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What is best-practice automated hydraulic head and gradient measurement? A systematic review of errors and how to minimse them

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Field measurements of hydraulic heads and gradients underpin the quantification of subsurface flow processes and properties throughout the geosciences. Their quantification is generally assumed to be trivial and hence few practitioners receive comprehensive field training, resulting in a high potential for error and misinterpretation. In this contribution we comprehensively review the four individual measurements required to calculate hydraulic heads and gradients: (1) geo-spatial positioning, (2) manual water depth, (3) automated pressure, (4) spatial reference point for the head. We systematically and concisely summarise the standard practice for each measurement and estimate the random error magnitudes from the literature, our own datasets and field experience. For example, the minimum random error for hydraulic head differences when applying standard practice is approximately 12 mm. We compare and propagate measurement errors for horizontal and vertical hydraulic gradient calculations and evaluate the impact of the error uncertainty on the quantification of subsurface flow processes. Our systematic assessment reveals some surprising aspects and demonstrates simple best-practice rules that should be followed to achieve the highest possible measurement precision. We categorise these recommendations in order of error magnitudes from highest to lowest. The largest errors contributing to hydraulic head and gradient measurements originate from borehole inclination and manual water depth measurement, respectively. Our analysis demonstrates that resolving head gradients that are smaller than 10^{-2} for boreholes that are closer than 10 m requires extraordinary effort. This work will provide fundamental information for students and practitioners in fields where hydraulic head data is vital; we anticipate that our synthesis will avoid common pitfalls as well as provide a starting point for the development of best-practice guidelines for hydraulic head and gradient measurements.