We thank Bruno Mazzorana for his useful comments. We will take them into account for the revised manuscript.

Reply to General comments

1.1. Suggestions to support the practical relevance of the research findings

The revised manuscript will emphasize the relevance of the long-term tendency of the Garona River for river corridor management in the study area. We especially want to thank the referee for letting us know the IDRAIM framework, an excellent guideline that integrates fluvial geomorphology at different temporal and spatial scales. We will contextualize our study of the Garona River and integrate it in this framework. Introduction and discussion (it will be reorganized) will be extended accordingly including the arguments displayed below.

The need of a geomorphological assessment for an adequate river engineering and management has been mentioned in previous works (e.g. Schumm, 1977; Thorne et al., 1997; Kondolf et al., 2003), and methodological frameworks for hydromorphological analysis have been proposed, which provide knowledge for risk mitigation (Belletti et al., 2015; Gurnell et al., 2015; Rinaldi et al., 2014). River management has evolved from a product-oriented engineering approach to a dynamic multi-objective management approach (Gregory et al., 2008). Our aim is to highlight how the regional context helps to understand present river response and therefore future evolution in our case study.

Emplacing Val d'Aran within the whole drainage basin enables us to understand the main processes and river channel changes. The Garona River drains a catchment area of 52.000 km^2 along ca. 600 km (Stange et al., 2014a). However, this valley corresponds to a headwater area of 620 km^2, where the Garona River flows along 45 km. This spatial setting is a key factor to understand the main processes occurring in the study area, located in the uppermost zone of the fluvial system. This is characterized to be the production or sediment-source area, from which sediment is removed and delivered downstream giving rise to the long-term erosional evolution of the landscape (Schumm, 1977; also presented in Rinaldi et al., 2014). Obviously sediment is eroded, stored and transported along the entire fluvial system, but one process is usually dominant in each part. Therefore, the main expected phenomenon along the main river and tributary streams in our study zone is erosion, where the geomorphological analysis (e.g. two generations of Holocene alluvial fans) and short-term event-based study (e.g. almost 50% of the river margins were eroded significantly) allowed us to classify it as a mainly sediment-producer zone dominated by lateral and vertical incision. Present erosion processes seem to be enhanced by the climatic and tectonic history, and the combination of these long-term factors (geologic, tectonic and geomorphological context) with short-term factors (catchment morphometry and anthropization) is essential to understand the dynamics of the Garona River.

Coming to the practical relevance of the long-term erosional landscape evolution for river management, we follow referee's suggestion to highlight the value of our study with respect to recently developed integrated flood risk management approaches, specifically the IDRAIM framework. In the revised manuscript we will include the following discussion. Rinaldi et al. (2014) present the IDRAIM framework as a "comprehensive methodological framework for the analysis, post-monitoring assessment and implementation of mitigation measures with the aim of an integrated planning envisaged by the Directives 2000/60/EC and 2007/60/EC”. This methodology considers and integrates environmental quality objectives with the mitigation of river-related risks, and is presented as a system to support the management of rivers and the related geomorphological processes. The IDRAIM system highlights the importance of different space and time scales for the assessment, analysis and monitoring of waterways, ranging from the catchment geologic and geomorphological characteristics, to the detailed study of specific river stretches. Regarding the temporal scale, Rinaldi et al. (2014) consider different scales: geologic scale (10^4-10^6 years), useful to contextualize the long-term evolution of the hydrographic network (e.g. captures, subsidence, neotectonics) and to provide a better understanding of the possible causes of changes which are usually imperceptible at a human scale; historical scale (10^2-10^3 years), used to understand the morphology of watercourses in historical times, accommodation, and other types of anthropogenic controls; and medium scale (last 100-150 years), which is the one used for management, including the last 10-15 year timescale and the annual scale. They state that the effective temporal scale preferably used in the field of modern fluvial geomorphology is the medium scale, in fact, that corresponding to 100-150 years (comparable to the scale of human life). However, they assert, like Shields et al. (2003), that current trends are more appropriately defined by restricting the temporal scale to the last 10 to 15 years, namely to establish whether a riverbed is dynamically stable or unstable. A channel is said to be in a dynamic equilibrium if, considering the mentioned time interval its shape and its characteristic dimensions (width and depth of the section, slope, grain size) maintain unchanged on average. This 10-15 year scale covers most of the hydrodynamic studies (Shields et al., 2003). Our study gains relevance in this framework, as it takes into account a broad range of time from the geologic scale to the decadal scale, this last one being represented by the 25- to 100-year return period floods. These are floods with an effective discharge, that is, they model the channel by erosion, changing its width and depth. We will discuss this topic with more detail in the section 2 of this response. We want to clarify that we do not suggest that this kind of analysis should be performed systematically, but if in the first steps of the analysis suggested in the IDRAIM framework, significant morphological indications are found, like in the case of the Garona in Val d’Aran, such an analysis is strongly recommended. As we discuss later on, we do not know if numerical estimations for sediment transport rates and river bed elevation would capture this tendency, because the time scale of the floods occurring along the Garona River is longer than 10-15 years (the timescale used to define the present tendency of the river), but it is clearly perceptible at 100-150 year human scale.

To conclude, our contribution for the management of the Garona River is that the long-term millennial timescale entrenchment tendency is reflected at a human scale (effective timescale for river evolution prediction according to the IDRAIM approach), which could be imperceptible in 10-15 year timescale detailed studies of channel morphology. In fact, channel incision is a progressive change that has slow, but progressive results and may carry a significant geomorphic hazard (Schumm, 1994). We do not suggest that strategies against floods should be designed exclusively based on the long-term fluvial tendency, but consider that this approach to long-term dynamics helps to better assess the present geomorphic changes, which are the basis for decision-makers. Our suggestion is to carry out this type of analyses when the study of the geologic and geomorphologic context gives enough evidences.

1.2. Suggestions with respect to the balance of the single sections of the manuscript

The referee is right when he says that we missed important previous work on applications and implications of fluvial geomorphology for river management. Key studies are summarized in Rinaldi et al. (2014), including the fundamental works by Schumm (1977), Thorne et al. (1997) and Kondolf et al. (2003). Belletti et al. (2015) presents a review of the existing main hydromorphological assessment methods, showing their strengths, limitations, gaps and need for further development. According to Belletti (2015), understanding evolutionary trajectories and past changes is an important component when assessing river conditions using robust, geomorphologically based approaches. However, one of the main limitations is the difficulty to assess the temporal component.

The importance of the timescales when studying fluvial systems and their evolution has been mentioned before (Harvey, 2002). Some studies deal with long-term processes that determine landscape evolution, but that are imperceptible in those timescales used for river management (Bishop, 2007). Others deal with river corridor management using fluvial geomorphology as a part of a hierarchical framework for hydromorphological analysis, but they tend to consider a decennial and centennial historical timescale (Rinaldi et al., 2014; Gurnell et al., 2015). The 100 years' time scale is very appropriate to detect changes, for instance, produced mostly by land use changes in the basin during this interval (Simon, 1989; Billi et al., 1997; Winterbottom, 2000; Liebaut et al., 2001; Gurnell et al., 2003; Surian and Rinaldi, 2003; Surian and Rinaldi, 2004; Rinaldi and Surian, 2005; Surian, 2006; Surian and Cisotto, 2007; Rinaldi et al., 2008; Surian et al., 2009), but these are meaningless in Val d'Aran during the last century. Last, there are also many studies giving importance to the anthropic actions which produce changes in the river evolution in a year to decennial timescale (Gregory et al., 2008 and references therein). Previous works on river hydrodynamics are mentioned in the following section (point 2 of the reply).

Introduction part will be extended in order to provide an adequate background of these research topics (see references at the end of this document and references included in the reply to referee Lorenzo Marchi) but also to specifically contextualize our study within the IDRAIM framework. Later the main body of the paper will be presented and finally, the discussion part will also be modified to justify our contribution and strengths of this study for an adequate and integrated river management.

<u>Reply to Specific comments and suggestions</u>

We answer both referee comments (2.1 and 2.2) together to integrate both the contribution for river incision predictions and the relevance of this tendency for risk assessment.

Agreeing with the referee, the quantification of the hydrodynamic behaviour of the river by means of shallow water equations and sediment transport rates would be of great value for the management of the Garona River in Val d'Aran. Anyway, this numerical estimation is out of the scope of this manuscript.

According to Rinaldi et al. (2014) the timescale preferably used in the field of modern fluvial geomorphology is the average timescale, which is of the order of 100 years, comparable to the scale of human life and useful for management purposes. However, to define the current trends, namely to establish whether a riverbed is stable or dynamic equilibrium it is more appropriate to further restrict the scale time to the last 10 to 15 years (Shields et al., 2003; Rinaldi et al., 2014). According to Shields et al. (2003) the stability assessment provides a foundation for prediction of system response. It consists of: a) an initial, preliminary qualitative assessment of the river state and its dynamism, better if made by an expert; b) a quantitative assessment including the collation of numerical data about the study area from a variety of sources to describe channel geometry, bed sediments, hydrology, and land use in the past and present. For this quantitative assessment, Shields et al. (2003) state that the numerical methods dealing with hydraulic geometry relations and planform predictors are best applied to regions with lightly perturbed alluvial channels in dynamic equilibrium for which extensive data sets are available. The weaknesses of these methods are that they can give misleading results when applied outside domain of the underlying data or when not extensive datasets are available (Allen et al. 1994; Van den Berg, 1995; Shields, 1996; Thorne et al., 1996). Regarding to the numerical methods that deal with the relationships between sediment transport and hydraulic variables, incipient motion type analyses including Shields' parameters are usually limited to channels with beds dominated by material coarser than sand, while sediment budgets are best for sand bed streams prone to aggradation. The limitations of these methods are that sediment inflows to the project reach are usually unknown, most sediment transport relations are imprecise (USACE, 1994) and there is a high level of uncertainty in sediment transport computations (Shields et al., 2003). About bank stability analyses, they fit to channels with cohesive banks higher than 3 m, and their weaknesses are that they require considerable field data (Thorne, 1999).

All these kind of analysis, with all their strengths and limitations, usually reflect a trend of about 10-15 years, as said before. The contribution of our work is that we found that the long term geologic and geomorphologic analysis is not imperceptible, but reflected in a time scale longer than 15 years, related to the extraordinary floods with a recurrence interval longer than 25 years, but included in the 100-150 years scale useful for management. Some aspects of geologic and geomorphologic context are very difficult to integrate in a systematic way in management approaches. We think that our approach can help to improve flood risk management under the scope of Jacobson et al. (2003), who state that the surficial geologic record, including deposits, are rarely complete enough to form precise predictive models, but they can provide contextual information that can constrain predictions and help guide choices and decisions. This is the case of our study. We do not know if hydrodynamic calculations would capture this tendency or not, given the temporal scale they usually cover. If they do, our study reinforces the results. If they don't, our study should be considered because it provides an important piece of knowledge about the dynamics of the river and concerns the management time scale.

With respect to flood risk assessment, as the referee says, in the case study the analysed flood event shows an alignment with the long-term pattern, but what if hydrodynamic simulations indicate flood patterns that diverge from the long-term tendency mainly due to particular features such as bridge clogging? We agree with the referee that "hydraulic bottlenecks" and other anthropic constrains can be an underlying factor during flooding events, as they can result in tipping points changing the river expected dynamics. But, to what extent these phenomena control the flood effects of the study area? In the case of the Garona River in Val d'Aran, we clearly observed that particular features as bridges and channels influenced the flow and the consequent effects, but only locally. Most of the river is not anthropized and was affected by intense erosion. Following referee's suggestion, in the revised manuscript we will consider more specifically the relevance of "induced" effects due to anthropic actions versus the effects related to the long-term entrenchment tendency of the river. In terms of "induced" effects, in urban areas, the 2013 flood event effects were aggravated by the presence of two main structures. First, channelization dykes partly prevented overflow so intensified vertical erosion. A good example of this phenomenon was recorded in Les, where vertical incision and dyke scouring occurred along most of this channelized river stretch (Fig. 12 and 13). Dykes also are responsible for local enhanced erosion of the channel downstream from these channelized stretches. Second, some bridges were clogged (or they had not enough dimension for the flood discharge) and adjacent areas were flooded due to an overflow phenomenon. Although these areas presented some sedimentation related to the overflows, the flood also produced erosion affecting the bridge foundations. Figure 10 illustrates the flood effects along Bossòst and shows the overflow of the Garona River in an area affected by bridge clogging. Concerning "natural" effects, in areas slightly or not affected by human influence, incision and lateral erosion were the main recorded phenomena (see table 1), with few overflow points and accumulation areas (see table 2). Local accumulation zones were found (see the table included in the reply to referee 1, showing the compilation of the available data on historic flood events), but they are generally restricted to local slope decreases (e.g. in Casarilh), some small overflows at meanders (e.g. upstream Bossòst) alluvial fans and confluences (e.g. in Vielha and downstream Arties towns at the confluence of the Valarties River). But note that a great part of the accumulated material in the Arties camping area came both from the Valarties River and from the induced embankment intense erosion due to a dam clogging in the Garona River upstream from Arties (see reply to referee 1). Another case is the accumulation induced by the embankment collapse in Era Bordeta, where river erosion produced the collapse, generating a wave that resulted on the overflow and sedimentation on the opposite bank. As far as we know, the existing numerical methods are also unable to predict these local effects due to dam clogging and collapse of embankments. Our study contribution cannot predict these effects, but keeping in mind the erosive tendency of the river can help to foresee this kind of phenomena.

However, the studied stretch of the Garona River mainly flows along not-urbanised areas. The actions on the channel that can influence in the river response are in a great extent limited to specific urban areas. The river is channelized along these stretches, whereas most of the studied length corresponds to a mountain river with few anthropic influence. So, coming to the point, we emphasize the relevance of long river natural stretches that determine the natural fluvial dynamics. We think that the identified erosive short-term river response can be explained by the combination of particular features inducing erosion (e.g. dykes) and the influence of the entrenchment tendency. Often flood risk assessment erroneously involves a perception of stability, believing that changes are exclusively caused by human actions and not by natural processes (Schumm, 1994), downplaying the importance of the river natural dynamics. Keeping in mind the long-term tendency to incision of the Garona River could help managers to improve some specific actions (e.g. inspection and maintenance of some structures or design of deeper foundations for specific dykes). Channel changes in time can have implications for flood frequency (Gregory et al., 2008), and in the Garona River, this changes, related to the entrenchment dynamics, reduce the flooded area and therefore, the expected flooded areas will be less frequently affected. But the most important consequence related to the entrenchment tendency of Garona River is the destruction of the river banks, the related loss of land and the generalised scouring of bridge and even dyke foundations. In this type of areas, protection of engineering works threatened by incision should be a priority (Bravard et al., 1999). Even though we admit that these progressive processes are very difficult to systematize in guidelines, we provide a piece of knowledge that should not be discarded.

Reply to concluding remarks

Timescale and process change consideration is essential for river management since present processes are part of the river long-term evolution. We analysed the Garona River considering different temporal and spatial contexts in order to assess how the river responds and give insights into its future evolution. Following the referee’s suggestion to outline the usefulness of our study for river managers, we will set our study of the Garona River within the IDRAIM methodological approach for hydromorphological assessment (see section 1.1 of this document). In our case study, the long-term entrenchment tendency is reflected in the timescale used for river management (100-150 years). Therefore, this kind of studies, when enough evidences are identified, can be a complementary step to the analysis of 10-15 year short-term processes.

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