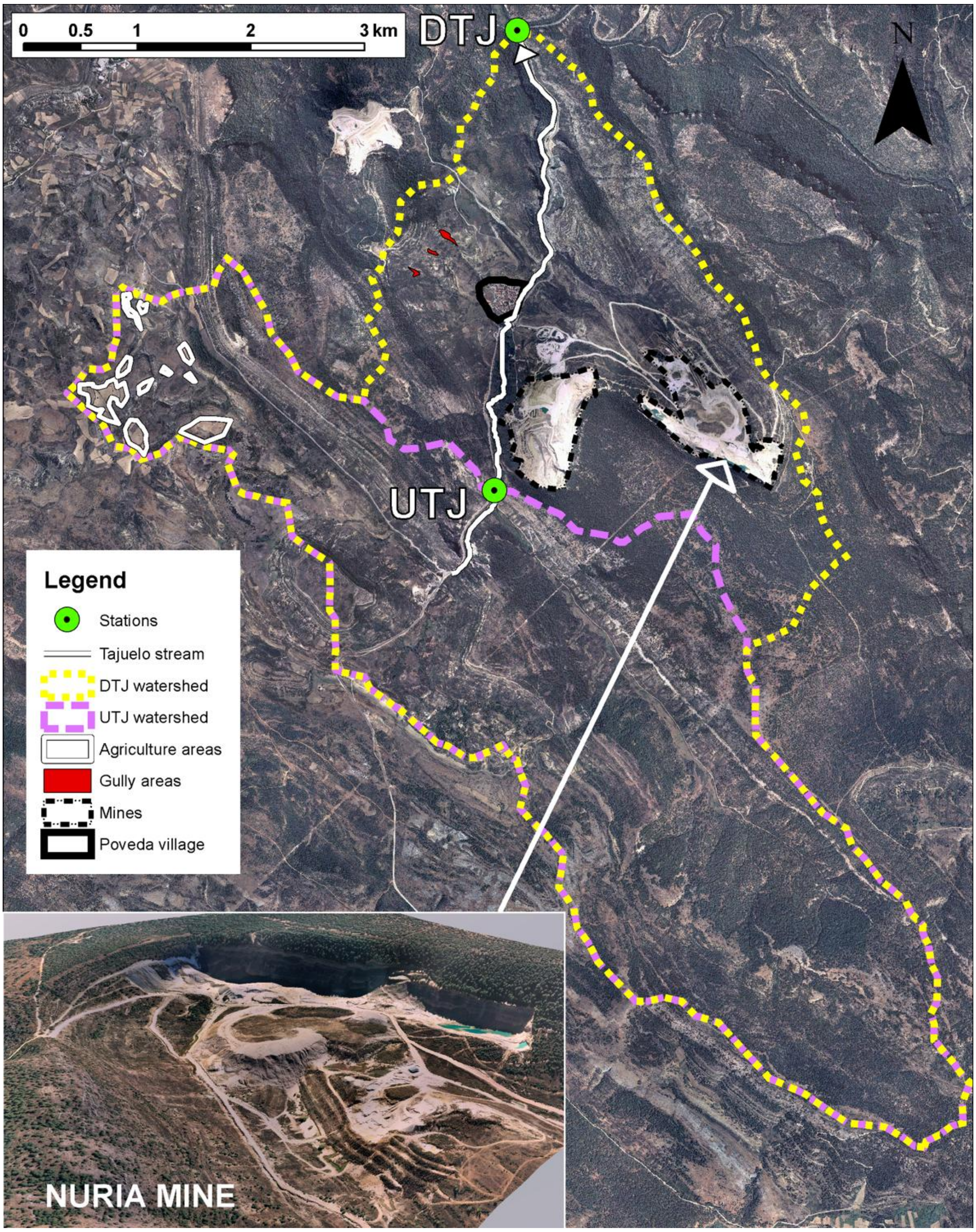

Figure 5. The Tajuelo Catchment. Data source: Orthophotograph sheet 539; PNOA 2009: ETRS89.

Table 1. Summary of number of samples taken at each sampling location.

hydrogaph segment	location	Tajuelo		Tajo	
		2012-13	2013-14	2012-13	2013-14
base flow	u/s	33	37	35	33
	d/s	33	38	n.d.	32
rising stage	u/s	19	13	30	14
	d/s	23	6	n.d.	15
recession	u/s	8	4	3	7
	d/s	8	5	n.d.	7
total		124	103	68	108

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

Table 2. Descriptive statistics for suspended sediment concentration (g l^{-1}) in the Tajuelo and the Tajo for the 2012/2013 and 2013/2014 hydrological years.

parameter	Tajuelo		Tajo	
	upstream	downstream	upstream	downstream
n	114	113	122	54
n manual samples	95	88	90	44
n siphon	19	25	32	10
mean	1.24	16.82	0.92	2.66
StDev	3.33	56.52	2.70	13.60
minimum	0.07	0.06	0.13	0.10
median	0.34	0.32	0.35	0.33
3rd quartile	0.42	0.57	0.41	0.40
maximum	24.40	391.00	26.20	52.30

Table 3. Comparative response of SSC at the upstream and downstream sampling locations on the Tajuelo and Tajo for two flow events during the 2012/2013 and 2013/2014 hydrological years.

event	event features					location	rising stage			event rainfall
	date	river	Q mean	Q peak	number of peaks		max SSC	mean SSC	number of samples	
#			$m^3 s^{-1}$	$m^3 s^{-1}$	#		$g l^{-1}$	$g l^{-1}$	#	mm
15	25.03.13	Tajuelo	9.14	33.9	6	u/s	24.40	10.60	4	97.8
						d/s	391.00	197.00	4	
		Tajo	43.6	69.3	4	u/s	26.20	12.00	3	
						d/s	n.d.	n.d.	n.d.	
27	01.02.14	Tajuelo	n.d.	n.d.	1	u/s	9.69	6.67	3	41
						d/s	215.00	149.00	4	
		Tajo	9.42	16.80	1	u/s	1.30	0.70	3	
						d/s	49.30	42.60	3	
30	24.04.14	Tajuelo	n.d.	n.d.	1	u/s	0.44	0.44	1	9
						d/s	0.38	0.38	1	
		Tajo	5.86	7.68	1	u/s	0.43	0.27	2	
						d/s	0.40	0.40	1	

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

Table 4. The Tajuelo and Tajo baselines. Hydrological years 2012/2013 and 2013/2014.

	hydrograph segment	Tajuelo				Tajo			
		max SSC	min SSC	mean SSC	number of samples	max SSC	min SSC	mean SSC	number of samples
		g l^{-1}	g l^{-1}	g l^{-1}		g l^{-1}	g l^{-1}	g l^{-1}	
autumn	base flow	0.43	0.13	0.30	24	0.45	0.23	0.37	26
	rising stage	0.31	0.31	0.31	1	0.43	0.28	0.31	6
	recession	0.34	0.34	0.34	1	0.33	0.33	0.33	1
winter	base flow	0.50	0.24	0.34	14	1.73	0.27	0.47	12
	rising stage	12.90	0.21	3.46	15	6.42	0.19	1.13	24
	recession	0.35	0.28	0.31	3	0.35	0.13	0.22	6
spring	base flow	0.93	0.22	0.40	15	1.97	0.16	0.39	12
	rising stage	24.40	0.39	3.52	9	26.2	0.11	2.55	13
	recession	0.75	0.21	0.42	6	0.56	0.25	0.34	6
summer	recession	0.43	0.07	0.29	18	0.38	0.17	0.29	16
	rising stage	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	recession	n.d.	n.d.	n.d.	n.d.	0.14	0.14	0.14	1

n.d.: no data.

Table 5. Maximum SSC in in the Alto Tajo Natural Park compared with: (i) various Mediterranean catchments; (ii) catchments with mining activity.

catchment		max SSC	area	Land use	reference
		g l^{-1}	km^2		
Alto Tajo Natural Park	Tajuelo d/s	391.00	28.7	forested fields with abandoned cultivated areas, small villages, some slope gullies and mining activity	This study
	Tajuelo u/s	24.40	18.6		
	Tajo d/s	52.30	537.00		
	Tajo u/s	26.20	484. 000		
Mediterranean	San Salvador	1.9	0.92	undisturbed forest environment	García-Ruiz *et al.* (2008)
	Arnás	16.0	2.84	abandoned cultivated area subjected to colonization by plants	Lana-Renault & Regüés (2009)
	Araguás	500.00	0.45	badlands	Nadal-Romero *et al*. (2008)
	Ca l'Isard	1740.0	1.32	forested with some badlands	Soler *et al*. (2008)
	Barrendiola	1.6	3.00	forested	Zabaleta *et al*. (2007)
	Can Vila	8.6	0.56	mainly abandoned agricultural fields and forests	Soler *et al.* (2008)
	Isabena	357.00	445.000	having patches of highly erodible areas (i.e., badlands)	López-Tarazón *et al.* (2009)
	Enxoé	3.80	60.80	agricultural fields	Ramos *et al.*, (2015)
	Tordera	1.00	894.00	forested	Rovira & Batalla

					(2006)
mining areas	Haggart Creek and Mc Questen River system	0.30	n.d.	forested area with gold mines	Pentz & Kostaschuk (1999)
	Vyvenka	2.70	13000.00	opencast platinum mine	Chalov (2014)
	San Francisco Bay Coastal	0.14	n.d.	urbanized estuary impacted by numerous[1] anthropogenic activities.	Buchanan & Morgan (2012)
	Ngarradj	0.10	0.13	mining activity adjacent to Kakadu National Park	Evans *et al.* (2004)

[1] Mining legacy, channel dredging, aggregate mining, reservoirs, freshwater diversion, watershed modifications, urban run-off, ship traffic, introduction of exotic species, land reclamation, and wetland restoration

u/s: upstream of mines, d/s: downstream of mines, n.d.: no data.

Table 6: The Tajuelo catchment land uses depending on upstream-downstream stations.

Land use	UTJ watershed		DTJ watershed	
	km^2	%	km^2	%
Forested and recolonized or reforested abandoned agricultural fields	18.6	098.8	28.71	95.06
Mines	00	000	01.17	03.87
Village	00	000	00.1	00.33
Gully areas	00	000	<0.01	<0.01
Agriculture areas	00.22	001.2	00.22	00.73
Total	18.82	100	30.2	100