HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain-size analysis

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1 author:

J.F. Devlin
University of Kansas

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EDITOR'S MESSAGE

Editor's Message: The 2015 Editors' Choice articles

Clifford Voss[1]

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Keywords Editorial · Hydrogeology Journal · Editors' Choice

"Editors' Choice" articles are ones selected for special attention by the *Hydrogeology Journal* (HJ) editorial team (Martin Appold, Jean-Michel Lemieux, Liz Screaton, Maria Schafmeister, Cliff Voss) and the guest editors of the 2015 HJ theme issue (Bithin Datta, George Kourakos, Brian Wagner). These articles were selected for one or more of several good reasons including: outstanding science, innovative approach, potentially important conclusions, interesting field area or phenomenon, unusual topic, political/social/historical/philosophical interest, etc.

At the conclusion of each publishing year, the editors select five articles from among the year's crop of about 130 published articles. The HJ editors believe that readers will find these articles to be somehow especially interesting or valuable.

Editors' Choice articles are highlighted on the International Association of Hydrogeologists' (IAH) website (https://iah.org/hydrogeology-journal/hj-editors-choice-articles), in the IAH newsletter, and on the *Hydrogeology Journal* website (http://www.springer.com/hydrogeologyjournal).

Our publisher, Springer, is making these articles freely accessible to all readers for two months from the publication of this editorial message. It is expected that further interest will be generated through the IAH and Springer social media, including, LinkedIn, Facebook, email alerts, and tweets via @IAHgroundwater and @SpringerGeo.

The 2015 selection comprises a mixture of Papers and Reports and one Technical Note. The diversity of article types, subject matter, and author nationalities associated with Editors' Choice articles since the start of the selection process (in 2010) demonstrates the principles by which IAH and HJ encourage global involvement in hydrogeology, and the editorial team is proud to promote such high quality articles.

The Editors' Choice articles for the 2015 publishing year are listed in Table 1.

Congratulations to all of these distinguished authors!

C. Voss is the executive editor of *Hydrogeology Journal* (HJ)

✉ Clifford Voss
cvoss@usgs.gov

[1] US Geological Survey, 345 Middlefield Road, MS 496, Menlo Park, CA 94025, USA

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Table 1 *Hydrogeology Journal's* 2015 Editors' Choice articles

Authors	Title	Vol./No., pages DOI
J. F. Devlin	HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain-size analysis	23/4, 837–844 DOI 10.1007/s10040-015-1255-0
Brian D. Smerdon, Chris Turnadge	Considering the potential effect of faulting on regional-scale groundwater flow: an illustrative example from Australia's Great Artesian Basin	23/5, 949–960 DOI 10.1007/s10040-015-1248-z
Zahra Jamshidzadeh, Frank T. -C. Tsai, Hasan Ghasemzadeh, Seyed Ahmad Mirbagheri, Majid Tavangari Barzi, Jeffrey S. Hanor	Dispersive thermohaline convection near salt domes: a case at Napoleonville Dome, southeast Louisiana, USA	23/5, 983–998 DOI 10.1007/s10040-015-1251-4
Josué Medellín-Azuara, Duncan MacEwan, Richard E. Howitt, George Koruakos, Emin C. Dogrul, Charles F. Brush, Tariq N. Kadir, Thomas Harter, Forrest Melton, Jay R. Lund	Hydro-economic analysis of groundwater pumping for irrigated agriculture in California's Central Valley, USA	23/6, 1205–1216 DOI 10.1007/s10040-015-1283-9
Heather A. Sheldon, Peter M. Schaubs, Praveen K. Rachakonda, Michael G. Trefry, Lynn B. Reid, Daniel R. Lester, Guy Metcalfe, Thomas Poulet, Klaus Regenauer-Lieb	Groundwater cooling of a supercomputer in Perth, Western Australia: hydrogeological simulations and thermal sustainability	23/8, 1831–1849 DOI 10.1007/s10040-015-1280-z

HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain-size analysis

J. F. Devlin

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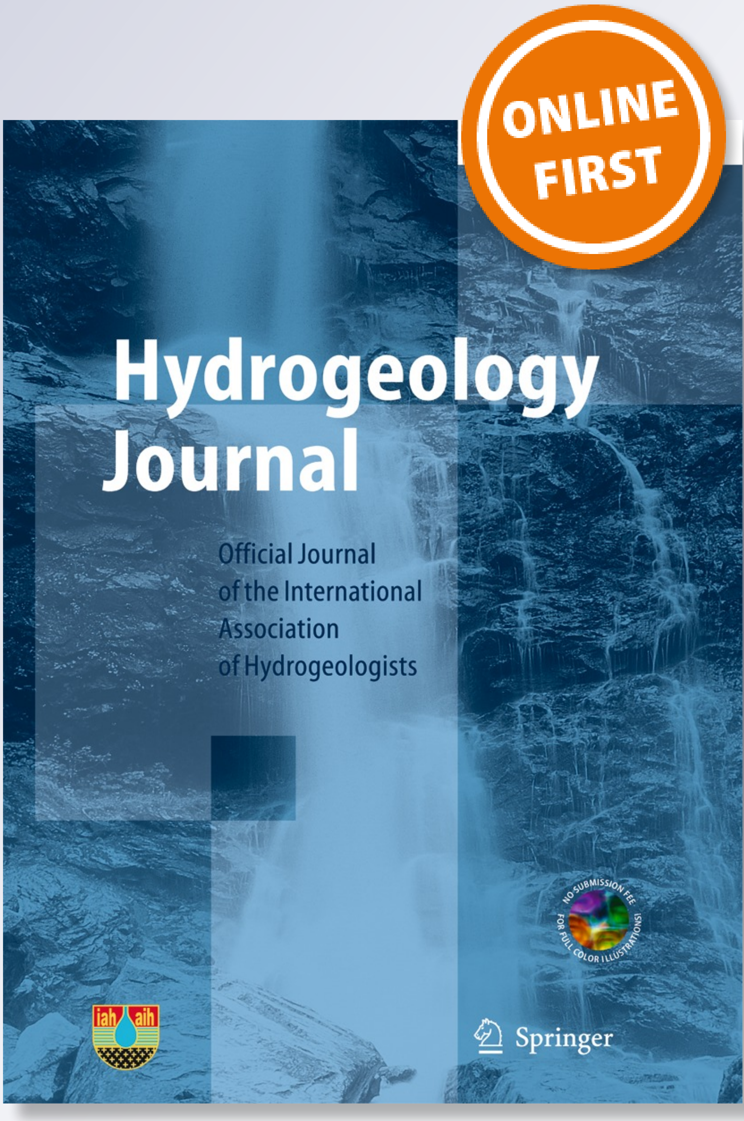

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HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain-size analysis

J. F. Devlin

Abstract For over a century, hydrogeologists have estimated hydraulic conductivity (*K*) from grain-size distribution curves. The benefits of the practice are simplicity, cost, and a means of identifying spatial variations in *K*. Many techniques have been developed over the years, but all suffer from similar shortcomings: no accounting of heterogeneity within samples (i.e., aquifer structure is lost), loss of grain packing characteristics, and failure to account for the effects of overburden pressure on *K*. In addition, *K* estimates can vary by an order of magnitude between the various methods, and it is not generally possible to identify the best method for a given sample. The drawbacks are serious, but the advantages have seen the use of grain-size distribution curves for *K* estimation continue, often using a single selected method to estimate *K* in a given project. In most cases, this restriction results from convenience. It is proposed here that extending the analysis to include several methods would be beneficial since it would provide a better indication of the range of *K* that might apply. To overcome the convenience limitation, an Excel-based spreadsheet program, HydrogeoSieveXL, is introduced here. HydrogeoSieveXL is a freely available program that calculates *K* from grain-size distribution curves using 15 different methods. HydrogeoSieveXL was found to calculate *K* values essentially identical to those reported in the literature, using the published grain-size distribution curves.

Keywords Grain-size analysis · Hydraulic properties · Spreadsheet · Unconsolidated sediments · Laboratory experiments/measurements

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J. F. Devlin (✉)
Department of Geology,
University of Kansas, Lindley Hall rm 120, 1475 Jayhawk Blvd., Lawrence, KS 66049, USA
e-mail: jfdevlin@ku.edu
Tel.: 785-864-4994

Introduction

Since the introduction of Darcy's Law, an enormous effort (by hydrogeological standards) has been directed at quantifying the hydraulic conductivity parameter, *K*. Since it was recognized early on that *K* was correlated with grain size—low in clays and high in gravels—it is not surprising that there were early efforts to estimate *K* from grain-size analyses. It is also not surprising that these efforts enjoyed some measure of success (Fuchs 2010). At the same time, it must be conceded that after more than a century of trying, the goal of obtaining a value of *K* in the laboratory that is fully representative of *K* in an aquifer has yet to be achieved (Rosas et al. 2014). The reasons for this include factors such as geologic heterogeneity (particularly as it affects aquifer structure, which is disrupted in the grain-size-analysis procedures), the nature of porosity, subtle effects related to grain shapes and packing (Dullien 1991), and in some cases variations in porewater pressure (Barth et al. 2001).

Despite the well-accepted limitations of *K* estimates from grain-size analyses, there are no simpler or more economical measurement-based techniques for obtaining *K* estimates from aquifer samples. Where preliminary calculations are concerned, these measured values still represent an attractive starting point for hydrogeological investigations, or an inexpensive source of supporting data, particularly where sand and gravel deposits are of concern.

Among the earliest attempts to relate *K* to grain size, or grain-size distribution, was work published by Hazen (1892). Since that time, a large number of variations on the theme have been developed. Aguilar (2013) reviewed a subset of 20 of these different empirical relationships. The equations range from the very simple, such as the simplified Hazen formula given by Freeze and Cherry (1979) (first entry in Table 1), to the considerably more involved calculation offered by Kozeny and Carmen (eighth entry in Table 1). Unfortunately, the various approaches can produce estimates of *K* from the same sample that are an order of magnitude or more apart (Vukovic and Soro 1992). Although each equation comes with recommendations for the sediment types they apply to, many of the restrictions overlap, so establishing a preference for one equation over another may be somewhat subjective. Rather than basing a *K* determination on any single equation, it may be prudent to estimate *K* from several methods and consider the range of

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Table 1 Selected equations relating hydraulic conductivity, K in cm/s, with porosity and effective grain size in cm (taken from Devlin 2014), modified and expanded from Vukovic and Soro 1992

Source	N	$\varphi(n)$	d_e	Applicable conditions
Hazen simplified (Freeze and Cherry 1979)	$10\frac{\mu}{\rho g}$	1	d_{10}	Uniformly graded sand, n=0.375 T=10 °C
Hazen (1892)[a]	6×10^{-4}	$[1+10(n-0.26)]$	d_{10}	$0.01\ \text{cm}<d_{10}<0.3$ cm $U<5$
Slichter (1898)[a]	1×10^{-2}	$n^{3.287}$	d_{10}	$0.01\ \text{cm}<d_{10}<0.5$ cm
Terzaghi (1925)[a]	10.7×10^{-3}smooth grains 6.1×10^{-3}coarse grains	$\left(\frac{n-0.13}{\sqrt[3]{1-n}}\right)^2$	d_{10}	Sandy soil, coarse sand
Beyer (1964)[a]	$5.2\times10^{-4}\log\frac{500}{U}$	1	d_{10}	$0.006\ \text{cm}<d_{10}<0.06$ cm $1<U<20$
Sauerbrei (1932)[a] (Vukovic and Soro 1992)	$(3.75\times10^{-5})\times\tau$ $\tau\cong1.093\times10^{-4}T^2+2.102\times10^{-2}T+0.5889$	$\frac{n^3}{(1-n)^2}$	d_{10}	Sand and sandy clay $d_{10}<0.05$ cm
Krüger (1919)[a]	4.35×10^{-4}	$\frac{n}{(1-n)^2}$	$\frac{1}{\sum_{i=1}^{m}\frac{\Delta w_i}{d_i}}$	Medium sand $U>5$ T=0 °C
Kozeny (1953)[a]	8.3×10^{-3}	$\frac{n^3}{(1-n)^2}$	d_{10} or $\frac{1}{\frac{3}{2}\frac{\Delta w_1}{d_1}+\sum_{i=2}^{m}\Delta g_i\frac{d_i^{g}+d_i^{d}}{2d_i^{g}d_i^{d}}}$ $d_1=\frac{1}{\frac{1}{2}\left(\frac{1}{d_i^{g}}+\frac{1}{d_1^{d}}\right)}$	Coarse sand
Zunker (1930)[a]	0.7×10^{-3} for nonuniform, clayey, angular grains 1.2×10^{-3} for nonuniform 1.4×10^{-3} for uniform, coarse grains 2.4×10^{-3} for uniform sand, well rounded grains	$\frac{n}{(1-n)}$	$\frac{1}{\sum_{i=1}^{m}\Delta g_i\frac{d_i^{g}-d_i^{d}}{d_i^{g}d_i^{d}\,ln\left(\frac{d_i^{g}}{d_i^{d}}\right)}}$	No fractions finer than d=0.0025 mm
Zamarin (1928)[a]	8.65×10^{-3}	$\frac{n^3}{(1-n)^2}C_n$ $C_n=(1.275-1.5n)^2$	$\frac{1}{\sum_{i=1}^{n}\Delta g_i\frac{\ln\left(\frac{d_i^{g}}{d_i^{d}}\right)}{d_i^{g}-d_i^{d}}}$	Large-grained sands with no fractions having $d<0.00025$ mm
US Bureau of Reclamation (Białas 1966)[a]	$(4.8\times10^{-4})(10^{0.3})$	1.0	${d_{20}}^{1.15}$	Medium-grained sands with $U<5$; derived for T=15 °C
Barr (2001)	$\frac{1}{(36)5C_s^2}$ $C_s^{\,2}=1$ for spherical grains $C_s^{\,2}=1.35$ for angular grains	$\frac{n^3}{(1-n)^2}$	d_{10}	Unspecified
Alyamani and Sen (1993)	1,300	1.0	$[I_o+0.025(d_{50}-d_{10})]$	Unspecified
Chapuis (2004)	$\frac{\mu}{\rho g}$	$10^{1.291\xi-0.6435}$ $\xi=\frac{n}{1-n}$	$d_{10}\left(\frac{10^{(0.5504-0.2937\xi)}}{2}\right)$	$0.3<n<0.7$ $0.10<d_{10}<2.0$ mm $2<U<12$ $d_{10}/d_5<1.4$

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Table 1 (continued)

Source	N	$\varphi(n)$	d_e	Applicable conditions
Krumbein and Monk (1942)	7.501×10^{-6}	$e^{(-1.31\times\sigma_\phi)}$ $\sigma_\phi=\frac{d_{84\phi}-d_{16\phi}}{4}\frac{d_{95\phi}-d_{5\phi}}{6.6}$	$2^{\left(\frac{d_{16\phi}+d_{50\phi}+d_{84\phi}}{3}\right)}$	Natural sands with lognormal grain-size distribution

[a] Indicates formulas were taken from Vukovic and Soro (1992)

N=constant dependent on characteristics of the porous medium

$\varphi(n)$=function of porosity

T=water temp. (°C)

g=980 cm/s^2

$\rho=3.1\times10^{-8}T^3-7.0\times10^{-6}T^2+4.19\times10^{-5}T+0.99985$

$\mu=-7.0\times10^{-8}T^3+1.002\times10^{-5}T^2-5.7\times10^{-4}T+0.0178$

$\tau=1.093\times10^{-4}T^2+2.102\times10^{-2}T+0.5889$

n=porosity as fraction of aquifer volume

d_i^g=the maximum grain diameter in fraction i

d_i^d=the minimum grain diameter in fraction i

d_{10}=grain size (cm) corresponding to 10 % by weight passing through the sieves

d_{20}=grain size (cm) corresponding to 20 % by weight passing through the sieves

d_{50}=grain size (cm) corresponding to 50 % by weight passing through the sieves

d_{60}=grain size (cm) corresponding to 60 % by weight passing through the sieves

$U=d_{60}/d_{10}$

Δg_i=the fraction of mass that passes between sieves i and i+1 where i is the smaller sieve

Δw_i=fraction of total weight of sample with fraction identifier 'i'

d_i=mean grain diameter of the fraction i

$d_{i\phi}$=mean grain diameter of the fraction i in phi units ($\phi=\log_2(d_e/d_o)$, d_e in mm, d_o=1 mm)

I_o=x-intercept (grain size) of a percent grain-retention curve plotted on arithmetic axes and focussing on data below 50 % retained

m = the total number of fractions from the sieve analysis

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values they produce. The goal of this work was to create a tool that would compute K estimates from several selected relationships that users could compare and evaluate.

The development of a software tool that estimates K from grain-size analyses is not new. Aguilar (2013) developed a Microsoft Visual Basic® code that computes K using 20 different estimation methods. Kasenow (2002) reviewed the subject in a 97 page book that included a software package to evaluate K using six different methods. Vukovic and Soro (1992) developed a Fortran program to compute K using 10 different grain-size analysis methods. However, the earlier software tools are either currently out of date, i.e., will not execute in the most common operating systems currently in use, or require some form of purchase to acquire. In contrast, the software described here, HydrogeoSieveXL, is readily available from the Devlin (2015) website, is free of charge, and runs in the Excel environment, to which most hydrogeologists have familiarity and ready access. It is also available as electronic supplementary material (ESM) with this article. The Vukovic and Soro (1992) report was used as the basis for this work. HydrogeoSieveXL includes all 10 of the methods they considered plus 5 additional methods representing more recent research or alternative approaches (see Table 1).

Theory

In accordance with Vukovic and Soro (1992), the general form of the relationship between K and grain size, which can be rationalized from the Darcy-Weissbach equation, is expressed as

$$K = \frac{\rho g}{\mu} N \varphi(n) d_e^2 \tag{1}$$

where, ρ is the temperature-dependent water density (g/ml), g is the gravitational constant (cm/s^2), μ is the temperature-dependent dynamic viscosity of water (g/cm/s), N is a case-specific constant regarded as a 'shape factor', $\varphi(n)$ is a function of porosity, and d_e is an effective grain size or function of the grain-size distribution. The values of N, $\varphi(n)$, and d_e have been defined in various ways, and these are summarized in Table 1. Note the similarity of this equation to the simpler representation given by Freeze and Cherry (1979),

$$K = k \frac{\rho g}{\mu} \tag{2}$$

where k is defined as the intrinsic permeability (cm^2). The equivalency of these two equations requires that k is dependent on the shape factor and porosity, both characteristics of the porous medium. The density and viscosity terms are representative of the fluid (water).

Implementation of the code

The majority of the calculations in HydrogeoSieveXL are performed in the Visual Basic® environment within

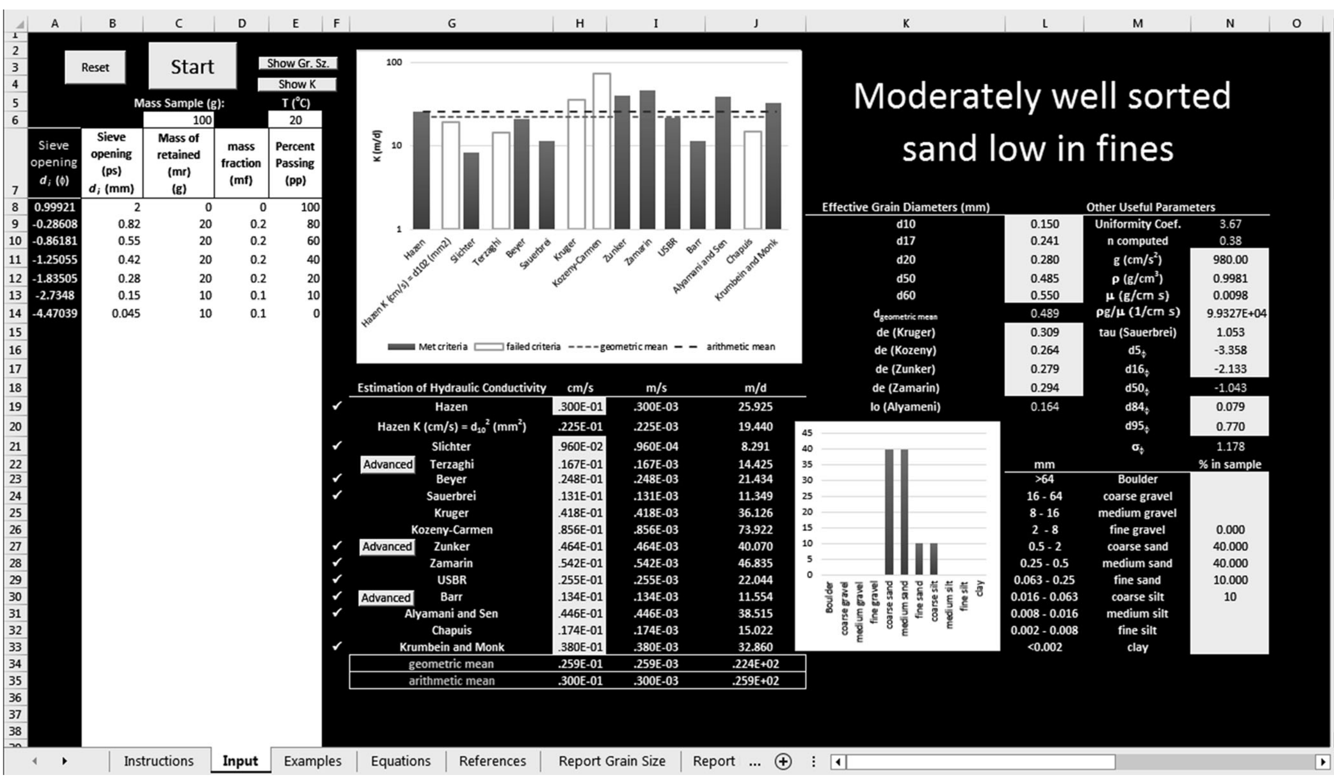

Fig. 1 Screen capture of the HydrogeoSieveXL Input screen

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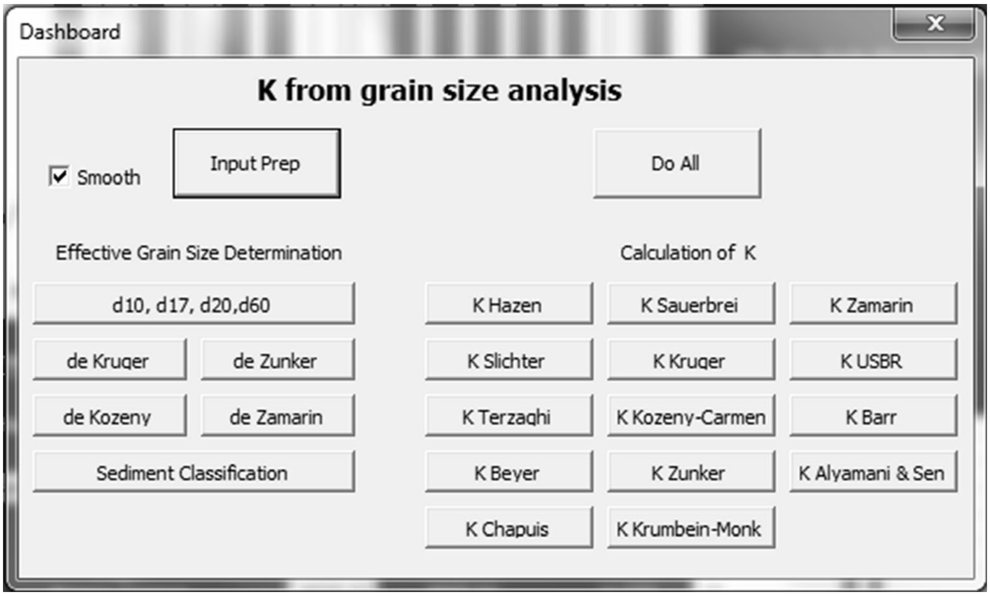

Fig. 2 Screen capture of the Dashboard userform

Excel®. The tool is suitable for use with Excel 2010 and 2013. Other versions of Excel® have not been tested. The computation of grain-size characteristics such as d_{10}, and K are initiated by clicking on labelled buttons in forms, and the code is contained in modules attached to those buttons. The primary user form in the program is the 'Dashboard', which is launched by clicking on the 'Start' button in the Input worksheet (Fig. 1).

The HydrogeoSieveXL workbook

The HydrogeoSieveXL workbook comprises 7 worksheets: (1) a user manual that describes the details of the operation and functionality of the tool, (2) the HydrogeoSieveXL input worksheet where all the computational work is initiated, (3) a worksheet with sample data from selected literature sources, and where user-specific data sets can be stored for future reference, (4) a copy of Table 1, for reference, (5) a reference list with citations to contributing literature, (6) a sheet that summarizes the grain-size data in a format suitable for pdf report generation and (7) a sheet that summarizes the K estimation calculations in a format suitable for pdf report generation. In general, work with HydrogeoSieveXL will be concentrated on the Input worksheet (Fig. 1).

Data can be entered into HydrogeoSieveXL in several ways. In all cases, the sieve openings (in mm) are entered beginning at cell B8 and proceeding down the sheet. Next the user can choose to enter the remaining data as mass

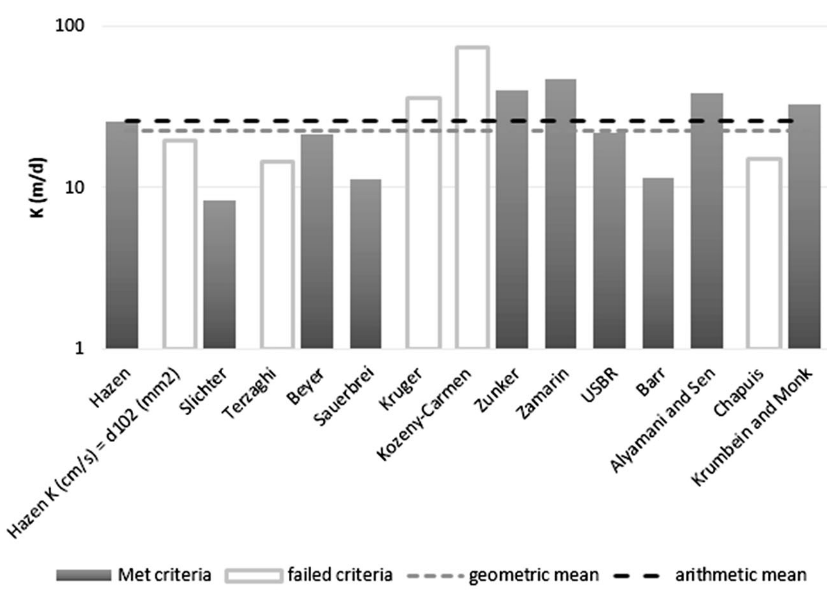

Fig. 3 Screen capture of the HydrogeoSieveXL calculated K summary graphic

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retained per sieve (in grams), mass fraction per sieve, or percent fraction per sieve. HydrogeoSieveXL will calculate and complete the remaining columns. To begin the data processing, the user clicks on the "Start" button under column C (Fig. 1). This action brings up the "Dashboard" userform (Fig. 2). The input data table is completed by clicking on the "Input Prep" button on the dashboard. This must be done before any further calculations are initiated or

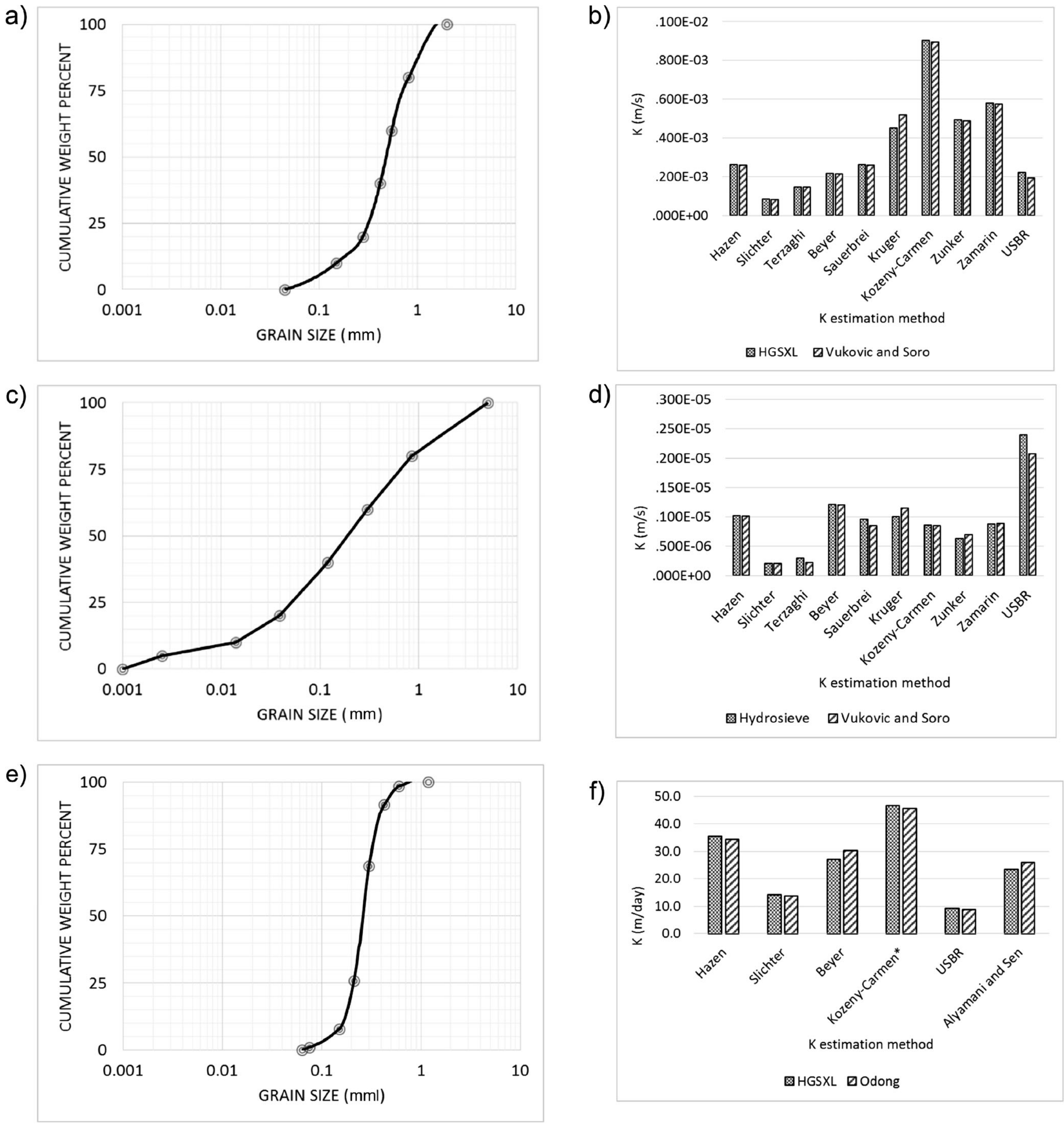

Fig. 4 Comparison of HydrogeoSieveXL estimated K values and those calculated by others for three different sediments. **a** The grain-size distribution curve of a moderately well sorted sand, **b** comparison of K estimates from various methods and comparison of HydrogeoSieveXL calculations vs. calculations reported by Vukovic and Soro (1992), **c** the grain-size distribution curve of a poorly sorted sand with fines, **d** comparison of K estimates from various methods and comparison of HydrogeoSieveXL calculations vs. calculations reported by Vukovic and Soro (1992), **e** the grain-size distribution curve of a well sorted sand, **f** comparison of K estimates from various methods and comparison of HydrogeoSieveXL calculations vs. calculations reported by Odong (2013). Note: to match the Kozeney Carmen K calculated by Odong, the d_e was set to d_{10}

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an error results. To interpolate between data points, for the purposes of estimating characteristic grain sizes, such as d_{10}, either linear interpolation can be used or a smoothed curve can be generated using the Akima spline—adapted from the Fortran code of Moreau (1981). The spline is activated by default, but can be disabled when the 'smooth' checkbox is deselected (see Fig. 2).

Upon completion of this step, a grain-size distribution curve is produced in the upper central portion of the sheet (Fig. 1). Next, the user can select the "Do All" button on the dashboard to launch the entire suite of functions in the sheet. If the user wishes to execute only selected functions, the dashboard features buttons for each module in the workbook. The functions can be initiated or updated one at a time with these buttons. Details of the program functions are given in the user manual in the workbook.

When fully executed, HydrogeoSieveXL presents the completed data table, a grain-size distribution curve, an extensive list of grain-size characteristics from which effective grain diameters are calculated, a histogram of grain-size distribution presented in terms of conventional grain-size classes (clay, sand, gravel, etc.), and 15 estimates of K calculated from the formulas in Table 1. Each method is tested against the 'applicable conditions' specified in Table 1, and those that pass are indicated with check marks in column F and solid bars in the K summary bar chart. Quantitative criteria were used wherever possible. Where only qualitative criteria were available, (e.g., Kozeny-Carmen only specified 'coarse sand'), d_{50} values were used to verify the sediment sample was in the range specified. Geometric and arithmetic means of the estimated K values are also calculated. A graphic illustrating the variation in K estimations can be displayed by clicking on the "Show K" button, located next to the "Start" button on the Input screen (Fig. 3).

Comparison with published *K* estimates

The validity of the calculations in HydrogeoSieveXL was verified by comparing calculated estimates of K with estimates calculated by Vukovic and Soro (1992) and Odong (2013) (Fig. 4). Not all methods executed in HydrogeoSieveXL are represented in the comparisons shown below, but similar care was taken to ensure the calculations were completed correctly in all cases. The comparisons show that HydrogeoSieveXL is computing K estimates that are consistent with the earlier literature reports, and that this conclusion applies across a range of sediments. The slight differences in estimated K values visible in Fig. 4 are attributable to differences in the estimated values of characteristic grain-size diameters such as d_{10}, and d_{60}, possibly related to round-off errors, and are of no practical significance.

Conclusions

Grain-size sieve analyses offer a convenient and economical means of acquiring preliminary estimates of hydraulic conductivity for sand and gravel deposits. Many techniques for extracting these estimates have been developed over the past century, and reliance on any single technique is probably unwise in many, if not most, cases. HydrogeoSieveXL is an Excel®-based tool for calculating K from grain-size distributions curves using 15 different methods. The tool is available for free downloading from the Devlin (2015) website, and includes a user manual in the workbook. The HydrogeoSieveXL calculations compare well against previously published work.

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References

Aguilar JR (2013) Analysis of grain-size distribution and hydraulic conductivity for a variety of sediment types with application to wadi sediments. M.B2:B19S, MSc Thesis submitted to King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia

Alyamani MS, Sen Z (1993) Determination of hydraulic conductivity from complete grain-size distribution curves. Ground Water 31(4):551–555

Barr DW (2001) Coefficient of permeability determined by measurable parameters. Ground Water 39(3):356–361

Barth GR, Hill MC, Illangasekare TH, Rajaram H (2001) Predictive modeling of flow and transport in a two-dimensional intermediate-scale, heterogeneous porous medium. Water Resour Res 37(10):2503–2512

Beyer W (1964) Zur Bestimmung der Wasserdurchlässigkeit von Kiesen und Sanden aus der Kornverteilungskurve [Determination of the hydraulic conductivity of gravels and sands from particle distribution curves]. Wasserwirtsch Wassertech 14(6):165–168

Białas Z (1966) O usrednianiu wspolczynnikow filtracji z zastosowaniem elektronicznej cyfrowej maszyny matematycznej [Averaging filter coefficients using digital electronic mathematical machines]. Przedsiebiorstwo Geologiczne we Wroclawiu, Warsaw, Poland, p 47–50

Chapuis RP (2004) Predicting the saturated hydraulic conductivity of sand and gravel using effective diameter and void ratio. Can Geotech J 41:787–795

Devlin JF (2015) HydrogeoSieveXL. Excel-based Visual Basic tool freely available at: http://www.people.ku.edu/~jfdevlin/Publications.html. Accessed 18 February 2015

Devlin JF (2014) Critical review of Darcy-based estimations of groundwater velocity. Chapter 2 in Groundwater Velocity, unpublished manuscript, Dept. of Geology, University of Kansas

Dullien FA (1991) Fluid transport and pore structure. Academic, San Diego

Freeze RA, Cherry JA (1979) Groundwater. Prentice Hall, Englewood Cliffs, NJ, 604 pp

Fuchs S (2010) Deterministische kf-Wert-Schätzung nach petrographischer Bohrgutansprache [Deterministic kf value estimation from petrographic borehole records]. Grundwasser 15:177–189

Hazen A (1892) Some physical properties of sands and gravels, with special reference to their use in filtration. 24th annual report, Massachusetts State Board of Health, Springfield, MA, pp 539–556

Kasenow M (2002) Determination of hydraulic conductivity from grain size analysis. Water Resources, Highlands Ranch, CO

 DOI 10.1007/s10040-015-1255-0

Kozeny J (1953) Das Wasser im Boden: Grundwasserbewegung [The water in the ground: groundwater flow]. In: Hydraulik: ihre Grundlagen und praktische Anwendung. Springer, Heidelberg, Germany, pp 380–445

Krüger E (1919) Die Grundwasserbewegung [Groundwater flow]. Int Mitt Bodenkd 8:105–122

Krumbein WC, Monk GD (1942) Permeability as a function of the size parameters of unconsolidated sand. Am Inst Mining Metall Eng Trans 151:153–163

Moreau JP (1981) Program to demonstrate the Akima spline fitting of Function SIN(X) in double precision. http://jean-pierre.moreau.pagesperso-orange.fr/Fortran/akima_f90.txt. Accessed 30 January 2015

Odong J (2013) Evaluation of empirical formulae for determination of hydraulic conductivity based on grain-size analysis. Int J Agric Environ 1:1–8

Rosas J, Lopez O, Missimer TM, Coulibaly KM, Dehwah AHA, Sesler K, Lujan LR, Mantilla D (2014) Determination of hydraulic conductivity from grain-size distribution for different depositional environments. Groundwater 52(3):399–413

Slichter CS (1898) Theoretical investigations of the motion of ground waters. 19th annual report, US Geological Survey, Reston, VA, pp 295–384

Terzaghi K (1925) Principles of soil mechanics. Eng News-Rec 95:832

Vukovic M, Soro A (1992) Determination of hydraulic conductivity of porous media from grain-size composition. Water Resources Publications, Littleton, Colorado, USA

Zamarin JA (1928) Calculation of ground-water flow (in Russian). Trudey I.V.H, Taskeni

Zunker F (1930) Das Verhalten des Wassers zum Boden [The behavior of groundwater]. Zeitschr Pflanzenernäh Düng Bodenkd A25(1):7

DOI 10.1007/s10040-015-1255-0