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Interactive comment on "Rainfall and streamflow sensor network design: a review of applications, classification, and a proposed framework" *by* Juan Carlos Chacon-Hurtado et al.

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» The manuscript presents a review of the existing methods for network sensor design for hydrological purposes. Moreover, in the introduction, the authors denote the lack of a unified methodology for network sensor design and, in the last paragraph, they propose a general procedure to fill this gap. I personally have only few comments and I would suggest the publication of the paper, provided that the authors extend the text keeping in mind the following comments: »

REPLY. We thank the reviewer for the precise and relevant comments. These comments have helped us to improve the manuscript.

» I agree with the other two reviewers that a general overview about the network sensor densities at global or continental scale is missing. I would suggest to support these considerations with tables or maps to show some relevant characteristics of the networks. In case this is not possible because of the lack of data, I would suggest to add some study cases or examples that might be useful for decision-makers. This would trigger considerations for stakeholders about any actions to be undertaken and to provide answers to questions like "Under which circumstances should I re-evaluate my sensors networks? Should I improve, reduce or relocate sensors?" »

REPLY. These comments were mainly pointed by Reviewer 1, and we replicate our reply to him/her in the following lines. We agree that practitioners may be interested in country-wise practices of hydrometric network expansion or modification. As the essence of the manuscript is to review the available mathematical methods to make such network expansions/modifications optimal, the connection to practical applications appeared weak.

In order to address the reviewer's comment, we have included references to country-scale network density, where the reader can find more detailed information (page 1, 31-34). We have also added statements to clarify that the optimal density of the network is case-specific (p3, 91-99), pointing out that practices in optimal monitoring network design would be, per-se, another in-depth study. We have framed these ideas in the new version of the paper without jeopardising its main focus. Also, main considerations about the selection of the appropriate number of gauges in the measurement-based methods are highlighted. In the new version of the manuscript we added the following text:

-> "Design of rainfall and streamflow sensor networks depends to a large extent on the scale of the processes to be monitored, and the objectives to address (TNO 1986, Loucks et al. 2005). Therefore, the temporal and spatial resolution of the measurements are driven by the measurement objectives. For example, information for long-term planning does not require the same level of temporal resolution as for operational hydrology WMO (2009). On the global and country scale, sensor networks are commonly used for climate studies and trend detection (Cihlar et al. 2000, Grabs and Thomas 2002, WMO 2009, Environment Canada 2010, Marsh 2010, Whitfield et al. 2012). This is also supported by the National Climate Reference Networks (WMO 2009). On a regional or catchment-scale, applications require careful selection of monitoring stations, since water resources planning and management decisions, such as operational hydrology and water allocation, require different temporal and spatial resolution data."

-> "The sensor network design can also be seen from an economic perspective (Loucks et al. 2005). In most cases, the main limitation in the deployment of sensor networks is related to cost, being the main driver for the reduction scenarios. The valuation between the costs of the sensor networks and the cost of lack of information is not usually considered, because the assessment of the consequences of decisions is made a-posteriori (Alfonso et al. 2016). In most studies, it is seen that the improvement of information content metrics (e.g., entropy, uncertainty reduction, among others) is marginal as the number of extra sensors increases (Pardo-Iguzquiza 1998, Dong et al. 2006, Ridolfi et al. 2011), and thus the selection of the correct density can be based on a threshold in the increase in accuracy. However, in many practical applications, the number of available stations may be defined by budget limitations. Therefore, the optimal density of a sensor network is strictly case-specific (WMO 2008)."

To address the reviewer's particular comment on the sensor network re-evaluation, we have added more references to support our statement that it should be made on a regular basis. Considerations of the frequency of this re-evaluation are driven by the changes in the monitoring objectives, the available observation methods, budget restrictions and changes in the observed variable, among others (highlighted in section 1.1 p-4.), and, as one can imagine, these aspects are totally case-dependent.

The questions the reviewer is suggesting, like "Under which circumstances should I re-evaluate my sensors networks?", and "Should I improve, reduce or relocate sensors?” are indeed very important and we believe they should be addressed in a separate manuscript. From a review point of view, considerations of the frequency of the re-evaluation are driven by the changes in the monitoring objectives, the available observation methods, budget restrictions and changes in the observed variable. These considerations are highlighted in section 1.1 p-4.

» Some considerations about the advantages and disadvantages of the various methods for network sensor evaluation is missing. For example fractal approach methods suffer from the fact that they consider the sensors located in a two dimensional space, ie not considering the elevation. On the contrary, orography might play an important role in the location of the precipitation maxima, thus fractal methods should be employed only in relatively flat areas. Another example where advantages and disadvantages might be relevant is the case of the methods based on expert judgment since these methods are, by definition, biased because of the expert. »

REPLY. Indeed, highlighting advantages and disadvantages of different design methods provide a reference to the readers towards the selection of one method over another. This is a very good point, so we have added Table 3 presenting advantages and disadvantages of the different design methods. Table 3 can be found in the attachments of this reply.

» Since the method proposed in Section 5 is the novel concept introduced in the paper, I would appreciate an application of the method in a real case (for example a case when the optimal criteria are met to exit the loop and another case when they're not met). This would help the readers to conduct their own experiments based on this new tool. »

REPLY. We agree with the reviewer that presenting an example application of the proposed design methodology may be of value to the reader. Although this is the ongoing research, we find it too difficult to add it here, as it may compromise the scope and length of the paper. We would like to keep it as a review paper, with a proposed framework. We understand that proposing a framework in a review paper may outreach its limits, but considering that this methodology is implicitly addressed in many of the references, we identified it as an opportunity.

» Specific comments. The numbering of the Sections is sometimes confusing, I would suggest to simplify it (eg reducing the sub-sections) to get the text more smoothly. For example the Section 4 is very meager and I would merge it with another section (perhaps the last one?) »

REPLY. Thank you for the suggestion. We have simplified the paper structure by removing section 5, and merging its content in section 6. Additionally, we expand section 4 with Table 3. Table 3 can be found in the attachments of this reply.

» Technical corrections C2 Please cite correctly the paper by Capecchi et al 2012 (not Cappechi et al 2011) and change the text accordingly »

REPLY. We regret this mistake. It has been corrected.

» Eq 13: The definition of joint entropy is not well explained for a non-expert. "max" in the right hand side of the formula is not clear, the dots ". . . " are not clear »

REPLY. The formulas have been clarified.

» Eq 14: "m" stands for? "H" stands for? Please specify »

REPLY. The formulas have been clarified.

» Since I'm not a native English speaker, I have no issues on the language. Anyway some typos are found; here some examples: – pag 16, line 531: "Heaviside function" with the capital letter – Figure 6, conditional block (7): "Is it..." instead of "Is It..." – Figure 6, conditional block (9): "Is it..." instead of "It is..." »

REPLY. A complete revision of the paper has been undertaken to address the language issues.

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Table 3 Advantages and disadvantages of sensor network design methods

	Advantages	Disadvantages
	Statistics-based	
Interpolation variance	Useful to assess data scarce areas No event-driven Minimise uncertainty in spatial distribution of measured variable	Heavily rely on the characterisation of the covariance structure No relationship with final measurement objective
Cross-correlation	Useful for detecting redundant stations Computationally inexpensive	Augmentation not possible without additional assumptions Limited to linear dependency between stations
Model error	Has direct relationship with the measurement objectives	Biased towards current measurement objectives Biased towards model and error metrics
	Information Theory	
Entropy	Assess non-linear relationship between variables Unbiased estimation of network performance	Formal form is computationally intensive Quantising (binning) of continuous variables lead to different results Optimal networks are usually sparse Difficult to benchmark Data intensive
Mutual information	Idem	Idem
	Expert recommendations	
Physiographic components	Well understood Functional for heterogeneous catchments with few available measurements Useful at country/continental level	Not useful for homogeneous catchments No quantitative measure of network accuracy
Practical case-specific considerations	No previous measurements are required Useful to observe specific variables	Biased towards expert Collected data does not influence selection Biased towards current data requirements
User survey	Pragmatic Cost-efficient	Extensive user identification Biased towards current data requirements
	Other methods	
Value of information	Provides a full economical assessment	Hard to quantify Usually decisions are made with available information Biased towards a rational decision model
Fractal characterisation	Efficient for large networks Does not require data collection	Not suitable for small networks or catchments Does not consider topographic or orographic influence
Network theory	Provides insight in interconnected networks	Not useful for augmentation purposes Data intensive

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Fig. 1.