Areal rainfall estimation using moving cars – computer experiments including hydrological modeling

Ehsan Rabiei[1], Uwe Haberlandt[1], Monika Sester[2], Daniel Fitzner[2], Markus Wallner[3]

[1] [Institute of Water Resources Management, Hydrology and Agricultural Hydraulic Engineering, Leibniz Universität Hannover, Hanover, 30167, Germany]

[2] [Institute of Cartography and Geoinformatics, Leibniz Universität Hannover, Hanover, Germany]

[3] [Federal Institute for Geosciences and Natural Resources, Groundwater Resources - Quality and Dynamics, Hanover, 30655, Germany]

Correspondence to: E. Rabiei (rabiei@iww.uni-hannover.de)

GENERAL REMARKS (BOTH REFEREES):

We are very grateful to G. Pegram and an anonymous referee for their remarks on our manuscript. We believe that considering all the points will improve the quality of the manuscript significantly.

In the following we will respond all the comments, separately. All the numbers corresponding to figures and tables in this document refer to the numbers used in the original manuscript provided for HESSD.

GENERAL REMARKS OF REFEREE #1:

We agree about the problems related to RainCars, in particular for practical purposes. Some of them are addressed in the text and many of them are discussed in previous publications (Fitzner et al., 2013; Rabiei et al., 2013). We have now included a brief discussion about the problems in the text. The main objectives of this study are using errors derived from laboratory experiments (Rabiei et al., 2013) and investigating scenarios with larger uncertainties considering the problems in field experiments, to assess the value of RainCars. The message of the paper is that the RCs would be beneficial when errors lay below a certain threshold and the car density is above a certain level. The practicability of the idea can only be assessed after carrying out extended field experiments which would be a necessary future step. Then, the errors from field experiments could be compared against the thresholds obtained here to decide about feasibility of the approach.

Finding volunteers for field experiment is hard. That is the reason we cooperated with taxi companies in Hanover in previous years. Considering the fact that more than 53000 taxis were available in Germany in 2012 (http://de.statista.com/statistik/daten/studie/36475/umfrage/anzahl-der-taxen-in-deutschland-seit-1960/), one realizes the huge potential of using public transportation as moving sensors. Using wiper frequency for rainfall measurement was the initial idea which we changed later to using the move objective optical sensors for rainfall measurement. The diurnal variation of the number of RCs was considered and discussed by Haberlandt and Sester (2010). Here, instead, the RC density scenarios from 1% to 5% could be used to assess different traffic densities during day and night. A possible method using RCs for practical purposes was proposed by Fitzner et al. (2013). In that study, a communication between the moving sensors and rain gauge network was proposed. This could in practice filter some of the errors out. Additionally, large rainfall amounts caused by front spray may be detected using statistical approaches. However, we agree that front spay is one of the main problems which must be considered when more data from field experiment is available. Wind is an important factor influencing under- or overestimation of rainfall by RCs and could be compensated in a similar way to car speed. A theoretical relationship for compensating car speed was suggested by Rabiei et al. (2013) which was tested in practice by Fitzner et al. (2013). Those findings could be used to compensate the influence of both wind and car speed.

There is no need to connect RC data with radar data. These would be two independent sources of data. However, the merging product of all available data sources might provide a more realistic rainfall field map. Considering the facts that we are able to record all the sensor readings every second and the assumed *conservative* car speed of 80 km/h, RCs would move up to 25 meters every second which give useful rainfall observations. Cars on highways are not used here because of the high speed and heavy road spray.

SPECIFIC COMMENTS

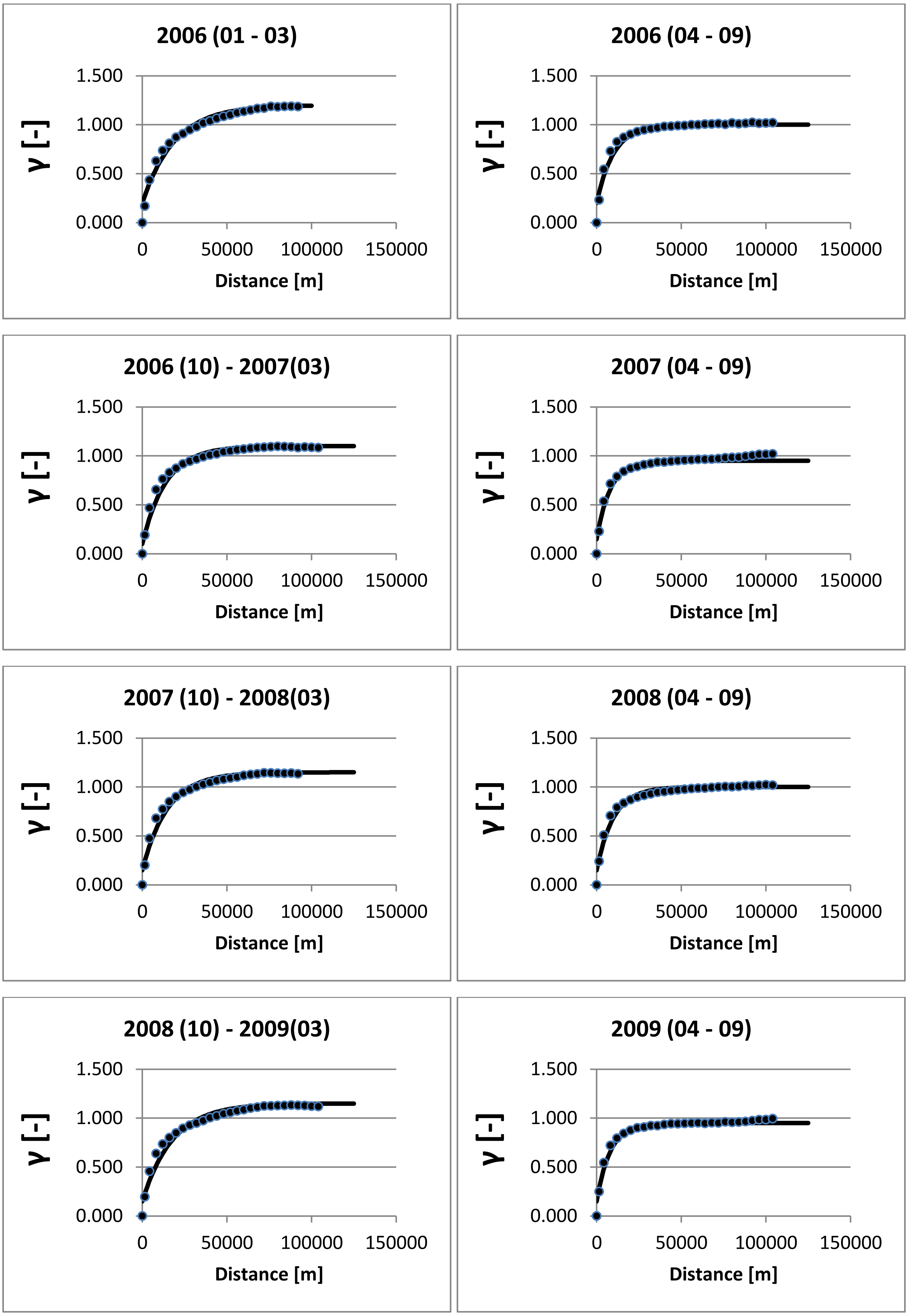
5: 14 We agree that this is an important factor. As explained, different RC density scenarios could address the diurnal fluctuation. This is added to the manuscript.

6: 27 (log ε) is assumed to be normally distributed and can be negative. After back transformation, $\varepsilon = 10^{\log\varepsilon}$, the error (ε) cannot be negative in Eq. (6).

7: 10 A linear relationship was proposed by Rabiei et al. (2013) in order to find a relationship between sensor readings and rain rate. Due to all the difficulties associated to this relationship, we decided to implement a simple data transformation to overcome the problems. One major concern was when the surface of the optical sensor is dry or at the vicinity of the origin. Not only the curve must pass through the origin, but also the rain rate at this point using the W-R relationship (1) must not be negative and (2) must be the most accurate value. Therefore, by taking the logarithm from both sides these two concerns would be satisfied. We agree that other transformations might be more suitable, but the simplicity of the method was also an important point considered in this step.

7: 15 We agree that implementing OK, in particular for fine temporal resolution, is questionable, but this approach is carried out in several studies. Although applying data transformation might overcome this theoretical issue, the results might still be very similar to the current results due to the fact that the main problem is rather the distance between the observations (network density). However, as comparing different sources of data is carried out using the same technique, this issue is relatively insignificant in this study. A summary of what is explained here is added to the text.

8: 4 It was decided to provide the variogram properties in a table instead. Following figures illustrate the variograms used in this study. The numbers illustrate different time windows considered due to seasonal change in variogram properties. Due to the relative comparison of the scenarios, the figures are not provided in the text.


2006 (01 - 03)
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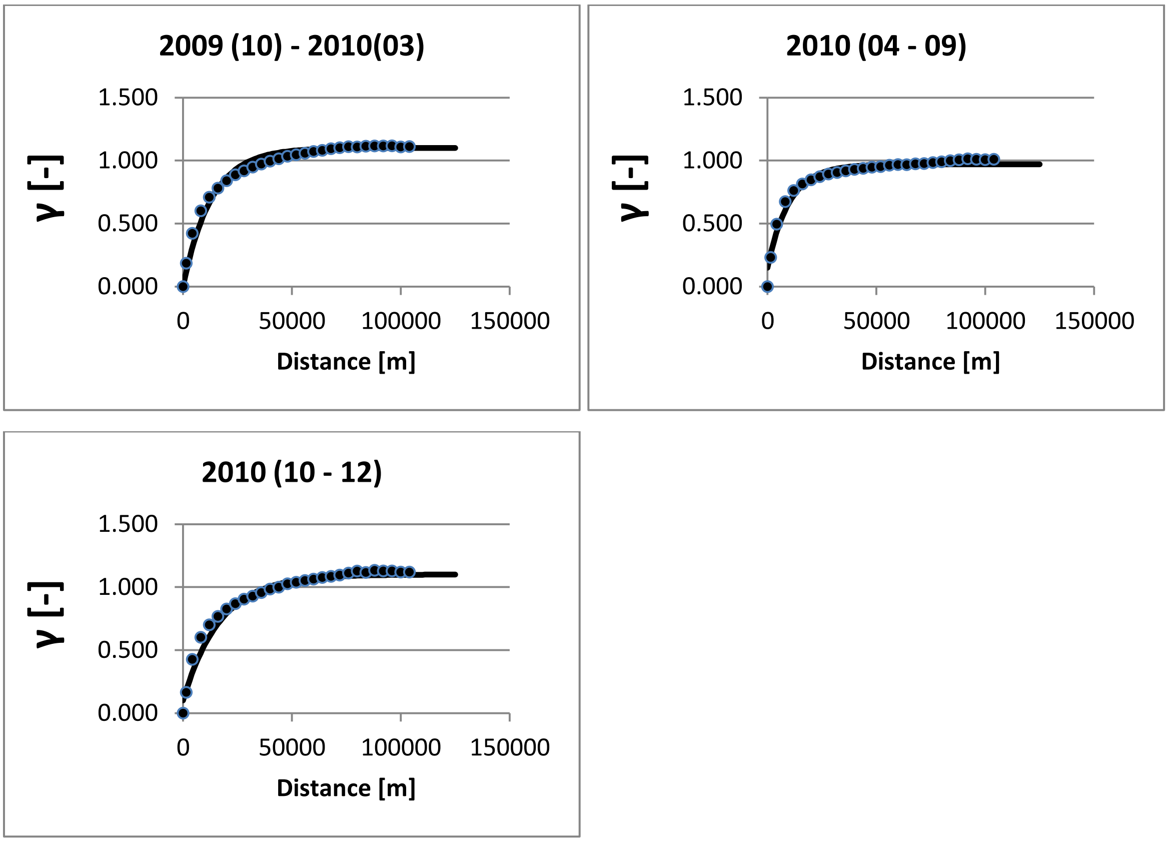
2007 (04 - 09)
2007 (10) - 2008(03)
2008 (04 - 09)
2008 (10) - 2009(03)
2009 (04 - 09)
γ [-]
1.500
1.000
0.500
0.000
0
50000
100000
150000
Distance [m]



10: 27 We agree that the description is not comprehensive. A better description of weather radar data is provided in the text.

15: 13 Here, the main purpose was to draw the reader's attention to the spatial rainfall variation explained earlier. To be clearer, the text is changed.

15: 24 It was decided to explain different sources of data, separately. Fig. 7 and Fig. 8 are provided in the same subsection which is discussed on page 16.

19: 19 Yes, the word is changed accordingly.

19: 20 Sigma was considered as a measure illustrating the magnitude of the device uncertainty. In addition to addressing the uncertainty derived from the laboratory experiment, we decided to investigate what happens if we face higher uncertainties. The large uncertainty could come from all the difficulties mentioned earlier such as wind. See also response to general remarks

The oval was used to make it easier for the reader to see the differences between the scenarios. A new figure is replaced illustrating the discharge over a shorter time period.

20: 10 Yes, MODELLED is added to the text

20: 15 please refer to the answer to comment 7:10. This transformation was implemented given all the points mentioned above. Another reason of implementing this transformation was the ease in finding the range for error, Fig. 6a.

20: 24 We agree that transforming the data in a way that they fit the Gaussian distribution function follows the assumptions behind OK, but implementing OK on rainfall observation data is a popular technique used for areal rainfall estimation in several studies. This method was considered for all sources of data, so a relative comparison is feasible.

21: 1 The text is changed accordingly.

GENERAL REMARKS OF REFEREE #2:

1. We agree that the term rain rate is a better term especially as we worked with radar data. Due to the fact that the data is used in a hydrological model, we decided to used rainfall estimation which is a term containing both rain rate and rainfall amount. Depending on the intention of each sentence, a more appropriate term is replaced. The term rainfall amount is omitted from the text.
2. Yes, we agree. However, as the hydrological model used in this study has a semi-distributed approach and the subcatchments are relatively small, the separated evaluation of the subcatchments may represent the sought information.
3. Yes, we agree that OK is only optimal when the data are Gaussian. Nevertheless, implementing OK is used in several studies without applying any transformation. However, the results may not be changed significantly even if transforming the data would satisfy the theoretical assumptions. The main problem, as it is discussed, is the number of observations. In other words, more information is required for a better areal rainfall estimation rather than Gaussianity of data under study. The part discussing this problem is added to the text. See also the answer to the comment of referee #1 (20: 24).
4. This was pointed out on p.2 L31-L32: "*A continuous investigation using RCs with the derived uncertainties from laboratory experiments for a long period of time as well as implementing the data in a hydrological model would answer three important scientific questions*". As explained in the text, a continuous approach was used. Yes, like any continuous approach there are time steps with no rain.
5. Yes, we agree that the conclusion of this study may not be valid overall. However, it is a new approach to investigate whether additional information of RCs would be useful. A better discussion is added to the text.

SPECIFIC COMMENTS

1. The terms describing the method is added to the text.
2. The second scientific question is explaining the reason of investigating several other uncertainties for RCs. This part is rephrased.
3. The text is changed accordingly.
4. Yes, car speed also causes overestimation of rain rate. As explained earlier, a theoretical relationship for compensating car speed was suggested by Rabiei et al. (2013) which was proved in practice by Fitzner et al. (2013). Those findings could be used to compensate the influence of both wind and car speed. A part is added to explain this approach for compensating car speed.
5. Please refer to the answer to the first comment of the first referee (SPECIFIC COMMENTS).
6. A constant value of 20000 m is used. This value is added to the text.
7. This was explained in details in Rabiei et al. (2013). A short summary is added to the text.
8. This explanation is added to the text.
9. The term is added to the text.
10. All the units are added to the text.
11. This is from ground observation and was mentioned in Berndt et al. (2014)
12. Those values are added to the text.
13. Please refer to the answer to comment 8) of the first referee.
14. Yes, we agree and it was discussed earlier here.
15. Yes, we agree. The term "can" is replaced by "may". A better discussion is added to this part.

16. Yes, RMSE is deleted from the sentence.
17. The sentences are rephrased to describe the situation only for this study.
18. The first sentence refers to the possible ways of using RCs even if the uncertainty is relatively large. The beginning of the new paragraph represents the situation when the RCs are as accurate as ground observations. The underestimation of rain rates were observed even in this situation.
19. Yes, this is added to the text.
20. The new citation is added to the text.
21. The units are added to the tables and figures.
22. Yes, this was generated automatically. The lower altitude is set now to zero.
23. The two figures represent the same relationship. On the left it is provided in a logarithmic scale and on the right after transforming back. This is the reason of having the same R^2 value. On the right a power relationship describes the relationship between the two variables, whereas the left figure is a linear relationship in logarithmic scale.
24. The colors are changed for the ease of identifying the global pattern.

References

Berndt, C., Rabiei, E., Haberlandt, U., 2014. Geostatistical merging of rain gauge and radar data for high temporal resolutions and various station density scenarios. Journal of Hydrology, 508(0): 88-101.

Fitzner, D., Sester, M., Haberlandt, U., Rabiei, E., 2013. Rainfall Estimation with a Geosensor Network of Cars Theoretical Considerations and First Results. Photogrammetrie - Fernerkundung - Geoinformation, 2013(2): 93-103.

Haberlandt, U., Sester, M., 2010. Areal rainfall estimation using moving cars as rain gauges – a modelling study. Hydrol. Earth Syst. Sci., 14(7): 1139-1151.

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