Riassunto: Il loess è un deposito continentale di origine eoli-
ca. Le acque sotterranee sono la più importante risorsa di ac-
qua potabile nelle zone dove i depositi di loess affiorano. Questo
lavoro ha lo scopo di analizzare i depositi di loess della Croa-
zia orientale che costituiscono lo strato a tetto di un acquifero
sabbioso sfruttato a scopi irrigui ed idropotabili. Il lavoro si è
svolto analizzando e revisionando sia la genesi di questo depo-
sito che i processi post-deposizionali che ne deformano la sua
struttura ed integrando le informazioni sedimentologiche con le
proprietà idrogeologiche del materiale per proporre un model-
lo idrogeologico concettuale del sistema acquifero studiato. La
porosità efficace e la conducibilità idraulica del loess sono state
calibrate in un approccio analitico partendo dai risultati
di analisi granulometriche pubblicate in letteratura. I depositi
studiani sono di tipo limoso e sono formati durante i periodi
glaciali del Pleistocene medio-superiore. Questi sedimenti sono
stati formati dall’erosione glaciale di rocce affioranti, trasportati
dal sistema fluviale del Danubio e successivamente rimobilizzati
dal vento e ridepositati formando il loess. Durante i periodi in-
terglaciali, i processi pedogenetici hanno portato alla formazione
di un suolo al tetto del deposito e di bioturbazioni e disconti-
nuità sia alla micro-ch alla macro-scala. La deposizione di un
nuovo strato di loess ha portato alla compattazione e alla conso-
lidazione dello strato precedente. Questo processo ha favorito la
riorganizzazione del sedimento alla micro-scala, formando una
struttura porosa maggiormente sviluppata lungo la verticale, e
lo sviluppo di fratture sub-verticali alla macro-scala. La stima
delle proprietà idrogeologiche mediante l’approccio analitico uti-
lizzato ha evidenziato la bassa porosità efficace (5-12%) e la bassa
conducibilità idraulica (~10^-9 m/s) sia del loess che dei paleosuoli
supportando il fatto che i depositi studiani agiscano come un
acquitardo. L’infiltrazione delle acque superficiali ed il loro flusso
verso l’acquifero sabbioso sottostante è incrementato localmente
dalle discontinuità post-deposizionali che rappresentano delle
vie di flusso preferenziali all’interno del deposito scarsamente
permeabile. Questi risultati evidenziano la necessità di studi
idrogeologici più approfonditi dei depositi di loess per chiari-l’impatto dei processi post-deposizionali sulle proprietà idroe-
ologiche del deposito, per analizzare la loro variazione al variare
della scala di indagine e per proporre delle azioni specifiche per
la protezione delle risorse idriche sotterranee nelle aree interessate
e dai depositi di loess.

Abstract: Loess is a widespread continental aeolian sediment.
Groundwater generally represents the most important source of potable
water in loess areas, where loess is the aquitard overlying the aqui-
fer system. This work investigates loess deposits of eastern Croatia that
overlie a sandy aquifer exploited for potable and agricultural purposes.
The genesis of the deposit and the depositional and post-depositional
processes affecting its structure were reviewed in this work and inte-
grated with the estimated hydrogeological properties of the material to
propose a preliminary hydrogeological conceptual model of the loess-sand
system. The results of published granulometric analyses were used to
calculate the effective porosity and the hydraulic conductivity of the ma-
terial employing an analytical approach. The eastern Croatian loess is
a silty deposit originated during Middle-Upper Pleistocene glacial pe-
riods. The sediments produced by glacial erosion were transported and
deposited by the Danube fluvial system and subsequently remobilised by
wind forming the loess. During the interglacial periods, the pedogenesis
of the deposit occurred, with bioturbations and discontinuities by living
organisms at the micro- and macro-scale. The deposition of a new loess
layer compacted and consolidated the previously deposited loess lead-
ing to the development of a sub-vertical pore structure and sub-vertical
cracks at the micro- and macro-scale, respectively. The calculations from
the grain size distributions point to the low effective porosity (5-12%)
and hydraulic conductivity (~10^-9 m/s) of both loess and pedocomplexes
supporting their aquitard behaviour. The infiltration of surficial waters
and their flow toward the underlying sandy aquifer is locally enhanced
by the post-depositional discontinuities that constitute preferential flow
paths within the loess aquitard. These results highlight the need of
detailed hydrogeological investigations in loess deposits to address the
impact of post-depositional processes on their hydrogeological behaviour
and the upscaling of their hydrogeological properties for proposing spe-
cific groundwater protection strategies in loess areas.

Keywords: aquitard, heterogeneity, hydraulic properties, conceptual model,
eastern Croatia.

Parole chiave: acquitardo, eterogeneità, proprietà idrodinamiche,
modello concettuale, Croazia orientale.

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Introduction

Groundwater management and protection are the main challenges of the 21st century. These tasks require extensive geological and hydrogeological knowledge of the aquifer/aquitard system for planning adequate groundwater utilisation and protection policies. The aquifer geometry and its hydrogeological properties are important for the sustainable management of the groundwater resource, while protection strategies also demand a detailed characterisation of the aquitard geological and hydrogeological settings.

The groundwater preservation is especially crucial in areas with quantitative and qualitative poor surface waters. These conditions are common in loess regions due to the (semi)arid climate and/or peculiar geological and geomorphological settings (Li and Qian 2018). Loess is a predominantly silt-sized continental aeolian deposit covering 10% of the world land area (Muhs et al. 2014; Pye 1987). Most of the loess deposits formed during Quaternary glacial periods draping over the pre-existing morphology as a mantle (e.g., Muhs et al. 2014; Wright 2001). This peculiar genesis defines the current hydrogeological setting of loess regions where loess separates the aquifers, and the potable waters, from the surface waters.

Sedimentological and geochemical investigations are usually conducted to assess the depositional environment of loess and its post-depositional alterations (e.g., Schaetzl et al. 2018; Sprafke and Obreht 2016). Besides the sedimentological features, the depositional and post-depositional processes affect the fabric of the material that is prone to land subsidence, landslides, and collapses (e.g., Derbyshire 2001; Peng et al. 2018).

Despite its importance in aquifer protection, hydrogeological studies on loess are far less frequent than sedimentological and engineering geological investigations. This paper presents the first results of a multidisciplinary research that investigates the hydrogeological behaviour of loess deposits in eastern Croatia. These deposits overlie a multi-layered aquifer exploited for water supply purposes acting as a partial aquitard. In particular, this work reviews the depositional and post-depositional processes developing the loess structure (e.g., Li et al. 2018; Smalley and Marković 2014).

The hydrogeological properties of eastern Croatian loess were determined through an analytical approach and using the results of available granulometric analyses that were conducted on 110 samples collected in three exposed loess sections (Galović et al. 2009).

The hydraulic conductivity was obtained employing the solution of the Kozeny-Carman equation (Urumović and Urumović Sr 2016):

$$K = \frac{DE^3}{\mu} \cdot 180(1-n_e)^2 D_g^2$$ (1)

where $K$ is the hydraulic conductivity (m/s), $g$ is the gravitational acceleration (m/s²), $\rho$ (kg/m³) and $\mu$ (Pa·s) are the density and viscosity of water, respectively, $n_e$ is the effective porosity, and $D_g$ is the geometric mean grain size (m). Considering the water temperature of 10°C and that the particle size is generally expressed as mm, equation (1) becomes:

$$K = 0.0417 \cdot \frac{n_e^3}{(1-n_e)^2} D_g^2$$ (2)

$D_g$ was calculated from the clay, silt, and sand contents of the samples employing a statistical approach (Shirazi et al. 1988). This approach assumes that the particle size curve of each size fraction can be reproduced with a log-normal
density function. The content and the grain size limits of a size fraction can be used to calculate its statistical parameters ($D_g$ and $\sigma_g$, geometric standard deviation). The parameters are input into the log-normal density function of the size fraction, and then the log-normal density functions of all size fractions are numerically integrated to assess the statistical parameters of the whole sample. These calculations were conducted in the R environment (R Core Team 2018).

The $D_g$ was calculated for all samples in Galović et al. (2009). The samples were grouped considering their lithological interpretation (Table 1), and the minimum, mean, and maximum $D_g$ for each group were calculated. The corresponding $n_e$ values were obtained using an experimental correlation with $D_g$ spanning over several grain sizes (Urumović and Urumović Sr 2016). Finally, the $K$ was calculated using equation (2). The results were compared with the hydrogeological properties of loess deposits that were determined by laboratory tests on 7 core samples collected during drillings (depths from 22 to 30 m) in the eastern part of Šrijem region (Figure 1a; Urumović 2013).
Results and Discussions

**Eastern Croatian loess depositional model**

The eastern Croatian loess (Figure 2a) is part of the loess-paleosol sequences of the Danube basin (Fitzsimmons et al. 2012; Marković et al. 2015, 2016) that are generally considered as “glacial loess” following the depositional model proposed by Wright (2001). The original silty/sandy particles were produced by glacial grinding of the bedrock surfaces in the Alpine region during glacial periods. The Danube fluvial system mobilised and reworked the glacial sediments depositing them in its floodplains. Strong winds entrained and retransported the finest alluvial sediments. The windblown silts redeposited either on land or in lakes and wetlands forming loess or loess-like deposits, respectively (Figure 1a).

During interglacial periods, the pedogenesis of the loess occurred. Many organisms lived in the soil and the underlying original deposit producing different types of discontinuities. The most common are micro- to macro-scale vertical or subvertical root channels (Figure 2c). Loading by newly deposited sediments and the concomitant wetting resulted in the compaction and contraction of the previously deposited loess (Smalley et al. 2016; Smalley and Marković 2014). The rainwater infiltration and the evaporation within the deposits acting preferentially along the vertical direction rearranged and piled up the particles (Li et al. 2018). These processes developed a sub-vertically oriented pore structure (Li et al. 2018) and polygonal cracks (Figure 2d) at the micro- and macro-scale, respectively. Neotectonic deformations could increase the fracturing of the deposit.

In eastern Croatia, the loess deposits are composed by meter-scale loess layers separated by several pedocomplexes (Figure 2a). The loess is a medium to coarse silt with secondary clays and sands (Figure 2b). The paleosols show similar textural characteristics with slightly higher clay content (Figure 2b). In addition, secondary laminated alluvial sediments, which originated from the fluvial reworking of previously deposited loess, are also found. Furthermore, several post-depositional features were recognised at both the micro- and the macro-scale (e.g., Galović et al. 2009; Figures 2c and 2d).

**Hydrogeological properties of eastern Croatian loess**

The described depositional and post-depositional processes influence the structure of the material and its hydrogeological properties. The compaction decreases the loess void ratio from 1 to 0.6 (e.g., Assadi-Langroudi et al. 2018) resulting in a theoretical total porosity similar to the loess porosities in literature (42-55%; Li and Qian 2018). Conversely, a low effective porosity is expected due to the fine texture of the material.

The results of the analytical approach used to assess the hydraulic conductivity (K) and the effective porosity (nₑ) of the different sediments constituting the eastern Croatian loess deposits, as well as their geometric mean grain size (Dₑ), are reported in Table 1.

The obtained values are comparable with the results of laboratory tests conducted on core samples, and only the minimum K values of the paleosol and laminated sediments groups are lower than measured values. This difference could be explained by: (i) the higher clay content in paleosol (Figure 2b), (ii) the regional heterogeneity of the investigated deposits, (iii) the minor occurrence of laminated sediments with respect to loess and paleosol diminishing the possibility of an extensive sampling, and (iv) the extension of the granulometric dataset used for the calculation of the hydrogeological properties being larger than the dataset on the hydrogeological testing of core sample.

**Table 1 - Hydrogeological properties of eastern Croatian loess.**

|                      | Dₑ (mm) | nₑ (%) | KₑKC (m/s) |
|----------------------|---------|---------|------------|
| Loess                | Min.    | Mean    | Max.       | Min.    | Mean    | Max. |
|                      | 0.010   | 0.016   | 0.023      | 0.06    | 0.08    | 0.10 |
|                     | 1.2E-09 | 5.2E-09 | 2.8E-08   |
| Paleosol             | 0.006   | 0.013   | 0.032      | 0.05    | 0.07    | 0.12 |
|                     | 2.3E-10 | 3.0E-09 | 8.3E-08   |
| Laminated sediments  | 0.008   | 0.016   | 0.024      | 0.06    | 0.08    | 0.10 |
|                     | 5.5E-10 | 5.2E-09 | 3.0E-08   |
| Modern soil          | 0.012   | 0.012   | 0.012      | 0.07    | 0.07    | 0.07 |
|                     | 2.0E-09 | 2.0E-09 | 2.0E-09   |

Core samples (Urumović 2013)

|                      | Dₑ (mm) | nₑ (%) | Kₑ (m/s) |
|----------------------|---------|---------|----------|
| Loess                | Min.    | Mean    | Max.     | Min.    | Mean    | Max. |
|                      | 0.011   | 0.015   | 0.019    | 0.05    | 0.07    | 0.08 |
|                     | 2.1E-09 | 1.5E-09 | 3.3E-08  |

Note. Dₑ: referential mean grain size; nₑ: effective porosity; Kₑ: hydraulic conductivity (subscript KC: Kozeny-Carman equation; t: laboratory tests)
Hydrogeological conceptual model of eastern Croatian loess

Locally infiltrated meteoric waters are the main recharge of eastern Croatian groundwaters (Bačani et al. 1999). They infiltrate through the loess deposits that represent the most extended surficial layer in the study area (Figure 1a). The hydrogeological properties of the deposit (Table 1) show its aquitard behaviour. However, this aquitard is deformed by persistent discontinuities (Figures 2c and 2d) that represent preferential paths for the water infiltration and flow. The role of these discontinuities as preferential flow paths is corroborated by the deposition of secondary carbonates at their borders (Barta 2011; Galović et al. 2009; Rubinić et al. 2018). Therefore, the infiltration of meteoric waters through loess deposits into the underlying sandy aquifer (Figure 3) could occur at different velocities due to its hydrogeological heterogeneity. This differential flow depends on: (i) the low hydraulic conductivity of the deposit, (ii) the highly permeable post-depositional discontinuities, and (iii) their possible infilling reducing their hydraulic conductivity.
Conclusion

This work shows the first results of a recently started research investigating the hydrogeological characteristics of loess deposits in eastern Croatia. The proposed hydrogeological conceptual model suggests that loess is a partial aquitard for the infiltration of meteoric waters into the underlying sandy aquifer. The infiltration could be highly heterogeneous and mostly driven by the post-depositional discontinuities acting as preferential flow paths. This differential infiltration could represent a prominent issue in the protection of the eastern Croatian groundwater resources that are exploited by local users for potable and agricultural purposes. Therefore, the quantification of the hydrogeological properties, the assessment of their dependence on the sedimentological processes, and their upscaling are crucial.

These aspects will be investigated in the next phase of the research. The available regional geological and hydrogeological reconstructions of 3 study areas (Baranja, Srijem, and Vinkovci; Figure 1a) will be updated to establish the horizontal and vertical contacts among recent alluvial sediments, loess deposits, and sandy layers. The reconstructions will be populated with porosity and hydraulic conductivity values obtained from core sample analyses and hydrogeological investigations on new exploration boreholes.

Pedological and geophysical surveys at the scale of the borehole and its surroundings and sedimentological analyses on the cores will be performed. The pedological investigations will elucidate the structure of the modern soil and its role in the infiltration of the surficial waters, while the geophysical surveys will clarify the geometry of the soil-loess-sand system integrating the local geological and hydrogeological reconstructions. Furthermore, the sedimentological analyses will favour the comparison of the drilled loess with other loess deposits in eastern Croatia strengthening the correlation between the local and the regional reconstructions. The assessment of the geological and hydrogeological heterogeneities in the soil-loess-sand system at local and regional scales will unravel the hydrogeological processes developing a strategic groundwater resource for eastern Croatia. These results will be beneficial to propose specific environmental policies and groundwater protection strategies that could be extended in the neighbouring regions being part of the Danube loess (i.e., northern Serbia and southern Hungary) or in other loess areas with similar geological settings where groundwater is a crucial and valuable resource.

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