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The CC-moving-lab of DIATI - Politecnico di Torino, an innovative way of understanding the laboratory.

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Editoriale

Cari Lettori e cari Soci

In questo numero della rivista Vi presentiamo una selezione di contributi scientifici provenienti dal mondo universitario e, più precisamente, da attività di ricerca svolte da docenti e collaboratori afferenti al Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture (DIATI) del Politecnico di Torino.
Il DIATI è risultato infatti tra i 180 **Dipartimenti Universitari di Eccellenza** (2018-2022) assegnatari del finanziamento MIUR. Il progetto di sviluppo del DIATI (del valore di 8.7 milioni di Euro), predisposto grazie all'ampia collaborazione dei diversi settori scientifici disciplinari del Dipartimento ed inerente i **Cambiamenti Climatici**, ha superato con successo anche la selezione finale. I fondi, come previsto dai progetti presentati ed approvati dal MIUR, sono stati destinati a rafforzare il capitale umano, le infrastrutture di ricerca e attività didattiche di alta qualificazione.
L'idea che è sorta è quindi quella di provare a racchiudere in un unico numero di una rivista le principali attività di ricerca svolte che, sebbene non siano esaustive, possono dare un'idea della trasversalità, multidisciplinarietà e innovazione delle ricerche che vengono quotidianamente affrontate. Sono orgoglioso di poter dire che il DIATI abbia scelto la nostra rivista per poter mostrare ciò e quindi in questo numero doppio, il 163/164 della rivista, trovate gli articoli più rappresentativi di tali tematiche che spaziano dai sistemi di trasporto sostenibili e inclusivi, allo studio dell'impatto ambientale nelle grotte turistiche, alle analisi ambientali relative ad agenti atmosferici, alla sostenibilità urbana, protezione del territorio, sfide geologiche e idrauliche oltre che attività di cooperazione internazionale.
Le tematiche sono varie e le innovazioni sono repentine: per cui vi lascio alla lettura di questo doppio numero e, augurandovi una buona fine di 2021, vi attendo per il primo numero del 2022.

Paolo Dabove

Dear Readers and GEAM Members

In this issue of the magazine, we present a selection of scientific contributions from the university world and more information from research activities carried out by professors and collaborators belonging to the Department of Environment, Land, and Infrastructure Engineering (DIATI) of the Politecnico di Torino.
In fact, DIATI was among the 180 **Departments of Excellence** (2018-2022) awarded the MIUR (Ministry of Education, *University* and Research) funding. The DIATI development project (worth € 8.7 million), prepared thanks to the extensive collaboration of the various scientific sectors of the Department and relating to **Climate Change**, has also successfully passed the final selection. As envisaged by the projects presented and approved by MIUR, the funds were intended to strengthen human capital, research infrastructures, and highly qualified teaching activities.
Therefore, the idea that has arisen is to try to enclose in a single issue of a journal the main research activities carried out, which, although not exhaustive, can give an idea of the transversality, multidisciplinarity and innovation of the researches that are dealt with daily. I am proud to say that DIATI has chosen our magazine to be able to show this and therefore in this double issue, 163/164 of the magazine, you will find the most representative articles of these issues ranging from sustainable and inclusive transport systems to the study of environmental impact in tourist caves, environmental analyses relating to atmospheric agents, urban sustainability, land protection, geological and hydraulic challenges as well as international cooperation activities.
The themes vary, and the innovations are sudden: so I leave you to read this double issue. Wishing you a good end of 2021, I look forward to seeing you for the first issue of 2022.

Paolo Dabove

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Characterization of marble weathering through pore structure quantitative analysis

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Stone weathering is strongly controlled by the intrinsic properties of the stone and by its use. Previous studies demonstrate that the response to natural or artificial ageing processes of the rocks seems to be strongly influenced by the pore structure of the stone. A better understanding of this phenomenon is provided by the study and characterization of porosity and of the pore structure at different degrees of alteration. The analysis of the evolution of the decay leads to the evaluation of the durability of marble in facades, and more generally in buildings, as well as for the protection and recovery of artistic and architectural heritage.

In this paper, we apply a methodology for the geometrical characterization of the pore structure to quantify alteration induced by natural weathering on marble slabs. The approach is based on the application of a path-finding algorithm to 2D binary images representative of thin sections of marble at different degrees of alteration. Through the identification of the paths within the porous domain, the methodology allows the characterization of the pore structure in terms of pore radius distribution along the identified paths. Analysis of the results demonstrate a good agreement between the degree of alteration of the pore structure and the corresponding variation of the physical and mechanical properties of the rock samples under investigation.
Keywords: *marble, weathering, microscope images, pore radius, path-finding algorithm, pore structure characterization.*

Caratterizzazione dell'alterazione del marmo dovuta ad agenti atmosferici mediante analisi quantitativa della struttura porosa. *L'invecchiamento delle pietre ornamentali è fortemente condizionato dalle proprietà intrinseche della pietra e dal contesto di utilizzo. Precedenti studi dimostrano che la risposta ai processi di invecchiamento naturale o artificiale delle rocce è influenzata dalla struttura dei pori della pietra stessa. Questo fenomeno può essere meglio compreso attraverso lo studio e la caratterizzazione della porosità e della struttura dei pori a diverso grado di alterazione. Informazioni utili sull'evoluzione del degrado portano alla valutazione della durabilità del marmo nelle facciate, e in generale negli edifici, e alla tutela e il recupero del patrimonio artistico e architettonico.*

In questo articolo, applichiamo un approccio per la caratterizzazione geometrica dei parametri della struttura dei pori per quantificare l'alterazione naturale indotta dagli agenti atmosferici su lastre di marmo. La metodologia si basa sull'applicazione di un algoritmo di ricerca del percorso ad immagini binarie 2D rappresentative di sezioni sottili del marmo a diversi livelli di alterazione.

I risultati forniti dai test preliminari confermano una buona concordanza tra la struttura dei pori e la corrispondente variazione delle proprietà fisiche e meccaniche del campione analizzato.
Parole chiave*: marmo, agenti atmosferici, immagini al microscopio, raggio dei pori, algoritmo di path-finding, caratterizzazione della struttura porosa.*

1. Introduction

Stone weathering is controlled by the intrinsic properties of the stone (mineralogical-petrographic, porosity and mechanical features) and by its uses (external and internal facades, paving, roofs etc.).

Previous studies underlined the influence of porosity in the weathering evolution processes in natural stones (Hudec, 1998; Siegesmund, 2008; Molina Ballesteros *et al.*, 2010) even in marble, characterized by a low porosity (Siegesmund, 2000, Sassoni *et al.*, 2014). Many tests of artificial and natural ageing, together with in situ analysis on exposed marbles, showed that an increase in weathering is connected to an increase in porosity as well as to a decrease in mechanical resistance (Warke *et al.*, 2006; Bellopede *et al.*, 2016).

The response to natural or artificial ageing processes seems to be strongly influenced by the pore structure of the stone. The presence of closed or interconnected voids in compact rock is one of the main features that needs thorough investigation.

Due to the existing correlation between movement of the fluids, such as water, and weathering, the analysis of the porosity evolution within a rock is the most interesting approach in order to investigate the correlation between decay and structure.

The study of the increase of total porosity and of the geometrical characteristic of the pore structure provides useful information on the evolution of the decay, and it allows evaluating the marble durability in facades, and more generally in buildings, as well as for the protection and recovery of artistic and architectural heritage.

In this paper, we apply a methodology recently presented by Viberti *et al.* 2020 for the geometrical characterization of the pore structure parameters to quantify marble weathering.

Porous media are complex materials characterized by a chaotic structure and tortuous fluid flow, with pore and grains dimension varying over a wide range (Ghanbarian *et Al.* 2013). Pore network model is considered to be an important platform for describing the geometry and topology of pore spaces and for performing flow calculations (Yao *et al.* 2015). Characterization of porous media geometry and properties, at different scales, is fundamental for several fields of application and scientific disciplines such as geology, reservoir engineering, underground water science, chemistry, material science and engineering.

The study of the pore characteristics has an important historical background, starting from ancient Egyptians, Greeks and Romans, passing through the significant progress in scientific evaluation during 19th century with the introduction of physical principles such as capillarity, diffusion and fluid flow, leading up to the modern experimental methodologies (Sing, 2004). In the last decades, the adoption of addressed experimental procedures coupled with the possibility to acquire high resolution images of porous media (microscope, etc.), several approaches for 2D pore structure image analysis have been developed and presented in the technical literature. These include grain recognition (Oren & Bakke, 2003), medial-axis (Lindquist *et al.*, 1996), medial surface (Al-Raoush and Madhoun, 2017), fractal geometry (Xu *et al.*, 2008; Xiao *et al.*, 2019; Cai *et al.*, 2019), Dijkstra's algorithm (Sun *et al.*, 2011), watershed (Sheppard *et al.*, 2004; Rabbani, *et al.* 2014) and percolation theory (Liu *et al.*, 2014).

In this paper we present a methodological approach for the investigation of the effect of weathering on marble samples through the application of a modified version of the A* path-finding algorithm. The pore structure characterization is carried out on macroscope-acquired images of marble thin sections at different degrees of alteration. The acquired images are then binarized so as to identify the porous domain within which the paths are calculated by A*. The visible paths can be exploited for pore structure characterization: along each path, the aperture of the channels can be estimated. An example of application of the methodology and the analysis of the output results is presented.

2. Dataset description and experimental procedure

2.1. Rock sample description

The methodology was applied to a case study of a Marble identified as ITQ4 quarried in Stazzena (LU).

The hand sample is a compact white breccia, characterized by veins varying in color from brown to dark gray with a very variable pattern and size. The marble clasts are elongated and stretched, with pluridecimetric dimensions, immersed in a locally dark gray cement.

The thin section shows a crystalloblastic metamorphic lithotype. Anisotropic blasts with mainly interlobate, inequigranular edges (300 ÷ 350 μm) are present in the clasts which are surrounded by an inequigranular calcitic mosaic of subhedral blasts with rounded and rectilinear edges (100 μm). Complex veins consisting of pyrite, quartz, sericite, muscovite, epidote, titanite and opaque are present (Fig. 1).

2.2. Weathering

Stone weathering is correlated with many different physicochemical processes (Bortz *et al.*, 1993, Winkler, 1987) operating both sequentially and synergistically (Bellopede *et al.*, 2016). Previous studies (e.g. Camuffo, 1995) proved that the aesthetic value loss is directly related to the intrinsic properties of the material as well as to natural agents. Rainwater, wind, solar radiation and thermic variations are the primary causes for the mechanical and physical weakening of stones. Moisture, which affects the inter-particle forces acting on independent granules,

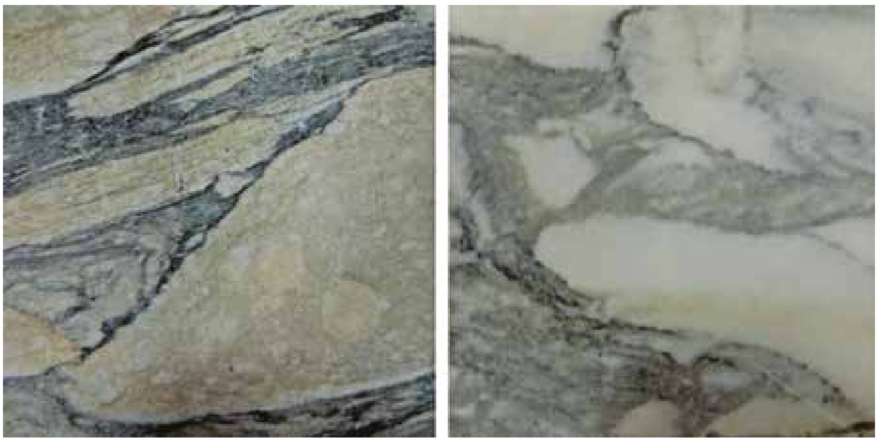

Fig. 1 – Comparison between non altered ITQ4 sample (left) and weathered slab (right).

is a critical factor for weathering processes, and the water movement within the bulk volume of the stone is strongly related to the porosity and the permeability of the material (Warke *et al.*, 2006). Moreover, the natural decay deeply modifies the edges between grains, it widens cracks resulting in an increase in porosity.

This indicates that the variation of the pore characteristics, such as open porosity, pore size and shape, depends on the weathering trend. These characteristics are important variables that may change with time, especially in the subsurface layer where the main physical, chemical and biological processes occur (Biscontin *et al.*, 1993).

The two analyzed samples come from two 50 x 70 cm slabs of ITQ4 marble. One underwent natural weathering, through ten years of outdoor exposure, while the second is the original sample that was kept indoors.

From the two original samples, the specimens have been cut and several thin sections were obtained from both the weathered and the original slab. The thin sections were impregnated with a blue methylene liquid in order to facilitate the microscopic analysis of the crystal structure.

2.3. Physical and mechanical tests performed on ITQ4

Physical and mechanical tests were carried out on the specimens both in natural condition and after ten years of natural weathering. The description of the test is provided in the following.

Water absorption by immersion in water at atmospheric pressure (WA) was carried out according to EN 13755 (2008). WA is expressed as the percentage of water mass inside the pores of the specimen after 48 hours of saturation. Open Porosity test was performed according to EN1936 (2006) and the value represents the percentage of open voids connected to the surfaces of the specimen. According to previous scientific studies (Manfredotti and Marini, 2006, Vandevoorde *et al.*, 2009), these methods are able to detect the weathering of a natural stone by comparing the results obtained on a fresh and weathered material.

Flexural strength was carried out to determine the resistance to flexural strength described by the European standard EN 12372 (2007). This test is a destructive method used to study the decay of stone and it is well correlated with non-destructive tests such as UPV and water absorption. The test has been performed on 200 × 50 × 30 mm specimens obtained from each slab.

Ultrasonic Pulse Velocity (UPV) is a very fast and efficient non-destructive methodology used to define the mechanical properties of a stone material. The test was carried out following the standard EN 14579 (2005). For each slab the indirect method has been applied using 250 kHz transducers. UPV is linked to the physical and mechanical characteristics of the material in which it propagates, such as in terms of crystal texture, porosity and cohesion. The results of the tests are summarized in Table 1.

Tab. 1 – Physical-mechanical test performed on the ITQ4 in natural condition and after ten years of natural weathering.

Performed tests	Not weathered slab	Naturally weathered slab
UPV f = 250kHz [m/s]	2725 ± 74	2205 ± 193
Open Porosity (%)	0,61 ± 0,04	1,65 ± 0,07
Water absorption WA [%]	0,20 ± 0.04	0,56 ± 0.05
Flexural strength [Mpa]	12,9 ± 3.5	9,2 ± 1.9

2.4. Quantitative pore structure analysis

In order to provide a quantitative characterization of the weathering effect on marble pore structure, we apply a methodology based on a modified version of A* path-finding algorithm. The approach allows the analysis of 2D binary images of marble thin sections at different degrees of alteration. The A* algorithm is able to identify the paths representative of the pore structure and to estimate, along each path, the aperture of the channels. The workflow of the methodology can be summarized in three steps:

- Image acquisition and processing
- Path identification in pore structure
- Pore size analysis

The above steps are described in the following sections.

2.4.1. Image acquisition and preprocessing

The images have been acquired using a Leica M420 macroscope (40X magnification) in *.Tiff format at 12 Mpixels. Digital processing is applied to the images in order to highlight and extrapolate the impregnated paths. The procedure first involves a preliminary tuning of some of the main image parameters such as intensity, gamma, saturation, brightness and contrast. Secondly, a histogram-threshold-based mask is applied on the RGB values of the pixel image. The identified threshold is used to identify the impregnated domain and for the construction of a binary image in which the grain pixels are represented by the digital number 1 while the impregnated pore pixels by 0.

2.4.2. Path identification in pore structure

The pore structure of each generated image is characterized using a path-finding approach. Given a set of n_{in} inlets (start) and n_{out} outlets (target), automatically located along the boundaries faces of the porous domain (i.e. 2D image), the shortest paths between each inlet-outlet pairs is computed along the main considered directions (X, Y) (Viberti *et al.*, 2020) (Fig. 2).

A modified version of the A* algorithm is used as a path-finding approach. The A* approach (Hart *et al.*, 1968; Nilson, 2014) allows the construction of the optimal path (i.e. shortest) between two locations using an heuristic function to guide the search through the minimization of the cost function $c_i(n)$:

$$c_i(n) = g_i(n) + h_i(n) \qquad (1)$$

where n indicates the considered node along the path, $g_i(n)$ is the cost of the path from the start node (inlet) to a considered node n on the path, $h_i(n)$ is the heuristic function representing a prior estimation of the cost to move from the considered node n to the target (outlet). The Euclidian distance is chosen as a forward cost $h_i(n)$. The path is constructed by progressively computing the cost function at each node from the inlet to the associated outlet. The final output is a graph $G = (N, E)$ where N are a set of reference nodes progressively identified through the cost function with $X - Y$ coordinates and E the connecting edges between nodes (2).

Since the marble could be poorly connected, the methodology was applied to image sub-windows. Moreover, a modified version of A* was used in this work, which also allows the characterization of dead-end paths (i.e. paths that are generated from a starting point that cannot reach the associated target because of obstacles).

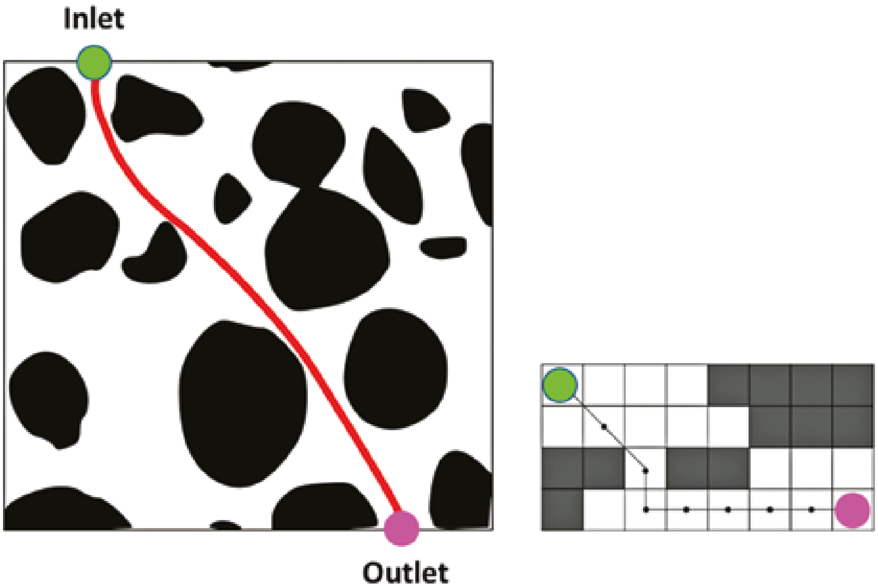

Fig. 2 – Schematic representation of an optimal path between an inlet/outlet pair.

2.4.3. Pore size analysis

The generated paths are used for the geometrical characterization of the pore structure. Along each identified geometrical path, the local pore size is estimated at each grid node location by measuring the extension of the pore section length orthogonal to the local path direction (Fig. 3), therefore the total pore size distribution of the porous domain within the image can be computed. The output provides a geometrical description of the pore size development along each simulated path and can be used for comparative quantitative analysis between pre and post rock weathering.

3. Results

Thin sections of marble samples described in paragraph 2, representative of pre and post weathering conditions, were analyzed and

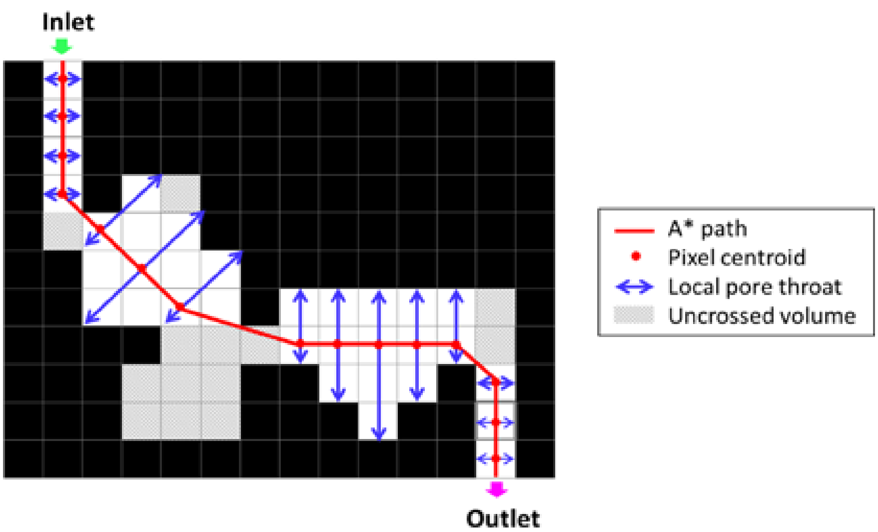

Fig. 3 – Qualitative representation of pore throat description along a path.

compared. Two images of different subsections were considered in the non-weathered thin-section because of the presence of a significant variability within the sample.

Square subsection of 2.47 mm per side of impregnated pictures are shown in Fig. 4 and the corresponding binarized images in Fig. 5. Each figure was divided into nine sub-windows of 0.823 x 0.823 mm to increase the algorithm exploration in poorly connected areas. The path-finding based algorithm presented in section 3.2 was applied for each direction (N-S, S-N, E-W, W-E) in each of the nine sub-windows. The merge of all individuated paths is shown in red in Fig. 6, where the sub-windows subdivision is displayed. For each path,

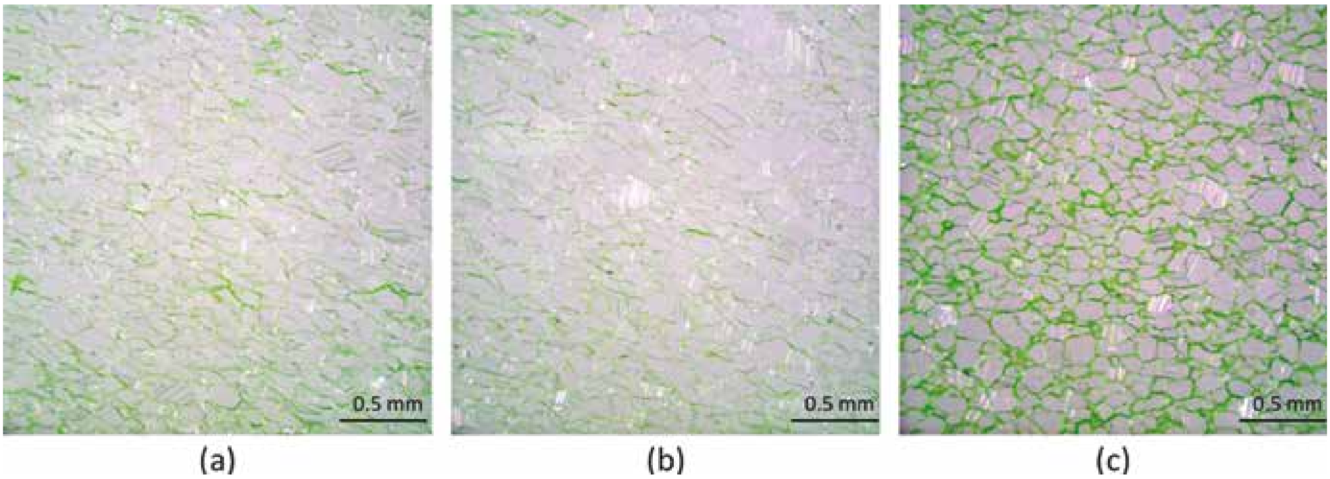

Fig. 4 – Thin sections of (a, b) non-weathered v.s. (c) natural weathering impregnated marble, after preliminary image processing. Figure resolution is 0.8 μm per pixel.

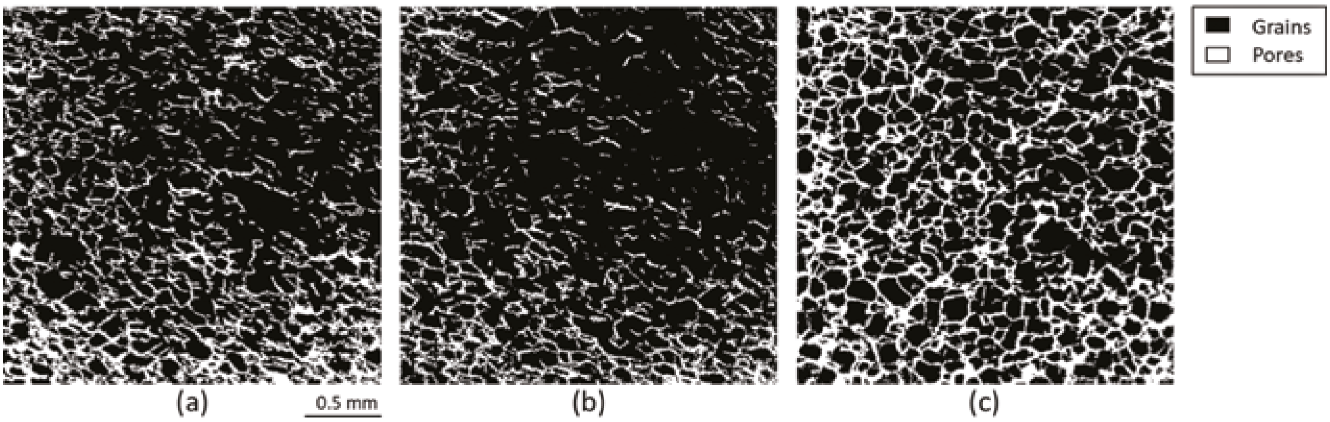

Fig. 5 – Binarized images of thin sections portions of (a, b) non-weathered and (c) natural weathering marble samples. Figure resolution is 4 μm per pixel.

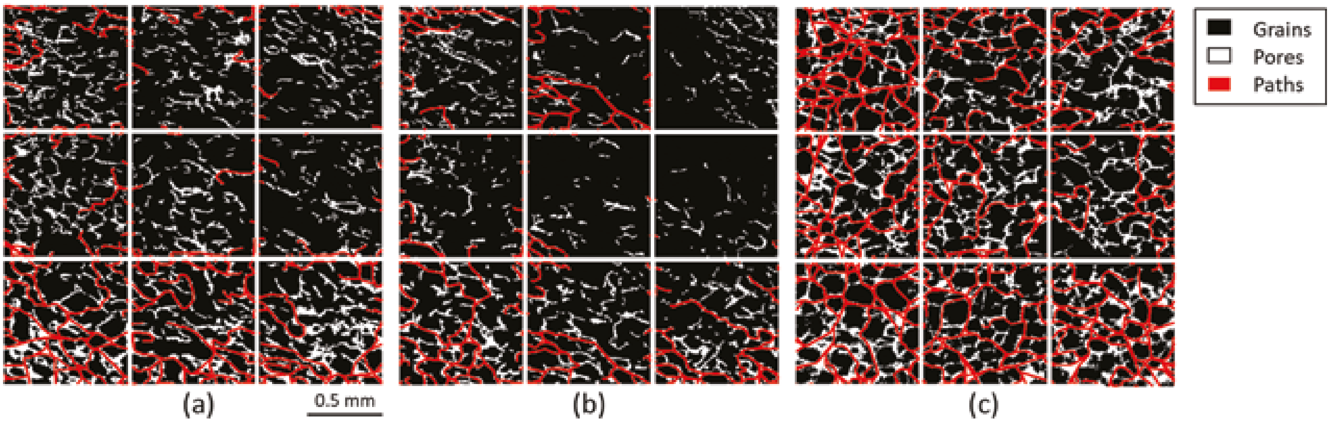

Fig. 6 – Paths individuated on the binarized pore structure images of Fig. 5, subdivided in 9 sub-windows of 0.823 x 0.823 mm.

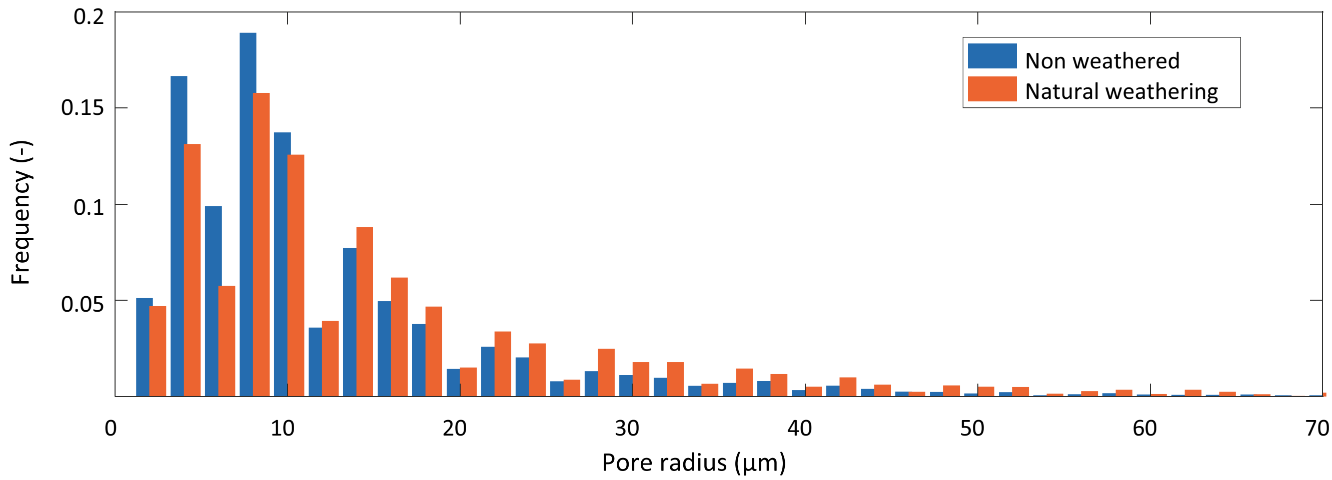

Fig. 7 – Comparison of pore radius distribution of non-weathered marble samples, in blue, and natural weathering, in orange.

the local pore radius was calculated as described in section 3.3. The resulting pore radius distributions before and after weathering are compared in Fig. 7. The comparisons between total porosity and quartiles of pore radius distribution is shown in Table 2.

Tab. 2 – Porosity and pore radius distribution comparison between non-weathered and naturally weathered samples.

		Not weathered (a)	Not weathered (b)	Natural weathering (c)
Porosity (%)		18.3	11	28.5
Pore radius distribution	P25 (µm)	6	6	8
	P50 (µm)	10	8.4	11.3
	P75 (µm)	17	12	20

4. Discussion and conclusion

The presented work is an example of application of a methodology for pore structure analysis based on the A* path-finding algorithm for characterizing ornamental stone degradation due to weathering.

Macroscope images of impregnated thin sections representative of the Marble ITQ4, at natural conditions and after a long term natural weathering, were processed in order to obtain 2D binary images used as suitable inputs for A* algorithm. Through the identification of the paths within the porous domain, the methodology allows the characterization of the pore structure in terms of pore radius distribution along the identified paths.

Results are summarized in Table 2 and Figure 7. The comparison between the considered parameters for the two non-weathered sections (a) and (b) indicate a degree of heterogeneity within the sample. However, the comparison between the porosity values and pore size distribution of the weathered (Fig. 4c) and the two non-weathered thin sections (Fig. 4a and 4b) clearly demonstrate a significant change in pore structure.

When comparing weathered with non-weathered thin sections (a) and (b), a significant increase in both porosity and pore size distribution is observed, especially with respect to the thin section (b), in which the third quartile (P75) of the pore radius distribution has almost doubled (from 12 µm to 20 µm) and the porosity has increased of a factor of 2.6 (from 11% to 28.5%). With regard to case (a), the increase of the third quartile (P75) of the pore radius distribution is limited to 17% (from 17 µm to 20 µm) and the porosity has increased of a factor of 1.5 (from 28.3 to 28.5).

The results obtained through image analysis highlight an increase in open porosity which occurred naturally in the specimen at 10 years exposure compared to the non-weathered sections, as reported in Table 1. The result is in good agreement with the experimental results demonstrating a decreasing of mechanical resistance measured by flexural strength and UPV (Tab. 1). In fact, the increase in the average size of the pores is closely correlated to the decrease in flexural strength, to the reduction in the ultrasound propagation speed and to an increase in open porosity.

Due to the high variability of the pore structure at the considered scale, analysis on a more extended number of thin sections is required to guarantee a statistical representativeness of the results.

References

Al-Raoush, R.I., Madhoun, I.T., 2017. TORT3D: A MATLAB code to compute geometric tortuosity from 3D images of unconsolidated porous media. Powder technology, 320, 99-107.

Bellopede, R., Castelletto, E., Marini, P., 2016. Ten years of natural ageing of calcareous stones, Engineering Geology, vol. 211, Pages 19-26, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2016.06.015

Biscontin, G., Driussi, G., Maravelaki, P., Zendri, E., 1993. Physical-Chemical Investigations of Stone Architectonic Surfaces in Venice: The Scuola Grande Dei Carmini. in Conservation of Architectural Surfaces: Stones and Wall Covering, pp. 125-136.

Biscontin, G., Graziano, L., 1993. Conservation of Architectural Surfaces: Stone Wall Covering, Il Cardo, Venice, pp. 125-136.

Bortz, S., Stecich, J., Wonneberger, B., Chin, I., 1993. Accelerated weathering in building stone Int. J. Rock Mech. Min. Sci. Geomech. Abstr.,30, pp. 1559-1562.

Cai, J., Zhang, Z., Wei, W., Guo, D., Li, S., Zhao, P., 2019. The critical factors for permeability-formation factor relation in reservoir rocks: Pore-throat ratio, tortuosity and connectivity. Energy, Elsevier, vol. 188, 2019, 116051. ISSN 0360-5442. https://doi.org/10.1016/j.energy.2019.116051

Camuffo, D., 1995. Physical weathering of stones Sci. Total Environ., 167, pp. 1-14.

EN 12372 Natural Stone Test Methods – Determination of Flexural Strength under Concentrated Load CEN Committee, Brussels, 2007.

EN 13755 Natural Stone Test Methods – Determination of Water Absorption at Atmospheric Pressure CEN Committee, Brussels, 2008, p. 8.

EN 14579 Natural Stone Test Methods – Determination of Sound Speed Propagation CEN Committee, Brussels, 2005, p. 12.

EN 1936 Natural stone test methods. Determination of real density and apparent density, and of total and open porosity, 2006.

Ghanbarian, B., Hunt, A.G., Ewing, R.P., & Sahimi, M., 2013. Tortuosity in porous media: a critical review. Soil science society of America journal, 77(5), 1461-1477.

Hudec, P.P., 1998. Rock properties and physical processes of rapid weathering and deterioration. Proceedings of the 8th International IAEG Congress, (IAEGC' 98), Balkema, Rotterdam, pp. 335-341.

Lindquist, W.B., Lee, S.M., Coker, D.A., Jones, K.W., & Spanne, P., 1996. Medial axis analysis of void structure in threedimensional tomographic images of porous media. Journal of Geophysical Research: Solid Earth, 101(B4), 8297-8310.

Liu, J., Pereira, G.G., Regenauer-Lieb, K., 2014. From characterisation of pore-structures to simulations of pore-scale fluid flow and the upscaling of permeability using microtomography: A case study of heterogeneous carbonates, Journal of Geochemical Exploration, vol. 144, Part A, 2014, Pages 84-96, https://doi.org/10.1016/j.gexplo.2014.01.021.

Manfredotti, M., Marini, P., 2006. The "Contact Sponge": Study of the Applicability of a New and Simple Methodology R. Fort, M.Á. de Buergo (Eds.), Book of Abstracts of Heritage, Weathering and Conservation 2006, Eighth Thematic Network on Cultural and Historic Heritage Scientific Meeting, Madrid (June 21-24, 2006).

Molina Ballesteros, E., Cantano Martín, M., García Talegón, J. 2010. Role of porosity in rock weathering processes: a theoretical approach. Cadernos Lab. Xeolóxico Laxe Coruña 35, 147-162.

Øren, P.E., Bakke, S., 2003. Reconstruction of Berea Sandstone and Pore-Scale Modeling of Wettability Effects, Journal of Petroleum Science and Engineering, 39, 177-199.

Rabbani, A., Jamshid S.i, Salehi, S., 2014. An automated simple algorithm for realistic pore network extraction from micro-tomography images, Journal of Petroleum Science and Engineering, vol. 123, Pages 164-171, Elsevier. doi: https://doi.org/10.1016/j.petrol.2014.08.020.

Sassoni, E. & Franzoni, E. 2014. Sugaring marble in the Monumental Cemetery in Bologna (Italy): characterization of naturally and artificially weathered samples and first results of consolidation by hydroxyapatite. *Appl. Phys. A* 117:1893-1906.

Sheppard, A.P., Sok, R.M., Averdunk, H., 2004. Techniques for image enhancement and segmentation of tomographic images of porous materials. Phys. A Stat. Mech. Appl. 339(1),145-151.

Siegesmund, S., Mosch, S., Scheffzuk, Ch., Nikolayev, D.I. 2008. The bowing potential of granitic rocks: rock fabrics, thermal properties and residual strain. Environ. Geol. 55, 743-795.

Siegesmund, S., Ullemeyer, K., Weiss, T., Tschegg, E.K. 2000. Physical weathering of marbles caused by anisotropic thermal expansion. Int. J. Earth Sci. 89, 170-182.

Sing, K.S.W., 2004. Characterization of porous materials: past, present and future, Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 241, Issues 1-3, Pages 3-7, (2004) ISSN 0927-7757, https://doi.org/10.1016/j.colsurfa.2004.04.003.

Sun, W.C., Andrade, J.E., & Rudnicki, J.W., 2011. Multiscale method for characterization of porous microstructures and their impact on macroscopic effective permeability. International Journal for Numerical Methods in Engineering, 88(12), 1260-1279.

Vandevoorde, D., Pamplona, M., Schalm, O., Vanhellemont, Y., Cnudde, V., Verhaeven, E., 2009. Contact sponge method: performance of a promising tool for measuring the initial water absorption J. Cult. Herit., 10.1, pp. 41-47, 10.1016/j.culher.2008.10.002.

Viberti, D., Peter, C., Borello, E.S., & Panini, F., 2020. Pore structure characterization through path-finding and Lattice Boltzmann simulation. Advances in Water Resources, 103609.

Warke, P.A.,McKinley, J., Smith, B.J.,

2006. Weathering of Building Stone: Approaches to Assessment, Prediction and Modelling S.K. Kourkoulis (Ed.), Fract. Fail. Nat. Build. Stones, Springer, The Netherlands , pp. 313-327.

Winkler, E.M., 1987. Weathering and weathering rates of natural stone Environ. Geol. Water Sci., 9, pp. 85-92.

Xiao, B., Wang, W., Zhang, X., Long, G., Fan, J., Chen, H., Deng, L., 2019. A novel fractal solution for permeability and Kozeny-Carman constant of fibrous porous media made up of solid particles and porous fibers, Powder Technology, vol. 349, 2019, Pages 92-98, ISSN 0032-5910, https://doi.org/10.1016/j.powtec.2019.03.028.

Xu, P., Yu, B., 2008. Developing a new form of permeability and Kozeny-Carman constant for homogeneous porous media by means of fractal geometry, Advances in Water Resources, 31(1), pp. 74-81, ISSN 0309-1708, https://doi.org/10.1016/j.advwatres.2007.06.003.

Yao, J., Hu, R., Wang, C., Yang, Y., 2015. Multiscale Pore Structure Analysis In Carbonate Rocks, Journal for Multiscale Computational Engineering, 13 (1): 1-9.

DX.DOI.ORG/10.19199/2021.163-164.1121-9041.013

Research activities on sustainable and inclusive transport systems carried out at the Politecnico di Torino – DIATI

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Transport systems are one of the cornerstones of any environmentally sustainable and socially inclusive modern society. It is therefore of critical importance to improve their performances under both these viewpoints. This contribution is presenting a selection of recent research activities carried out by the Transport research group at the Politecnico di Torino – Dept. DIATI that touch at some of these key issues: starting from a closer look at the opportunities and challenges of electrification and the use of shared vehicles the paper lands to a broader view on how transport planning processes can be supported by researchers to limit environmental impacts and promote inclusiveness.
Keywords: *electrified vehicles, car sharing, mobility plans, gender studies.*

Attività di ricerca sui sistemi di trasporto sostenibili e inclusivi svolte presso il Politecnico di Torino – DIATI. *I sistemi di trasporto sono uno degli elementi fondanti di ogni società moderna che sia sostenibile sul piano ambientale ed inclusiva sul piano sociale. E' perciò d'importanza fondamentale migliorare le loro prestazioni considerando entrambi questi aspetti. Il presente contributo descrive una selezione di recenti attività di ricerca svolte dal gruppo "Trasporti" del Politecnico di Torino – Dip. DIATI che indagano alcune di queste tematiche: a partire da un approfondimento sulle opportunità e le sfide poste dall'elettrificazione e dalla mobilità condivisa, l'articolo approda ad un allargamento della prospettiva su come la ricerca può assistere i processi di pianificazione dei trasporti nel limitare gli impatti ambientali e promuovere l'inclusività sociale.*
Parole chiave: *veicoli elettrificati, mobilità condivisa, piani della mobilità, studi di genere.*

1. Introduction

Transport systems are one of the cornerstones of any environmentally sustainable and socially inclusive modern society. It is therefore of critical importance to improve their performances under both these viewpoints, where many progresses have been made in past decades and are undergoing though sometimes only partially meeting the high level of ambition and expectations from decision makers, stakeholders and the general public. It is generally acknowledged by researchers in this area that there is a need to more effectively tackle the transforming problems of transport systems, tacking stock of new technologies from different sectors, better exploiting mobility data that are available nowadays and, more in general, developing new inter- and trans-disciplinary research approaches. This contribution is presenting a range of recent research activities carried out by the Transport research group at the Politecnico di Torino, Dept. DIATI, that touch at some of these key issues, starting from a closer look at the opportunities and challenges of electrification and the use of shared vehicles in road transport to a broader view on how transport planning processes can be supported by researchers to limit environmental impacts and promote inclusiveness.

2. Sustainable road transport: how far electrification is pursuable?

According to Eurostat, the impact of transport systems in Europe (EU-25) on the overall energy consumption in EU countries was around 33% (2008-2019, EIA, UP/UNEM); as concerns CO_2, transport systems account for almost a quarter of the total emissions from human activities. Globally, according to the IEA (International Energy Agency) WEO (World Energy Outlook) 2020, for 2019, in terms of World Energy Demand, more than 90% of the world's transport-related energy demand is met by crude-oil. In addition, of the total percent of the world's energy demand for oil, 59% comes from the transport sector; of the total primary energy demand, 20% comes from transport. A decade ago, light-duty vehicles were considered responsible for approximately 13.5% of global CO_2 emissions, and considering extraction and the supply chain, the percentage reached 15%; these values are almost conservative in the last years.

On the other hand, it is necessary to consider the constraints imposed on transport systems, focusing on the European ones: pursuit of the partial independence of urban mobility from oil-derived fuels, effects of emissions at global level, containment of urban pollution, the competitiveness of the automotive sector and related industry.

Secondly, the European legislation on air quality (Directive 2008/50/EC) is based on precise principles: as regards the emissions generated by transport systems, it is important to underline the difference between global aspects (carbon dioxide emissions), implying a Well-to-Wheel analysis on the life-cycle, and local ones, linked to Tank-to-Wheel efficiency (Dalla Chiara and Pellicelli, 2016).

Thirdly, the European Community has set ambitious emission performance levels for newly manufactured automobiles and light-duty commercial vehicles, which are consistent with EU commitments under the Paris Agreement. So, to what extent transport research may contribute to these three main purposes?

At first, both studies from ISFORT, at Italian level, and from Politecnico di Torino, at an international one (Dalla Chiara *et al.*, 2019; Caballini *et al.*, 2021), found that more than 60% of daily trips take place within a distance of 10 km whereas only approximately 3% exceed 50 km.

Car driving habits were detected using a dataset obtained from automobiles in use in Europe (Dalla Chiara *et al.*, 2019). A very aggregated analysis of demand trends is not yet sufficient to understand the actual daily mobility of people. To this end, recent researches have been developed with real data from the automotive industry. An analysis was conducted on real trips undertaken in Europe by more than 1,000 vehicles and more than 200,000 automobiles, referring to an extended period that lasted more than one year; the obtained results are an example of the information that can be extracted from rough data to support future decisions of stakeholders and end users (e.g., car makers, authorities, drivers).

The main scope of such study was to investigate whether hybrid and electric powertrains can represent suitable alternatives to traditional engines to pursue abovementioned environmental aims, taking into account available battery ranges, idle times for recharging and charging alternatives. Long distance trips were analysed to better understand whether they could be covered by pure electric cars. In the extensive sample analysed, it would be necessary to increase the driving range to 400 km/day in order to satisfy 99.9% of trips, however not satisfying the queuing issues for recharging. This aspect can be alleviated by adopting a PHEV (plug-in), given box their flexible recharging and less energy requesting batteries. The study provided a quantitative analysis of the energy needs, considering a wide range of road vehicles usage, and the chance for recovering energy during vehicles idle times.

The driving analysis was conducted in two phases. The first step was devoted to identify the most frequent car usages and the structure of the most representative trips; more specifically in this phase single trips were considered, classified according in relation to their length, duration, idle time and frequency of use. The second step aimed at providing an overview of the daily usage of vehicles, considering all the trips performed each day. This second step showed how different trips comprised the entire daily usage, and provided the daily travelled length and duration with reference to a 24h driving cycle.

The frequency of the daily distance for all trips is shown in Figure 1. Extended daily trips are relevant because, although 99% of

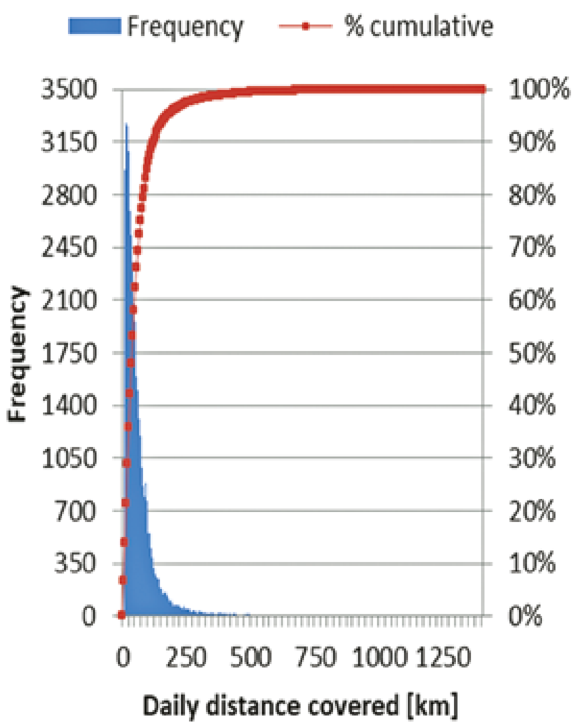


Fig. 1 – Frequency [#days] of the daily distance covered over all the driving cycles (contexts) for all the trips.

the days per user involves at most 400 km/day, only 60% of the days per user involves less than 50 km/day. Instead, this range was observed in 99.9% of the days for an urban context.

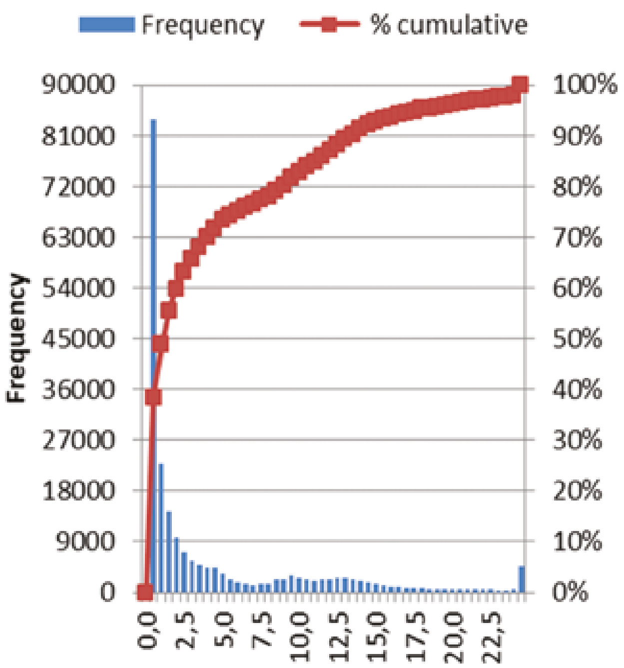
The idle time after concluding a journey, was depicted for the entire dataset; all the contexts (urban, extra-urban and motorway) were included (Figure 2).

As it can be seen, in approximately 50% of the cases, the total idle time after finishing a journey is less than 1 hour, 10% is between 1 to 2 hours, 10% is between 2 to 4 hours, 10% is between 4 to 9 hours, and it is more than 9 hours for the remaining cases (20%). The obtained results point out again that the most flexible automobile is the PHEV; yet, for drivers who cannot afford it, BEV-sharing (i.e., a car sharing of plug-in automobiles) may be a good solution, at least during a transitional phase.

Another issue faced by our research was to propose a methodology, unexplored in the literature, aimed at comparing battery recharging scenarios with differently electrified plug-in vehicles (hybrid and full electric, i.e. BEV, with different levels of energy storage). The obtained results have provided interesting insights about both the operability of different types of domestic recharging and the potentiality of recharging architectures that involve the use of larger installed structures, for example at work places.

The results related to a generic simulation day show that PHEVs are much more flexible than the other considered vehicles and have the characteristics necessary to travel with zero local emissions within an urbanised context, with obvious benefits for the environment and for the quality of life of citizens. In addition, their recharging times are compliant with the periods of night rest, as they would be for regular daily work in a stable place. Furthermore, they also show much greater compliance with the electric grid, since the limited capacity allows them to use a slow recharging, also competitive in terms of unit costs when compared to traditional fuels, without penalising the available driving range. Fast and rapid charging not only shows higher costs of energy per kWh, even higher than an equivalent refuelling, but also frequently does not comply with the required time and expected queues, having to deal with shared areas and spots available on public soil; fast and rapid charging also facilitate battery aging. With slow charging, more compliant with a typical daily scheduling of the driver if overlapping with night rest or a daylight physically stable work, PHEVs represent a winning choice to eliminate exhaust gas emissions in urban centres and cities, where the dispersion of pollutants is problematic and the health of citizens is at risk, without sacrificing the benefits associated with ICE (Internal Combustion Engines). As far as BEVs are concerned, their charging times, which are usually approx. four times longer than those of a PHEV charged at home, unless supply contracts are modified, require more attention, but offer the advantage of being able to be connected to the grid in a V2G configuration.

The spread of electrified vehicles with an average distance driving range in pure electric mode (8-12 kWh, indicatively), particularly suitable for covering medium-short



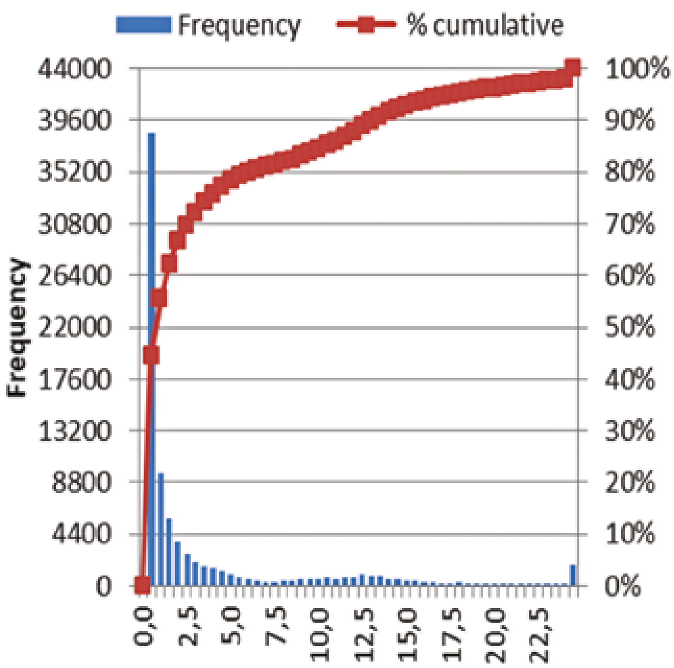


Fig. 2 – Idle time after finishing a trip [h] for all the driving cycles (left) and in an urban driving cycle (right).

distances, such as those from home to work places, or traveling in urban and sub-urban environments, could also benefit from the availability of extended facilities, such as public car parks equipped with recharging points.

Concluding, urban areas have a technological solution at disposal for the next one-two decades, suitable to satisfy both demand of drivers – according to analysed data – and supply of automobiles by carmakers. Meanwhile, extra urban area require much more ambitious and financially brave perspectives if BEV – and not a flexible PHEV – was deemed to be supported at all costs for any environmental reason, as detailed below.

3. Traffic simulation to analyse innovative solutions for charging electric vehicles

The majority of fully electric vehicles (BEV or FEVs) currently satisfy the electric energy requirements for their motion with on-board batteries. Extensive literature on their limitations focuses on battery problems, particularly on limitations in size and power, battery weight, life and recharge time, and the lack of a wide network of electric charging points. These problems are even more relevant for freight distribution services, where the vehicle masses and daily distances are much greater compared with those of passenger cars (12-20 times higher). In this case, a stationary recharge could require many charging stations not only located at depots, but also distributed in the service area, to provide more charging opportunities during the delivery routes. For this reason, the charging-while-driving (CWD) system or dynamic wireless charging could provide a technology to contain the battery sizes and recharging infrastructure costs without impacting on the vehicle autonomy, while investing on the "technological infrastructure".

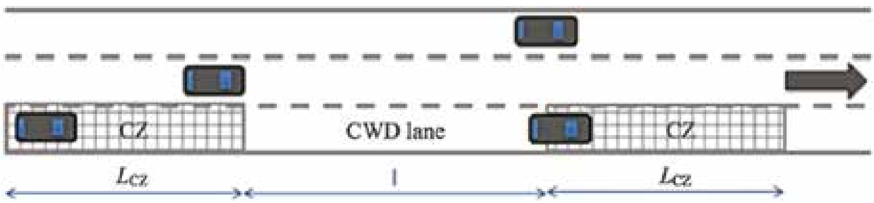


Fig. 3 – Scenario layout for CWD in a road with three lanes.

Figure 3 shows a CWD lane scheme, with two charging zones (CZs) represented. The EVSE (Electric Vehicle Supply Equipment) includes inductive coils placed under the pavement surface, at a relative distance, which generate a high frequency alternating magnetic field to which the coil on the car couples and power is transferred to charge the battery. A proper design procedure should consider both the service provider's need to minimize the installation and maintenance costs and the users' acceptance of the time required for a proper recharge in the CWD lane.

3.1. Traffic and energy assessment

A method for analysing the performance of the wireless inductive charge-while-driving (CWD) electric vehicles, from both traffic and energy points of view is presented in Deflorio *et al.* (2015). To accurately quantify the electric power required from an energy supplier for the proper management of the charging system, a traffic simulation model is implemented. This model is based on a mesoscopic approach, and it is applied to a freight distribution scenario. Lane changing and positioning are managed according to a cooperative system among vehicles and supported by Advanced Driver Assistance Systems (ADAS). From the energy point of view, the analyses indicate that the traffic may have the following effects on the energy of the system: in a low traffic level scenario, the maximum power that should be supplied for the entire road is simulated at approximately 9 MW; and in a high-level traffic scenario with lower average speeds, the maximum power required by the vehicles in the charging lane increases by more than 50 %.

The implemented dynamic traffic simulator in Deflorio and Castello (2017) adopts a mesoscopic approach by updating traffic and energy data only for the simulated vehicles at defined nodes along the road, generally spaced in hundreds of metres. The traffic simulator operates according to a cooperative driving behaviour among vehicles, for both the overtaking manoeuvres and the entries management. Primary traffic parameters can be estimated in the CWD lane, such as vehicle count, average speeds, and delays, which are time dependent and significantly changed along the road. The model also allows the implementation of a speed control strategy to manage temporary incidents, for example due to extraordinary maintenance operations. This strategy could also be applied in the case of high traffic volumes to facilitate the entries of vehicles from on-ramps. The traffic model is able to manage queuing conditions and delays caused by the strategy, when headways in the CWD lane are required to be higher than an established value. With respect to conventional dynamic traffic models, the current vehicle energy requirements affect the drivers' behaviour.

3.2. Dynamic charging along urban arterial roads

A method based on traffic micro-simulation to support feasibility studies on CWD systems for fully electric vehicles in urban environments is presented in Deflorio and Castello (2015). The examined CWD solution is deployed by charging zones (CZs), which are installed before the stopping lines at signalised intersections. The opportunity to charge an electric vehicle en route is provided for almost stationary vehicle conditions, when it may be in queue for junction control requirements. The analysed scenario refers to a 2 km urban arterial with eight signalised intersections, where 10% of the traffic is assumed to be electric vehicles. CWD performance results are reported from the viewpoints of both driver and energy provider. The estimated stop time for electric vehicles at any section can vary and is often below 30 s. However, the entire stop time for a vehicle along the arterial is higher: ~50% of the vehicles can charge in a range of 10-65 s. From the energy operator's viewpoint, a support analysis for the CZ location was performed by observing the charging opportunities at various sections. Finally, the total electric power provided for the entire system is estimated.

3.3. Simulation for the daily energy to dynamic charge electric vehicles on motorways

An application for motorway scenarios of charge while driving (CWD) also known as dynamic charging systems for fully electric vehicles (FEVs) is investigated with three lanes, where the right-hand lane is reserved for charging at defined speeds for FEVs. The input traffic flow for the motorway is simulated according to an hourly time profile along the day. To generalise the simulation for various traffic levels, the traffic flow for any time interval is estimated on the base of the traffic density, known from available data. The FEVs are only a part of the whole traffic and their input traffic is estimated as a percentage. The principal aim of this study is to estimate the daily energy provided to electric vehicles by the CWD system, which can be used, together with other data if available, to build possible business models and help stakeholders configure charging services. For this reason, the total energy provided is estimated by simulation for different scenarios.

3.4. Travel Patterns from Floating Car Data in Electric Mobility Scenarios

Understanding the potential of electric vehicles in current car mobility scenarios is crucial to plan a realistic deployment of charging stations and vehicle features. In the Incit-EV project, daily travelled distances are analysed to understand if the observed car usage can be satisfied with the expected range of electric vehicles (EVs). Moreover, idle times between trips are studied for assessing the vehicle needs for electric charging stations (ECSs) infrastructure to support EV travel. The datasets are derived by floating car data recorded for 365 days and contain more than 30 million trips crossing Turin Metropolitan City. Approx. 70,000 km are daily observed for more than 10,000 vehicles (up to 18,000) in each day of 400 different vehicle models, to identify daily activities, considering electric vehicles can be preferably recharged for long periods overnight. This assumption can be considered a reference scenario, in synergy with the battery range, to plan ECSs in road networks. Results show that 97% of daily VKT (vehicle kilometres travelled) is less than 200 km, over a year of observation for the whole set of vehicles. Cars are also classified according to their market segment to identify specific vehicle usage. Indeed, daily VKT values estimated for segment A (i.e. mini cars) have an average of 34 km, whereas for segment E (i.e. executive or large cars) the average is 75 km. The idle times analysis reveals a higher number of shorter breaks in the city centre compared to peripheral districts, suggesting that recharging solutions should be adapted to zones according to how they are used by vehicles.

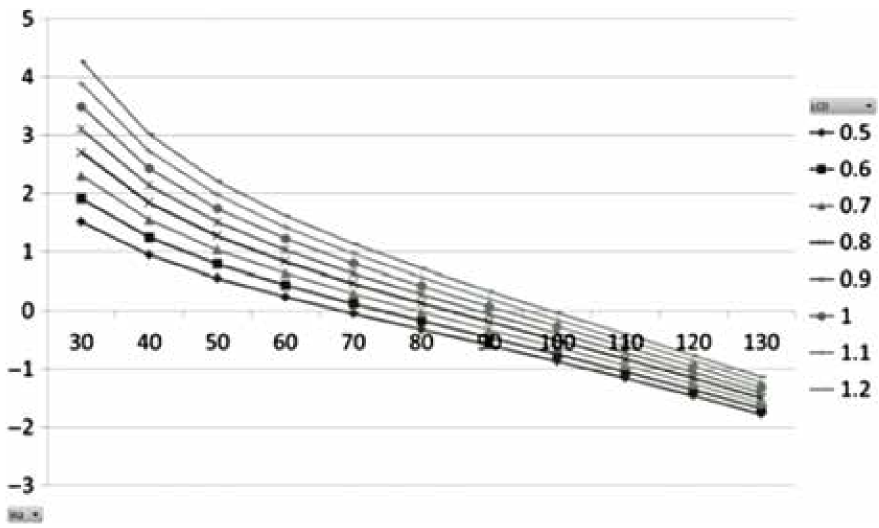


Fig. 4 – Gain of energy [kWh/km] at various speeds [km/h] for different lengths of the charging device [m].

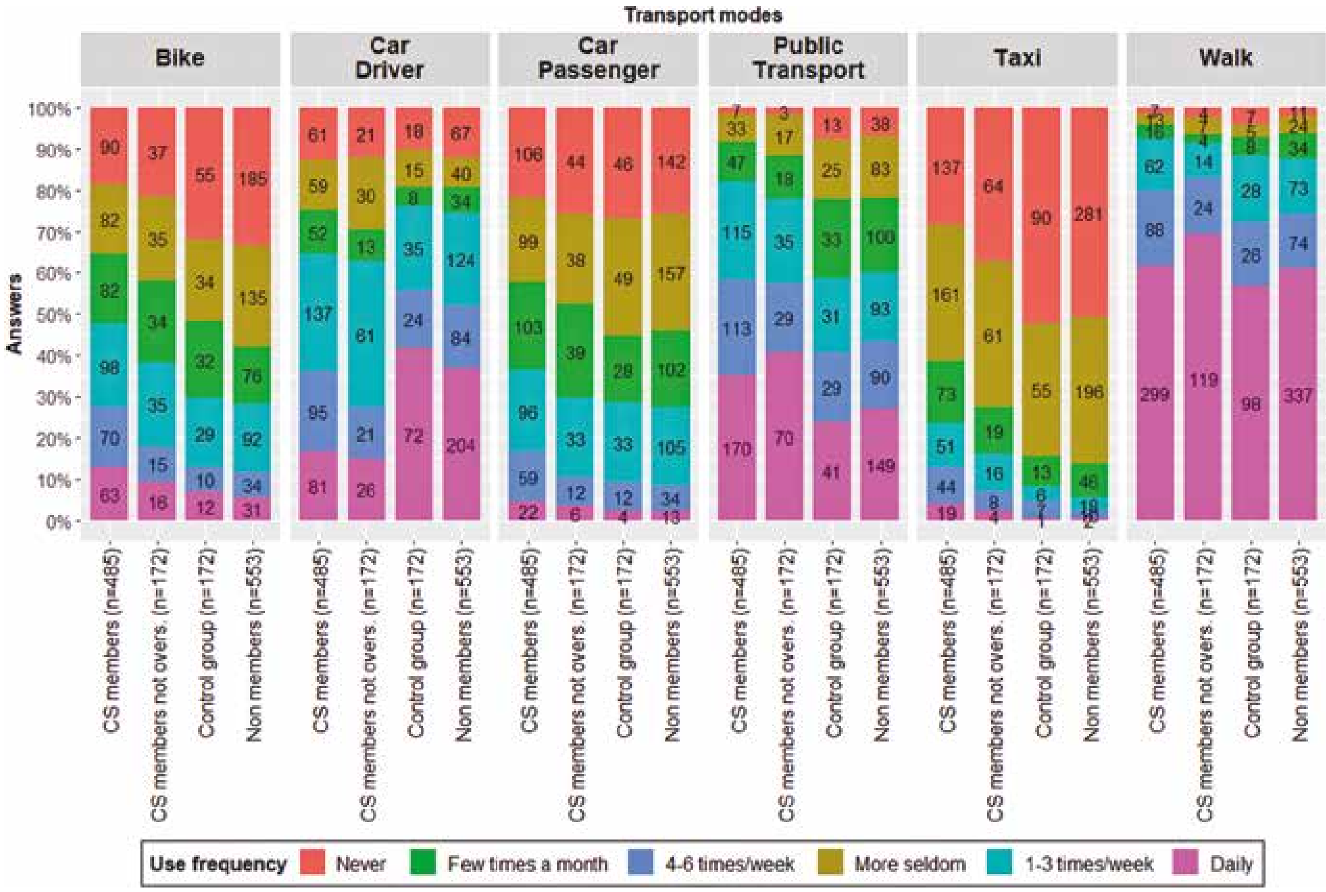


Fig. 5 – Use frequency of different travel modes – car sharing members and non-members – source: http://stars-h2020.eu/wp-content/uploads/2020/04/STARS-5.1.pdf.

4. *Car sharing services impacts on urban mobility scenarios*

Beyond electrification issues that have been discussed in the previous sections – that, in some cases, can be satisfied by placing car-sharing before the technological affordability of new powertrains – a wider change of paradigm in the ownership and use of private vehicles is another promising avenue to improve the sustainability and the inclusiveness of transport systems. The STARS project aimed at understanding the potential benefits of shared vehicle services that are steadily expanding in urban areas and their impacts in terms of congestion mitigation, environmental footprints and social inclusion.

Acting both as project coordinators and technical delivery partners, the DIATI transport research group was involved in many research activities, starting from an inventory of existing car sharing systems in Europe. Data collected through desktop research were used to develop a multidimensional classification of CS services with a bottom-up approach that considered service operational characteristics, vehicles type, pricing, and subscription fee. Then we collaborate in the distribution and analysis of a questionnaire mainly developed by the University of Gothenburg to understand the profiles of both users and non-users of car sharing in European cities concerning their travel patterns and psychological aspects (e.g. attitudes, acceptability of car sharing, personal norm). Five distinct mobility styles were identified and furtherly characterized by sociodemographic variables and by the motives for making use of car sharing (Ramos, Bergstad, Chicco, & Diana, 2020).

Another activity led by our group consisted in the design and distribution (at least in Italian cities) of a mobility questionnaire targeted to car sharing users and non-users of different European cities (from Germany, Italy and Belgium) aimed at evaluating the car sharing impacts on personal long-term mobility choices (such as car ownership) and how these changes are influencing the use of different travel modes and everyday mobility decisions. In this perspective, we evaluated car sharing's potential role in satisfying the current travel demand by looking at the substitution and complementary patterns that may change the travel demand for all competing modes (motorized individual means, taxis, active means, and public transport). The questionnaire consisted of four main sections: travel behaviour and mobility habits (where the use frequency of different travel means was investigated), a compact travel diary about the last trip performed with any mode (non-users) and with car sharing (users), changes in car ownership, and sociodemographic characterization of the respondents.

Descriptive person-level analyses about changes in the use of different transport modes and changes in car ownership levels after car sharing registration showed that car sharing users tend to own fewer cars, more public transport passes and bike-sharing membership than non-users. Consequently, car sharing users are more multimodal (Figure 5). Among car sharing users, however, differences were found according to the variants they are registered for. In particular, when modelling the car shedding among German car sharing users living in inner cities areas (where all main car sharing variants were available, namely roundtrip station-based, one-way free floating, and combined), albeit all car sharing users reported significantly lower levels of car ownership than before registering to the service, roundtrip station-based users were about 15 times more likely to reduce car ownership than free-floating unique users.

Besides, in order to predict the switch from the current mode used to car sharing for a specific trip and personal characteristics of respondents (the potential travel demand that can be attracted by car sharing as mentioned above), trip level analyses were carried out. Binomial logit models calibrated on a previously collected dataset (Ceccato, Chicco, & Diana, 2021; Ceccato & Diana, 2021) were applied to the non-users data that were collected in Italy and different mobility scenarios were identified. Related emissions of pollutants and greenhouse gases were quantified and monetized through unit costs to understand how to maximize car sharing's positive environmental impacts.

According to the switch models' explanatory variables, the configuration that determined the lowest externalities – the planning scenario – was obtained by changing car sharing and private car costs. In this way, car sharing should substitute trips currently performed by private cars rather than trips performed with more sustainable modes (PT and active ones).

Modal switch models' results showed that one-way car sharing has the potential to cover up to 10% of the daily travel demand in the planning scenario (Figure 6). Although the diverted travel demand was mainly subtracted from private cars, the environmental benefits were partially offset by switches from public transport and active modes. Concerning the externalities related to the whole transport system's emissions, the planning scenario would lead to a reduction of 1% in terms of social costs. Such benefits can be increased up to 3.6% by promoting electric car sharing fleets (Figure 7) (Chicco & Diana, 2021).

5. *Supporting local authorities in sustainable transport planning*

Sustainable transport planning is a fundamental requirement for cities that want to improve their citizens' mobility and freight significantly. Although larger authorities are relatively well equipped

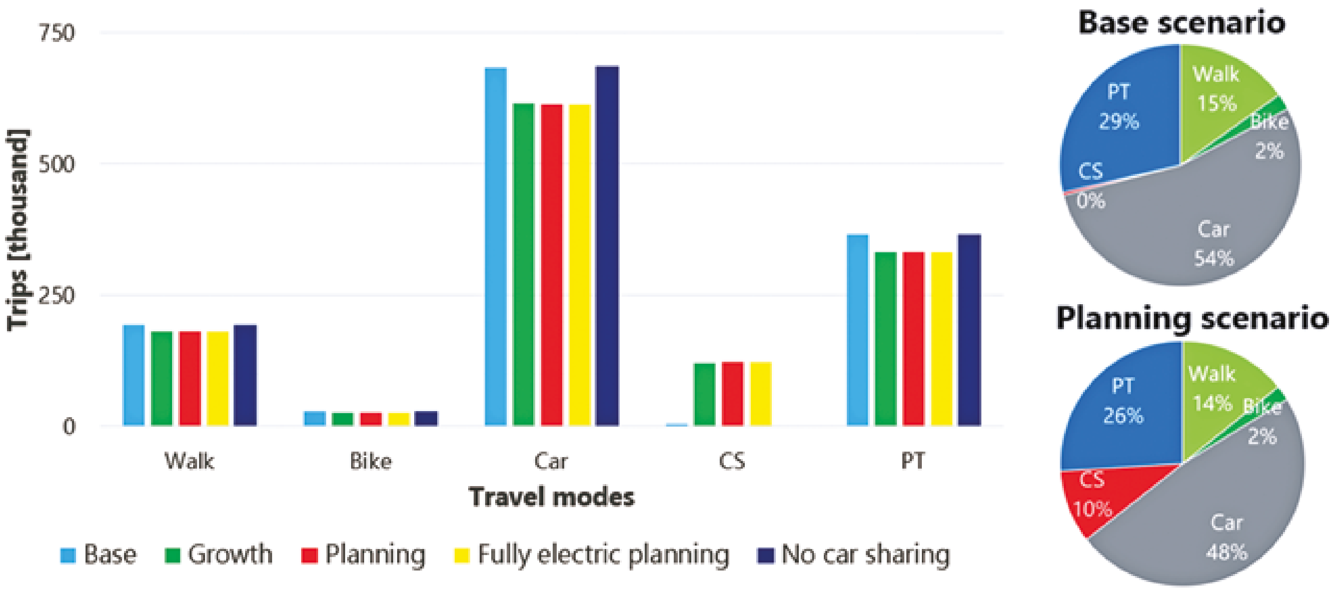


Fig. 6 – Diverted daily trips and market share in scenarios – source: Data retrieved from (Chicco & Diana, 2021).

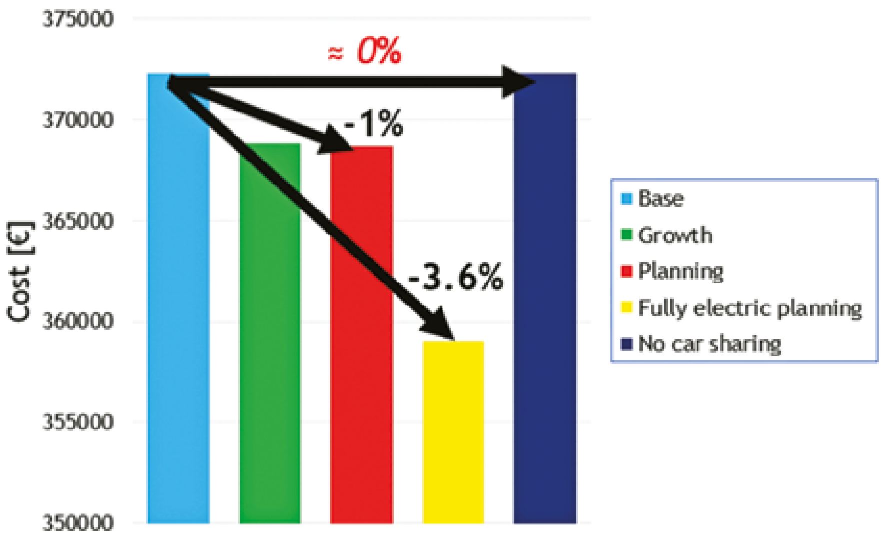


Fig. 7 – External costs of pollutants and GHG emissions in scenarios – source: Data retrieved from (Chicco & Diana, 2021).

to face these challenges, smaller, more traditional Local Authorities (LAs) may lack the knowledge and capacity to plan and implement innovative and sustainable transport measures. The H2020 European project SUITS aimed at supporting the capacity building of small – medium local authorities in developing sustainable transport measures. The project adopted a socio-technical approach and focused its first activities on understanding how nine European LAs were addressing the challenges associated with developing sustainable transport measures, the use of real-time mobility and more interdepartmental and technologically supported ways of working (Diana *et al.*, 2018). The larger LAs had more time to engage with the project and piloted the tools and methods developed, thanks to their larger departments. Their experiences and practices were transferable to the follower cities who could learn from the larger LAs and benefit directly from the proven outputs.

Data collection is known to be a fundamental step for the observation of passenger and freight movements at the city level. Furthermore, data analysis is a priority in developing proper sustainable measures and planning and implementing solutions at the city level. However, as found in the project's preliminary activities, an absence of an appropriate focus on data collection and modelling is observed in most of the LAs. Within SUITS, a pilot activity based on the freight data gathering in Turin (Italy) has been conducted to inform the implementation of new measures to meet congestion problems and the level of know-how needed to extract useful data.

The methodology is developed to help cities investigating a specific aspect characterising and influencing their mobility, namely the observation of freight flows from the demand side, through the exploitation of existing datasets such as Global Position System (GPS) vehicle traces. This latter information was combined with another kind of data derived from the infrastructure, namely traffic flows characterizing the road network. The innovative combination of these two kinds of data aims at identifying the most congested areas, thanks to the creation of a highly disaggregated Key Performance Indicator (KPI) based on the time lost in congestion by each vehicle in each road segment (Pirra & Diana, 2019). This KPI can be used to inform a wide range of policy actions within the transport sector, both from the viewpoint of a municipality and from that of an individual actor in the transport system. For example, the analysis provided information about the most congested points of the city in terms of the total amount of time wasted by vehicles in traffic (Figure 8).

The assessment of how urban deliveries affect various areas in the city, mostly those commonly affected by congestion, is a further challenging point while dealing with urban freight policies. Starting from the GPS vehicle traces dataset, spatial analysis is then conducted through a specific GIS-based data mining technique to find the most significant clusters (groups) of service stops in Turin (Diana *et al.*, 2020). Then, a specific area in the Limited Traffic Zone in the city centre was selected as the most suitable where running a survey designed to collect information on the dynamics of freight deliveries and pickups at these locations: operators usually delivering, where the vehicles are parked, exploitation of the available unload/load areas, duration of stops, the number and dimension of packs supplied, and the final destination of such deliveries. This tool can be used to inform a range of policy actions at the municipality level, mainly on the freight delivery side.

As highlighted previously, LAs are starting to deal more and more with managing data collected from different stakeholders involved in urban freight transport. Another challenging point is the evaluation of the city accessibility for freight distribution services. Pirra *et al.* (2019) proposes an innovative approach that starts from the previous GPS vehicle traces data available in Turin and evaluates the accessibility to the city. It is ba-

Fig. 8 – Value of the mean indicator computed for all the arcs of the road network, zoom in the Turin city centre (Reproduced from Pirra and Diana (2019) under the licence https://creativecommons.org/licenses/by/4.0/legalcode).

sed on the travel time estimations along the most frequently used routes that connect relevant areas and their average speed through a simplified road network model. The results obtained confirm the value of this kind of data in assessing the accessibility of different zones interested in delivery operations and provide a fruitful monitoring function to urban logistics operators and LAs while managing urban freight flows.

6. *Gender-related contemporary challenges for smart and inclusive mobility ecosystems*

Nowadays, when dealing with sustainable transport systems, it is relevant to focus on a buzzword of the beginning of the 21st century: Smart Mobility (SM). This innovative concept involves four main contents: vehicle technology, intelligent transport systems, data, and new mobility services (Carboni *et al.*, 2021). Smart Mobility is seen as a means of delivering key benefits such as containing local pollution, global emissions, traffic congestion, and noise pollution, while increasing safety and improving transfer speed. However, substantial gender inequalities are seen in current transport provision, with SM being a way of opening exciting opportunities for social inequity reduction; an inequity that includes also other aspects, as that of ageing of the population, with possible digital divide, that the SM itself brings with it.

The ambition of the H2020 project TInnGO – Transport Innovation Gender Observatory – is to address contemporary challenges, such as employment, education, and prevalent male-dominated Science, Technology, Engineering and Maths (STEM) cultures and future mobility scenarios in EU transport strategies, in a gender and diversity sensitive way.

The project operates through the development of a pan-European Observatory that leads, coordinates and is fed by 10 Hubs across EU providing leadership, innovation and critique of SM innovations.

Having these concepts in mind, the project considers women not merely as passive users of SM, but also as providers – designers, engineers and innovators. Thus, the project activities move on several fronts. On one side, a modelling approach that embraces multiple methods for understanding women's mobility needs is adopted. The preliminary steps include investigating the literature on the topic and proceeded with focus group activities in the Hubs, intending to explore the thoughts and feelings related to their travel behaviour (Pirra *et al.*, 2021). This approach was the basis for identifying the most pertinent aspects of gendered mobility experience and helped in designing a survey proposed in the 10 Hubs. Data collected will help transport planners and mobility operators to identify needs and differences between men and women, to measure the impact of new services and transport features on gender-equal mobility opportunities.

A pilot data collection activity started in September 2020, intending to collect the first wave of a limited number of responses investigating how the COVID emergency has affected mobility choices (Carboni *et al.*, 2021). Preliminary results reveal that public transport is the mode that has been most affected by the changes in mobility due to the spread of the pandemic, probably being perceived unsafe in terms of infection. Women, found to be the primary users of this transport solution, are indeed the ones who report the main changes, especially for work-related trips. In general, a shift to more sustainable modes of transport, such as walking and biking, is observed.

While dealing with women as users, it is worth investigating their attitude towards new paradigms in the transport offer, such as sharing vehicles and means, being these potential answers of SM to environmental sustainability problems. Shared mobility is one of the focus of the Italian Hub. Some preliminary Hub activities were based on the analysis of a dataset collecting 2934 responses to a survey addressed to both car-sharing users and non-users. Results revealed that, when women and men are considered as different kinds of users, the main characteristics of various clusters of respondents using this service are rather similar despite the gender (Chicco *et al.*, 2020).

As highlighted previously, the project considers women not only as SM users but also as providers. This would require highlighting how a lack of diversity in STEM professionals has contributed towards a fractured and gender-biased transport ecosystem (embracing education, employment, operation, data collection, and innovation) that does not allow a gendered Smart Mobility transport provision. A low number of initiatives for encouraging and supporting women in the transport sector are found in TInnGO countries, so the project will try to fill this gap by yielding new knowledge and proposing innovative ways to tackle this topic. Moving on to a higher level in the provision of innovation, further analyses investigate the research footprint of female transport researchers, revealing that women working in research environments are subjected to similar discriminatory practices as their sisters in industry, indicative of a broader malaise in the sector.

7. Final remarks

This paper has presented an array of recent researches dealing with sustainable and inclusive transport systems. Through the heterogeneity of disciplinary perspectives, research methods and outcomes that have been showcased, it is clear that a radical improvement of such systems cannot come from a single approach or discipline. Through a diversity of backgrounds, research interests and personal experiences, the Transport research group at Politecnico di Torino, at Dept. DIATI, is actively seeking to give contributions in this sector that are at the forefront of international research, thanks to a relatively wide portfolio of funded projects mostly at the European level.

Bibliography

Caballini, C., Agostino, M., Dalla Chiara B, 2021. "Physical mobility and virtual communication in Italy: trends, analytical relationships and policies for the post COVID-19", Transport Policy, 2021, ISSN 0967-070X, https://doi.org/10.1016/j.tranpol.2021.06.007

Carboni, A., Costa, M., Kalakou, S., Pirra, M., 2021. Gender, Smart Mobility and COVID-19. In: Krömker H. (eds) HCI in Mobility, Transport, and Automotive Systems. HCII 2021. Lecture Notes in Computer Science, vol. 12791. Springer, Cham. https://doi.org/10.1007/978-3-030-78358-7_33

Ceccato, R., Chicco, A., Diana, M., 2021. Evaluating car-sharing switching rates from traditional transport means through logit models and Random Forest classifiers. Transportation Planning and Technology, 44(2), 160-175. https://doi.org/10.1080/03081060.2020.1868084

Ceccato, R., Diana, M., 2021. Substitution and complementarity patterns between traditional transport means and car sharing: a person and trip level analysis. Transportation, 48(4), 1523-1540 https://doi.org/10.1007/s11116-018-9901-8

Chicco, A., Diana, M., 2021. Air emissions impacts of modal diversion patterns induced by one-way car sharing : A case study from the city of Turin. Transportation Research Part D, 91(January), 102685. https://doi.org/10.1016/j.trd.2020.102685

Chicco, A., Pirra, M., Carboni, A., 2020. Preliminary investigation of women car sharing perceptions through a machine learning approach. In: HCII 2020, CCIS 1224, Editors C. Stephanidis and M. Antona, Springer Nature, pp. 1-9, DOI: 10.1007/978-3-030-50726-8_81

Dalla Chiara B, Deflorio, F., Eid, M., Analysis of real driving data to explore travelling needs in relation to hybrid–electric vehicle solutions, Transport Policy, vol. 80, Pages 97-116 (August 2019)

Dalla Chiara, B., Pellicelli, M., Sustainable road transport from the energy and modern society points of view: Perspectives for the automotive industry and production, Journal of Cleaner Production, 133, p. 1283-1301 (October 2016).

Dalla Chiara, B., Deflorio, F., Pellicelli, M., Castello L, Eid, M., Perspectives on Electrification for the Automotive Sector: A Critical Review of Average Daily Distances by Light-Duty Vehicles, Required Range, and Economic Outcomes, Sustainability, 2019, vol.: 11, Number: 5784; https://www.mdpi.com/2071-1050/11/20/5784

Deflorio, F.P., Castello, L., Pinna, I., Guglielmi, P., 2015. "Charge while driving" for electric vehicles: road traffic modeling and energy assessment. Journal of Modern Power Systems and Clean Energy 3, 277-288.

Deflorio, F., Castello, L., 2015. Assessing the performance of a charge-while-driving system in urban arterial roads: insight from a microsimulation model. IET Intelligent Transport Systems 9, 505-514.

Deflorio, F., Castello, L., 2017. Dynamic charging-while-driving systems for freight delivery services with electric vehicles: Traffic and energy modelling. Transportation Research Part C: Emerging Technologies 81, 342-362.

Diana, M., Pirra, M., Woodcock, A., 2020. Freight distribution in urban areas: A method to select the most important loading and unloading areas and a survey tool to investigate related demand patterns, European Transport Research Review, 12, 40, DOI: 10.1186/s12544-020-00430-w

Diana, M., Pirra, M., Woodcock, A., Martins, S., 2018. Supporting Urban Integrated Transport Systems: Transferable tools for Local Authorities (SUITS), Proceedings of Transport Research Arena TRA2018, 16-19 April 2018, Vienna, Austria, DOI: 10.5281/zenodo.1441138

Pirra, M., Kalakou, S., Carboni, A., Costa, M., Diana, M., Lynce, A.R., 2021. A preliminary analysis on gender aspect in transport systems and mobility services: presentation of the survey design, Sustainability, 13(5), 2676, DOI: 10.3390/su13052676

Pirra, M., Diana, M., 2019. Integrating mobility data sources to define and quantify a vehicle-level congestion indicator: an application for the city of Turin, European Transport Research Review, 11:41, DOI: 10.1186/s12544-019-0378-0

Pirra, M., Carboni, A., Deflorio, F., 2021. Freight delivery services in urban areas: Monitoring accessibility from vehicle traces and road network modelling, Research in Transportation Business & Management, 100680, https://doi.org/10.1016/j.rtbm.2021.100680

Ramos, É.M.S., Bergstad, C.J., Chicco, A., Diana, M., 2020. Mobility styles and car sharing use in Europe: attitudes, behaviours, motives and sustainability. European Transport Research Review, 12(1). https://doi.org/10.1186/s12544-020-0402-4

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GEAM AMBIENTE

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Study of the environmental impact in show caves: a multidisciplinary research

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Caves are one of the most important and well-known geological features in the world, an environmental and cultural heritage, as well as an important economic resource for many countries. Their scientific and aesthetic value is often threatened by tourism, which unfortunately exposes them to a series of risks of degradation and, sometimes, irreparably changes. Therefore, the study of underground environment becomes essential in order to protect and preserve it over time. The national project "SHOWCAVE" aims to study, classify and mitigate the environmental impact in the tourist caves to finally propose useful solutions for their management. In particular, the DIATI team of the Politecnico di Torino deals with the acquisition of monitoring data of the main environmental parameters, the analysis of the speleothems corrosion and the analysis of the presence of microplastics in caves. The most advanced geomatics techniques are used to illustrate the topography of these cavities, their development relative to the surface and the studied areas. The researches have just begun, and in this work the study methodologies used and the first results obtained by our multidisciplinary research group are presented.
Keywords: Geoheritage, microplastics, speleothems corrosion, environmental parameters monitoring, geomatics.

Studio dell'impatto ambientale nelle grotte turistiche: una ricerca multidisciplinare. *Le cavità naturali rappresentano una tra le più importanti e conosciute manifestazioni geologiche del mondo, e sono un patrimonio ambientale e culturale, oltre che un'importante risorsa economica per molti paesi. Il loro valore scientifico ed estetico è spesso minacciato dalla fruizione turistica, che purtroppo le espone ad una serie di rischi di degrado e talvolta le modifica irrimediabilmente. Diventa dunque essenziale lo studio dell'ambiente ipogeo per poterlo tutelare e conservare nel tempo. Il progetto nazionale "SHOWCAVE" ha lo scopo di studiare, classificare e mitigare l'impatto ambientale nelle grotte turistiche per proporre infine soluzioni utili alla loro gestione. In particolare, il team del DIATI del Politecnico di Torino si occupa dell'acquisizione dei dati di monitoraggio dei principali parametri ambientali, dell'analisi dei fenomeni legati alla corrosione degli speleotemi e dell'analisi della presenza di microplastiche in grotta. Per illustrare la topografia di tali cavità, il loro sviluppo rispetto alla superficie e le zone oggetto di studio, vengono utilizzate le tecniche geomatiche più avanzate. Gli studi sono appena iniziati e in questo lavoro vengono presentate le metodologie di studio utilizzate e i primi risultati ottenuti dal nostro gruppo di ricerca multidisciplinare.*
Parole chiave: *Patrimonio geologico, microplastiche, corrosione degli speleotemi, monitoraggio dei parametri ambientali, geomatica.*

1. Introduction

Show caves are made accessible to the public for touristic purposes, managed by a governmental or commercial organization. Over the past decades, the interest for the underground karst environments and its natural wonders has grown remarkably, not only from a scientific viewpoint, but also from an economic perspective (Cigna, 2016; Cigna & Forti, 2013). The numbers of visitors (sometimes up to 50,000/year/cave) and the profits deriving from such activities have recently gained importance at global scale (Cigna & Forti, 2013). Caves are fragile environments which can be easily damaged by negative effects of tourism, such as air temperature and CO_2 increment (e.g. Cuevas-González *et al.*, 2010; Dominguez-Villar *et al.*, 2010; Faimon *et al.*, 2006; Fernandez-Cortes *et al.*, 2011; Lang *et al.*, 2015a; Lang *et al.*, 2015b; Lang *et al.*, 2017; Lobo *et al.*, 2014; Pulido-Bosch *et al.*, 1997; Šebela *et al.*, 2013; Singh, 2011), lampenflora growth (e.g. Baquedano Estevez *et al.*, 2019; Havlena, 2019; Kurniawan *et al.*, 2018; Mulec & Kosi, 2009; Piano *et al.*, 2015; Pulido-Bosch *et al.*, 1997) or pollution (e.g. Chang *et al.*, 2008; Christman, 2019; Šebela *et al.*, 2015), therefore, scientific investigations are necessary to better understand cave environment and to protect them (Cigna, 2016; Cigna & Forti, 2013; De Freitas, 2010).

The National Project "SHOWCAVE – A multidisciplinary research project to study, classify and mitigate the environmental impact in tourist caves" (PRIN2017.0000375.26-03-2018) started in 2020, aiming to provide an in-depth characterization and quantification of the environmental impacts related to tourist exploitation in show caves, focusing on the biological, geological, hydrogeological, archaeological and physical components of the cave environment. Within this research, the Department of Environment, Land and Infrastructure Engineering (DIATI) team of the Politecnico di Torino (PoliTO) is carrying out different studies with an innovative and multidisciplinary approach which will be described below.

The geological features of the show caves have been investigated with a special attention on the classification of speleothems and the study of the internal and external geomorphology of the karstic system. Physical indicators as temperature, relative humidity and CO_2, have been monitored to track the air and water quality. An internal and external 3D survey of the Borgio Verezzi Cave has been carried out with integrated GNSS Total Station, Lidar and photogrammetry techniques. The survey of the path allows to estimate the subjacency of the cave with respect to the urbanized territory. Microplastics (MPs) pollution in cave sediments has been monitored too, for the first time. MPs pollution in sediments has been observed in different natural environments (e.g. Ballent *et al.*, 2016; Blumenröder *et al.*, 2017; Mathalon & Hill, 2014; Naji *et al.*, 2017; Phuong *et al.*, 2018; Qiu *et al.*, 2015; Van Cauwenberghe *et al.*, 2013; Vianello *et al.*, 2013), moreover, only few researches on lint (natural and synthetic fibers from clothing) in cave have been done (e.g.Chelius *et al.*, 2009; Christman, 2019; Jablonsky *et al.*, 1993) and the potential impact of MPs in cave has not been studied. Secondly, it will be possible to make different correlations between the presence of MPs and biotic and abiotic factors in cave. Finally, a study on the indirect impact of tourism on the mineralogical and petrographic properties of the carbonate rocks have been started, with the aim of relating it to the corrosion degree.

In the present paper, we reported first evidences of our studies developed in the Bossea Cave, Toirano Caves, and Borgio Verezzi Cave (NW Italy), providing new insight on subterranean environments and on tourist impact in these caves.

2. Study area

This study provides a systematic monitoring of the Bossea Cave, Piedmont, Toirano Caves, Liguria, and Borgio Verezzi Cave, Liguria, in Italy (Fig. 1).

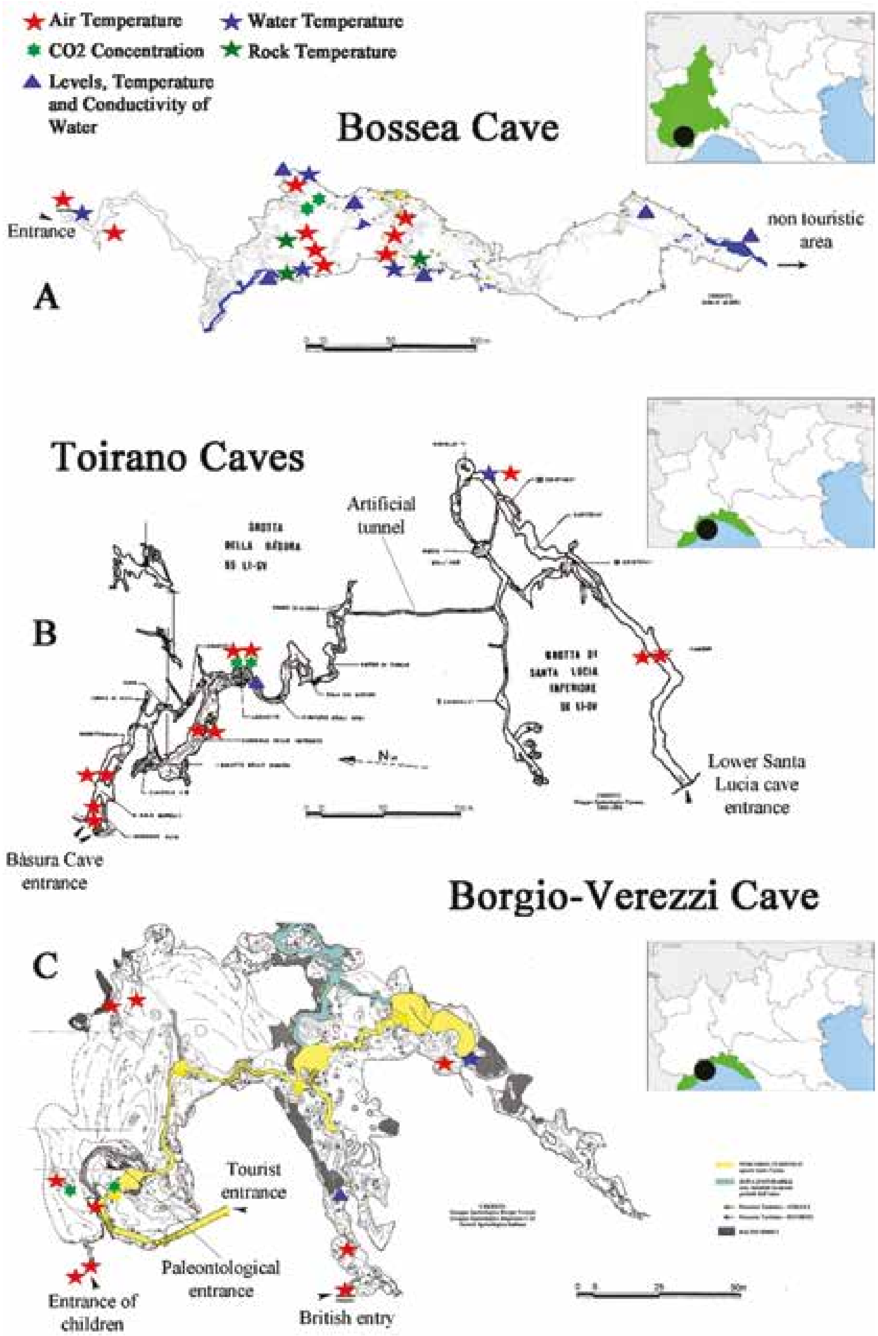

Fig. 1 – Location of the investigated tourist caves and their monitoring points. A-Bossea cave (survey: Sella *et al.* 2005, modified), B-Toirano Caves (survey: Gruppo Speleologico Cycnus, from http://www.openspeleo.org/openspeleo/, modified), C-Borgio Verezzi Cave (survey: Gruppo Speleologico Borgio Verezzi, Gruppo Speleologico Imperiese CAI, Società Speleologica Italiana, from http://www.openspeleo.org/openspeleo/, modified). The black dot indicates the location of the studied show caves (maps used for the plate retrieved from: https://d-maps.com/carte.php?num_car=5892&lang=en).

2.1. Bossea Cave

Bossea Cave (Fig. 1A) is located in Frabosa Soprana municipality, Piedmont, Italy at 836 m.a.s.l. The cave develops in a tectonic contact between permotriassic meta-volcanics and Dolomie di San Pietro dei Monti formation (Middle Triassic), composed by carbonate rocks and dolostone (Antonellini *et al.*, 2019). It is the first show cave of Italy and was opened to the public in 1874. In 1948 the tourist route was modified and the first electric lightning was installed. In 2020 a new LED lightning system was done. It is one of the nicest Italian tourist caves due to its variety of concretions, plenty of water and underground lakes. Different bear bones (*Ursus spelaeus*) were found in Bossea Cave and a skeletal reconstruction can be seen in the "Bear saloon". An underground karst laboratory is located inside the touristic trait of the cave, managed by Struttura Operativa (SO) Bossea CAI and by the DIATI of the PoliTO, working together with ARPA Piemonte. A secondary lab is located in a non-touristic area of the cave. Thanks to these laboratories, hydrogeology, hypogeal meteorology, Radon activity and subterranean biology are studied (Peano & Fisanotti, 1994).

2.2 Toirano Caves

Toirano Caves (Fig. 1B) are located in the municipality of Toirano, Liguria, Italy. They developed in Dolomie di San Pietro dei Monti formation and an hypogenic speleogenenis origin has been recently supposed in Columbu *et al.* (2021). Toirano Caves are characterised by two different caves: Bàsura Cave (Grotta della Bàsura, 186 m.a.s.l., 890 long) and Lower S. Lucia Cave (Grotta di Santa Lucia inferiore, 201 m.a.s.l., 778 long). Bàsura Cave was explored in 1950 and opened to the public in 1953. S. Lucia inf. Cave and new galleries of Bàsura Cave were explored in 1960. In 1967 a 110 m long artificial tunnel was made to connect the two caves. Bàsura Cave preserves hundreds human (14400 years old) and animal footprints (Avanzini *et al.*, 2018). Recent studies revealed that footprints in this cave belonged to 5 different individuals (*Homo sapiens* groups), 2 adults and 3 children, from the upper Paleolithic (Romano *et al.*, 2019). This cave contains also a lot of cave bear (*Ursus spelaeus*) bones and signs of presence (Giacobini & D'Errico, 1985; Rellini *et al.*, 2021), an extinct plantigrade from the upper Pleistocene (50000-24000 years old). Lower Santa Lucia Cave is characterised by beautiful speleothems such as coralloid and cave clouds (Martini, 2008).

2.3. Borgio Verezzi Cave

Borgio Verezzi Cave (Fig. 1C) was discovered in 1933 by three children but was opened to the public only in 1970. It is located in the municipality of Borgio Verezzi, Liguria, Italy at 32 m.a.s.l. and develops in Dolomie di San Pietro dei Monti formation. It is rich in coloured speleothems and has an 800 m touristic path. Different paleontological finds datable between 500,000 and 750,000 years ago were found in different parts of the cavity (Breda, 2015 and references therein), witnessing the alternation between glacial and hot periods.

3. Investigation method

3.1. Environmental parameters monitoring

Preliminary surveys were performed to better understand the environmental conditions of the caves, using portable instruments, in order to decide the representative sample points. The on-site instrumentation has been installed in different areas of caves, taking into account the tourist paths, in order to monitor the influence of tourism. Different instruments have been installed in non-touristic areas too, to measure natural cave conditions.

In Bossea Cave environmental parameters are monitored by two different laboratories. The Giovanni Badino Center for Climatological Research, funded by Paleolab – PoliTO and the Underground Karst Lab of Bossea – SO Bossea C.A.I., in collaboration with INRI Turin and ARPA Piedmont, monitor air, water and rock temperatures (T), air circulation, CO_2 air concentrations and atmospheric pressure. In the cavity have been installed four main stations to monitor air, rock and water temperature (Fig. 1A). The surface station detects air temperature, atmospheric pressure, air velocity and rock temperature near the entrance. Inside the cavity, different probes at different heights monitor the environmental conditions of the biggest halls characterizing the cave. Other probes are installed in the depth of the cave rocks from few centimeters up to 3 m. A detector with two probes at different heights detects the concentration of CO_2 in the air. Almemo multiple-channel sensors with temperature probe (accuracy: 0,01; resolution 0,001 °C) are used with a data acquisition interval of 10 minutes. The hydrogeological parameters are measured by the Karst Hydrogeology Lab (DIATI – PoliTO) which detects the flow values, electrical conductivity and water T of the main collector and of other 10 secondary water streams. A real-time OTT monitoring system and data recording every 10 minutes is used for hydrogeological parameters measurements. The electrical conductivity sensors are with double graphite cell and have an accuracy of 0.5 % mv, T probes have a resolution of 0.1 °C and an accuracy of 0. 5°C, water level measurement cells are ceramic-capacitive with 1 mm resolution and accuracy 0.05 % fs.

In Toirano Caves (Fig. 1B) and Borgio Verezzi Cave (Fig. 1C) from January 2021, a Tinytag acquirers (accuracy: 0.2 °C; resolution: 0,001 °C) to detect the air temperatures at different height (near the floor and the ceiling) have been installed, with data acquisition interval of one hour. For the monitoring of water levels, electrical conductivity and water temperature, OTT instrumentation has been installed with hourly data acquisition. Sensors' characteristics are the same described in the Bossea Cave monitoring system. A VAISALA system with INDINGO 520 acquirer and GMP 252 probes with an accuracy of 40 ppm is used for the CO_2 value. The data are captured every hour.

3.2. Geomatic surveys

The survey operations are performed both inside and outside the cave, to identify the path with respect to the external area and determine the thickness of the rock layer. However, the survey also serves to georeference points of interest or to detect speleothems in greater detail.

In complex surveys involving indoor and outdoor environments it is necessary to integrate different measurement techniques but first of all materialize a common and stable reference system consisting of some points of known coordinates to support photogrammetric and Lidar measurements. For compatibility with technical maps, the ETRF2000 national geodetic system was used. The external Grount Control Points (GCPs) are materialized with stable nails and 60 cm x 60 cm markers, clearly visible on the frames taken by a drone. They allow to determine with a photogrammetric operation of aerial triangulation (AT) the position and attitude of each frame for absolute orientation. The photogrammetric survey was done with DJI Phantom 4 RTK UAV. The position of the external points was surveyed with Trimble-Spectra Precision SP80 GNSS geodetic receivers in RTK mode, with the RTCM products transmitted by the Network RTK HxGN SmartNet (https://hxgnsmartnet.com/it-it/). Achieving the fixation of phase ambiguity allows to obtain a precision (standard deviation) of the planimetric and altimetric coordinates of 1 or 2 cm.

The interior of the cave was surveyed with LiDAR Optec Polaris. It allows you to directly georeference scans from station points and known orientation. The recognition of the orientation point occurs automatically by the instrument if a specific target is used. The operation is strongly conditioned by the lighting conditions, often critical in underground environments. The position of the station and orientation points was previously determined with a polygon, which extends from the entrance to the entire extension of the cave, with the Leica MS50 precision total station, oriented on the external GNSS points.

3.3. Laboratory analysis

An initial classification of speleothems has been made, simultaneously detecting the main types of alteration in caves (CO_2 corrosion, undersaturated water and lampenflora). In the first in situ campaigns the research of a proper method to sample a micro portion of speleothems has been carried out. After, a microdrilling technique to sample a representative portion has been chosen. The alteration and the characterization of speleothems have been analyzed in the DIATI Laboratory (PoliTO) with XRay Diffractometer Rigaku, SEM EDX Fei.

Different cave surveys with UV flashlight have been showed the presence of different kind of materials left by visitors, as shoes and clothes, with high probability of plastics. Hence the need to describe the anthropogenic impact measuring probable MPs pollution. MPs pollution in cave sediments has been evaluated testing different separation methods in the DIATI Laboratory of PoliTO.

4. First evidences and results

4.1. Environmental parameters in Bossea Cave

All data of Bossea Cave are collected from December 2019. In 2020, different periods of closure of the cavity, due to Covid 19 pandemic and the installation of the new LED lightning system (started in March 2020), allowed to monitor the natural parameters of the cave without the modifications caused by tourists and lights. Therefore, the data collected in the closing periods of the cave (with no visitors and no lights) (Fig. 2) and in periods of considerable tourist flow as during the Christmas holidays of 2019 (Fig. 3) are extremely interesting to better understand cave environment and tourist impact. Equally interesting are air temperatures influenced by lights, before (hot lights-incandescent lamps) and after LED lightning system installation (cold lights). Moreover, there is a considerable difference in temperature at the same site linked to the stratification of air: in the sectors close to the floor of the cavity, where the underground stream flows, temperature is over 1°C colder than the ceiling.

Initial assumptions on cave T variations have been done comparing hydrogeological monitoring data (flow and T variations of collector water and secondary inputs) and surface air T data: air T in the cavity is influenced by the flow rate and T of the water collector, reaching the minimum annual values in May, linked to the great flood due to the snow fusion and to the spring precipitation. The air surface T minimum values occurred in January-February 2020 and 2021 both. The maximum thermal value found on the surface has monitored in August 2020 and it corresponds to that inside the cavity. In this period the flow rates of the hypogeum collector reached the minimum annual values and water temperature has its annual maximum.

Only after the concert of 26 December 2019 there was an abnormal increase in air T in the cavity, due to an influx of more than a hundred tourists within a few hours. Air T returned to normal value over the next three hours (Fig. 3).

The CO_2 concentrations in the cavity resulted quite high with values from 1200 ppm in November 2019 to 900 ppm in spring 2020.

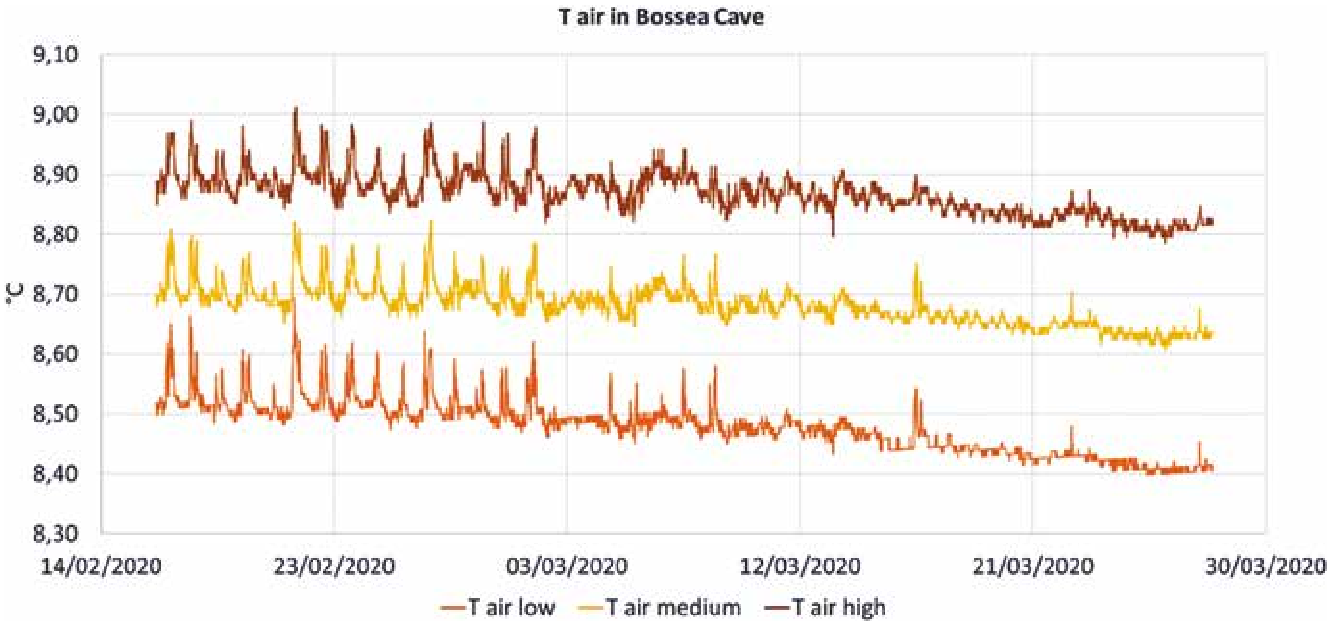

Fig. 2 – Air temperature trend at different heights in Bossea Cave, before and after Covid-19 pandemic. Air temperature is clearly conditioned by lighting system in the period before pandemic.

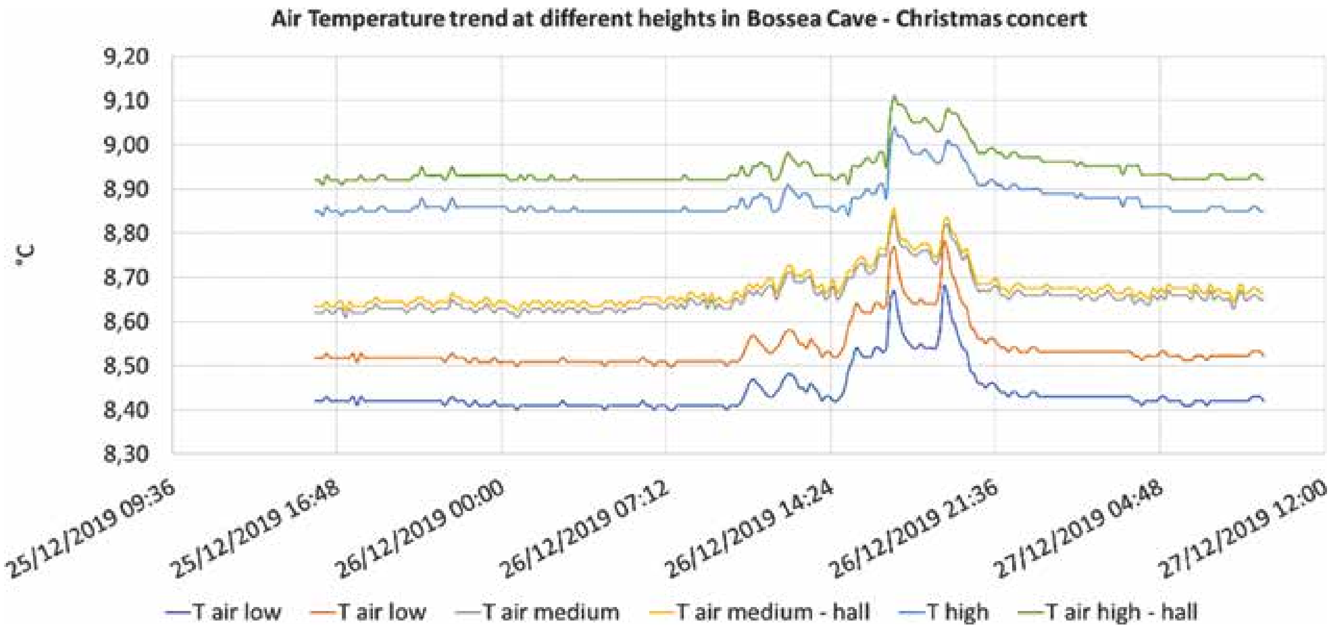

Fig. 3 – Air temperature trend in the central part of the Bossea Cave, at different heights, conditioned by tourist presence during Christmas concert.

4.2. Environmental parameters in Toirano Caves

The Toirano Caves have the entrances placed at an altitude difference of only 15 m. Therefore, this inlets altimetric difference favors an air circulation, slowed down by a series of doors placed at the entrances and in the artificial tunnel. However, these doors allow the passage of air through the crowning spaces between the walls and the artificial structures.

The temperature detectors, located at different heights and along the entire route, highlight the progressive heating of the air conditioned by the rock cluster T which is constant throughout the year. In the winter period the warm air inside the cavities (constant T around 15.6 °C) tends to come out from the entrance of Lower Santa Lucia Cave, consequently, a same volume of cold air enters from the Bàsura Cave. The surface air T heavily conditions underground circulation: in the winter period (especially at night) Lower Santa Lucia cave entrance have a T around 14.5 °C while Bàsura Cave entrance T values drop down to 8.6 °C (Fig. 4). The minimum surface air T value was reached on 14/02/2021 (-0.01 °C) while at the entrance of the Bàsura Cave there was a value of 4.5 °C and at the entrance of Lower Santa Lucia of 14.2 °C. A convective cell is present in the first part of Lower Santa Lucia Cave, characterized by a large tunnel with an evident stratification of the air.

The two CO_2 probes present in the Bàsura Cave show reduced carbon dioxide levels characterized by oscillations between 390 ppm and 500 ppm. These values seem to be mainly influenced by the natural circulation of incoming air flows, since the cavity is closed to the public now.

The groundwater circulation in the two cavities is very small and limited to droplets that usually increase only during particularly humid periods.

4.3. Environmental parameters in Borgio Verezzi Cave

On the basis of the new data acquired, the Borgio Verezzi Cave seem to be characterized by a particular genesis linked to the mixing of fresh water above the salt water of the saline wedge. The cave, located at a distance of only 550 m from the coast line, is made up of a large collapse hall that reaches an altitude of only 5 m a.s.l. where there are a series of freshwater lakes that seem to belong to an extended karst aquifer above sea salt water. Within three months of monitoring, the multiparametric probe positioned in the main reservoir (Gulliver Lake) showed a significant change in water levels related to precipitation and remarkable values of electrical conductivity and water temperatures constancy, emphasizing the presence of an important karst aquifer.

This cavity has a significant air circulation linked to the presence of three low entrances (tourist entrance, 32 m a.s.l, entrance of children, 34 m a.s.l, and paleontological entrance, 36 m a.s.l.). In the cold season these entrances aspire important volumes of air which quickly warm up circulating in the cavity (Fig. 5). A fourth entrance (British Entry, 36 m a.s.l.) acts as a high entrance that seems to expel only a small part of the incoming air. Evidently there are

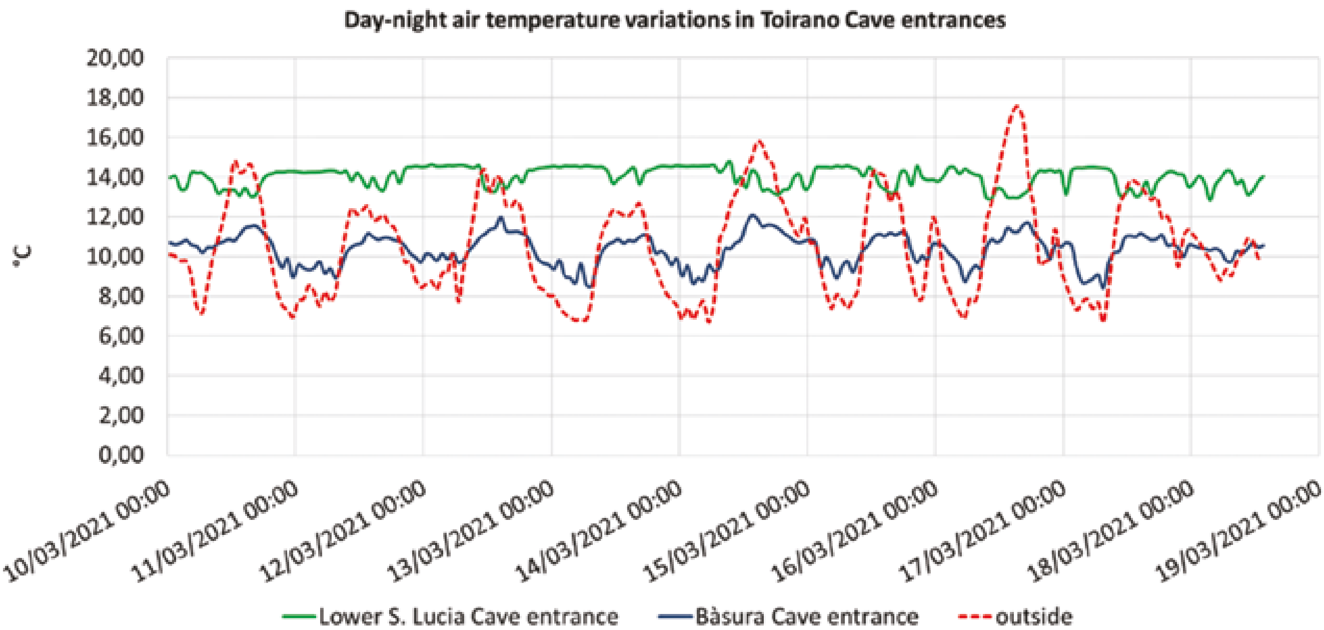

Fig. 4 – Daily air temperature trend outside the Bàsura Cave and at the Bàsura Cave and Lower Santa Lucia Cave entrances.

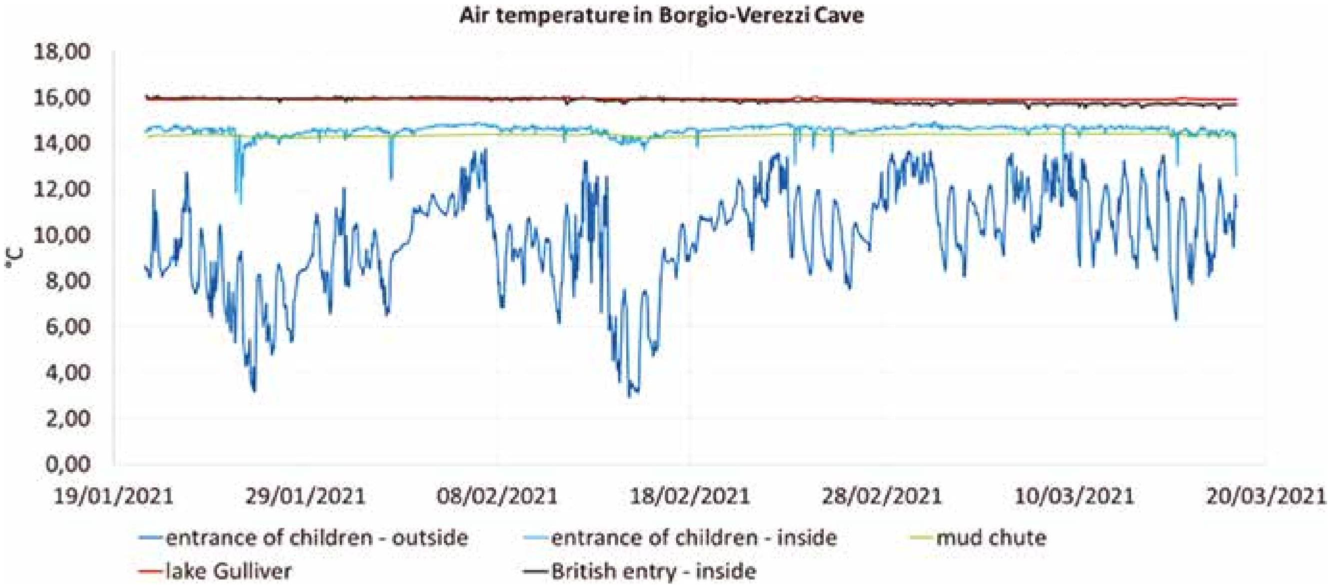

Fig. 5 – Progressive air heating in Borgio Verezzi Cave, from entrance of children (lower entrance) to inner parts of the cavity.

other outputs not yet identified to balance the total volumes circulating in the cavity.

The CO_2 concentration data are significant and characterized by clear multi-day fluctuations of values between 450 ppm and 650 ppm highlighting a singular contribution of natural origin (Fig. 6). These data well describe the environmental situation not affected by tourist use, being the cave closed for the entire monitoring period.

4.4. Geomatic surveys in Borgio Verezzi Cave

The Borgio Verezzi Cave was surveyed with the instruments and methods described in the paragraph 3.2. The external survey was done with a DJI Phantom4 drone flight with 396 frames, to obtain a transverse and across coverage greater than 80 %. The characteristics of the flight and the sensors are shown in Table 1.

With the dual frequency GNSS receiver on board the drone, the position of the projection centers of digital camera at the time of shooting were determined in RTK mode, with an accuracy of 1-2 cm (Teppati Losè *et al.*, 2020). It is theoretically possible to directly orient the photogrammetric block with only the coordinates of the projection centers but it is always better to use some GCPs to improve the accuracy and reliability of the solution (Casella & Franzini, 2016).

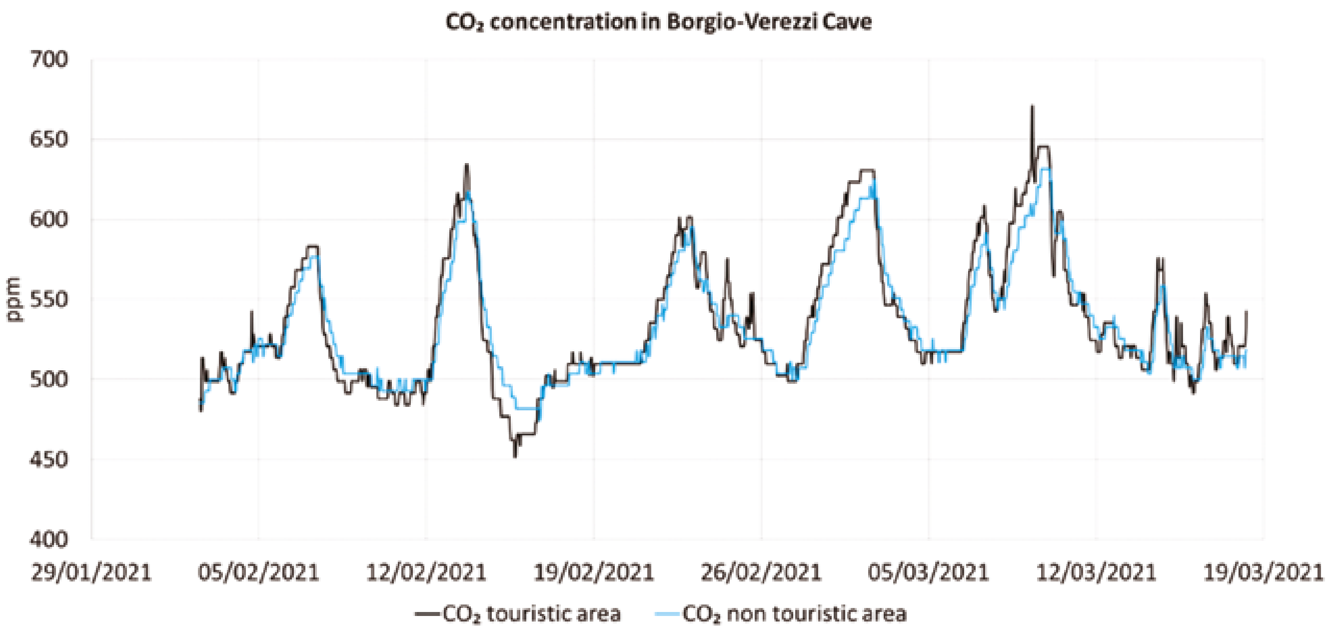

Fig. 6 – CO_2 air concentration trend in a touristic and non-touristic part of the Borgio Verezzi Cave.

Tab. 1 – Camera and flight parameter used in Borgio Verezzi Cave survey.

Camera	Sensor size and memory 1'': 20 M pixel
	Pixel size = 2.4 μm
	Principal distance = 8.8 mm (24 mm FF)
The fly	Relative height average on the ground = 50 m
	Average scale of photos = 1:5680
	Ground Sample Dimension of 1 pixel (GSD) = 1.4 cm
	Number of photos: 246
	Ground size of photos 90 m x 60 m
	Coverage: along track > 80%, across track 80%
Area Measured at ground RPAS	54'800 m^2 5 GCP (5 markers) DJI PH4 (Phantom 4 RTK)

Tab. 2 – Camera projection centers and GCP Errors.

	X error (cm)	Y error (cm)	Z error (cm)
Average Camera location error (396 camera projection center)	1.2	0.8	1.1
Estimated Gorund Control Point RMS (5 marker)	2.1	1.0	1.6

5 GCPs were detected, made with markers clearly visible on the frames and detected with GNSS RTK. The operations of alignment of the frames and compensation of the AT is done with the software AGISOFT Metashape. The residuals of the least square adjustment on the projection center of the digital camera and 5 GCP are a maximum of a couple of cm, consistent with the size of the GSD (Tab. 2).

From the orientation of the frames, estimated from the positions of the GCPs and the projection centers of camera, it is possible to derive cartographic products such as DSM with 3 cm resolution (Fig. 7) and orthophotos with 2 cm resolution (Notti *et al.*, 2021). The DSM refers to ellipsoidal heights: to obtain the orthometric heights, the undulation of the geoid must be subtracted. It can be estimated using the ITALGEO model to be 47.43 m, without appreciable differences in the area considered.

The internal survey of the cave is referred to a polygon of 18 points. This is the most delicate and important part of the survey, where precision is strongly conditioned by the length of the visuals between the collimation points. On views of only a few meters, as in the case of this cave, small centering and collimation errors on the signal strongly propagate the angular measurement error. The lack of an external "closing" ground control point does not allow to compensate for these errors. Figure 7 shows the polygon with 95% error ellipses, with an amplification factor = 100. The measurement of the differences in height was made with total station from the reciprocal stations. The accuracy (standard deviation 68%) obtained for the dimensions is a maximum of 1.3 cm on the last point of the polygon.

The polygonal allowed to georeference 15 scans performed with Lidar Polaris Optec, on the whole tourist route of the cave. The acquisition was made in short range mode since the distances generally

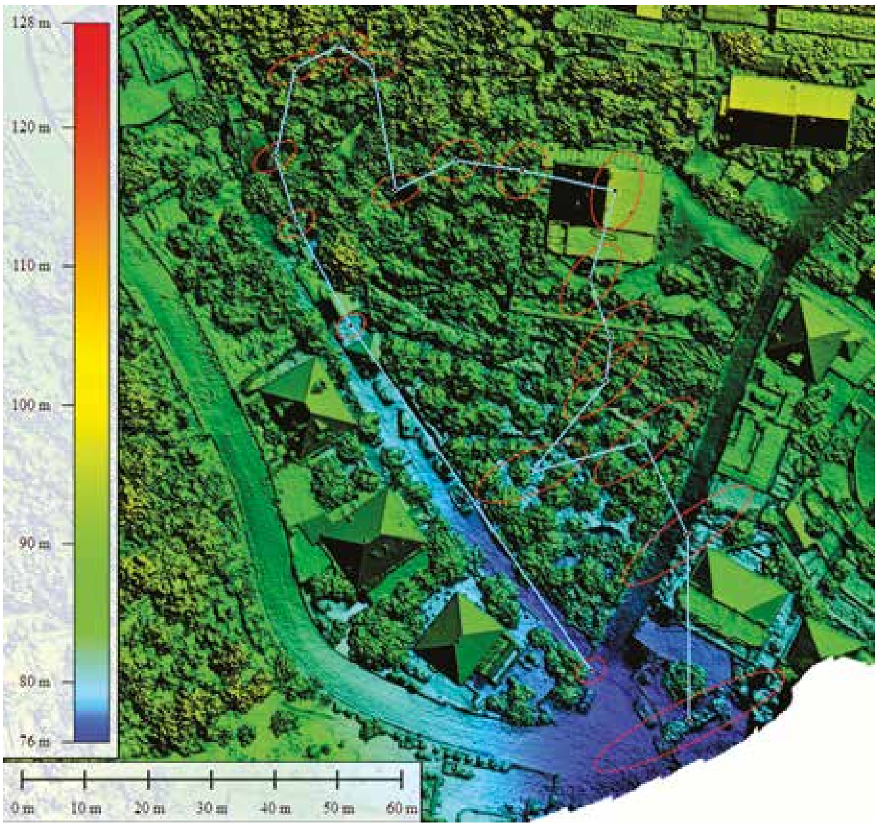

Fig. 7 – Ellipsoidal Digital Elevation Model (DEM resolution = 3 cm) and polygonal inside Borgio Verezzi cave with 95% error ellipses (ellipsis amplification factor = 100). Undulation of the Geoid = 47.43 m.

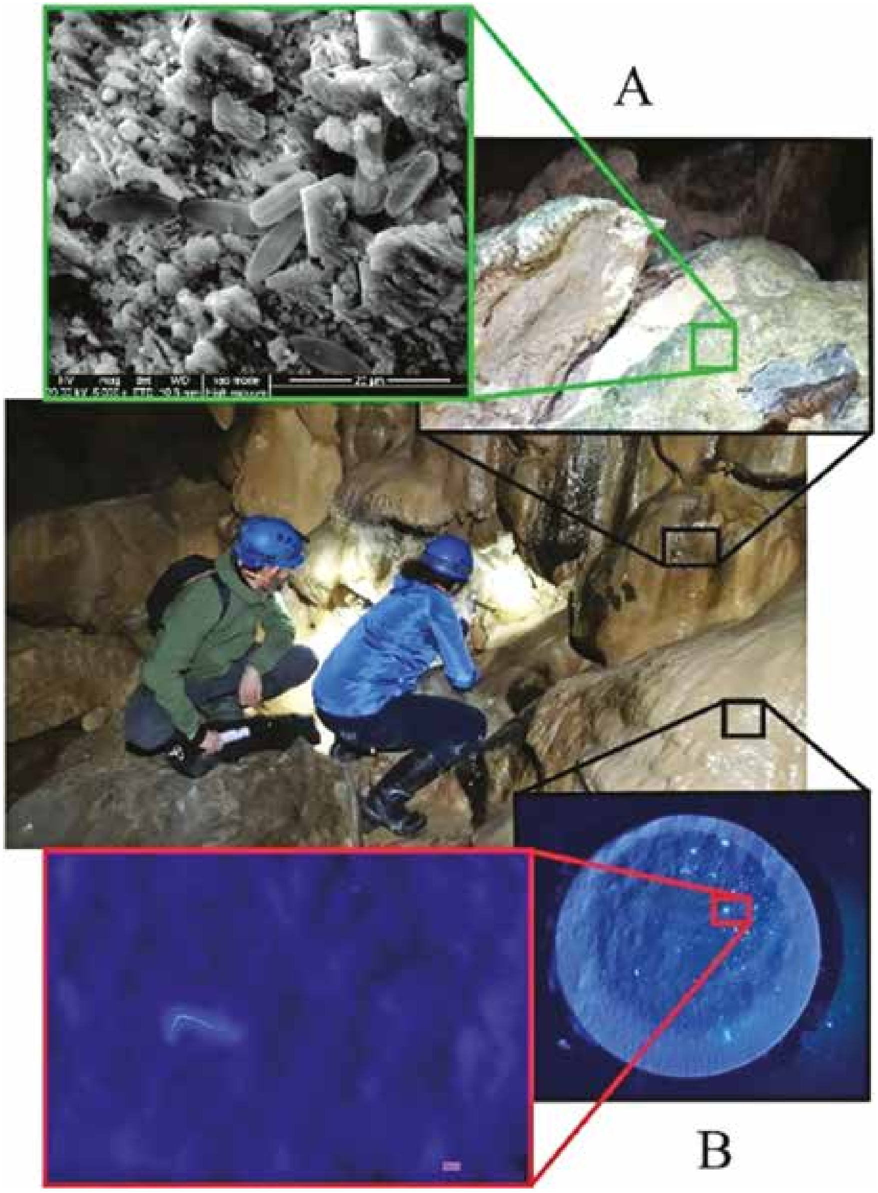

Fig. 8 – Bossea Cave in situ monitoring. A. Lampenflora on speleothem and SEM blow up of diatoms and lampenflora corrosion. B. Microplastic fibers analysis on filter, after sediment separation, and microscopic blow up under UV light.

did not exceed 50 m. The adopted resolution is 1 cm on 50m with acquisition time of about 10 minutes per station. The resolution of the scans allows not only the calculation of the volumes of the underground rooms but has sufficient detail for the observation of the speleothems. An external 24 MPx digital camera allows you to color the point cloud with higher quality than the internal camera of the instrument. The processing of LiDAR measurements is in progress.

4.5. Corrosion of speleothems

Evidences of CO_2 corrosion on different speleothems in all examined caves have been found as well as the presence of lampenflora near tourist paths and lights.

SEM analysis on speleothems samples with lampenflora have been done to better understand the level of corrosion on their shallows. Presence on diatoms has been detected on the speleothems with lampenflora alteration. (Fig. 8A). Environmental factors influencing the presence and the growth of lampenflora in Bossea Cave have been previously investigated (Piano *et al.*, 2015). First sampling in this cave has been made to estimate the alteration of speleothems by lampenflora in different part of tourist path. The micro samples will be analyzed by SEM, looking for an analytic method to quantify the decay and correlate it with the presence of Diatoms, Cyanobacteria and green algae in collaboration with DBios – Università di Torino.

Evident CO_2 corrosion damages on speleothems are present in the Toirano Caves and Borgio Verezzi Cave. These phenomena are linked to different processes as high CO_2 concentrations in the air or the presence of undersaturated water. These processes can be linked to natural origins but also visitors and lighting along tourist paths can cause significant increasing in air T and CO_2 concentration.

4.6. Microplastics pollution

MPs pollution has been observed both on sediments and on speleothems and in all examined caves. Different laboratory tests have been performed on cave sediments samples, in order to identify the correct method to separate MPs from cave sediments and quantify them (Balestra & Bellopede, 2021). To assess the presence of MPs, UV light has been used in situ and in lab simultaneously with visual identification (Fig. 8B). Advanced microscope techniques as Raman and FTIR microscopy (which, however, still need to be optimized, considering the complexity of the sample examined) have been used to confirm MPs presence and typology.

Visual identification and different photographic techniques, in association with different software have been used to count and measure MPs in cave sediments. After the validation of laboratory technique, the goal to apply the quantification of MPS in situ by means of proper photographic technique will be carried out.

5. Discussion and conclusions

The first results of the study related to the monitoring of the three cavities examined highlighted the environmental parameters (air temperatures and CO_2 concentration) variations, related to the air and groundwater circulation. Following the closure of the tourist caves for Covid pandemic, it was possible to acquire useful information on the natural environmental of the cave, without tourism influence (tourists and lights). Usually, these data are unfortunately not recorded in cave before public opening; however, they are essential to understand the following environmental tourist impact (Calaforra *et al.*, 2003; Cigna & Burri, 2000; Cigna & Forti, 2013).

Geomatic survey, yet started for Borgio Verezzi Cave, allowed to estimate the subjacency of the cave with the respect to the urbanized territory and to obtain a georeferenced survey of underground cave with a proper resolution.

The identification of altered speleothems is essential to link the in situ survey with the laboratory research. At microscope level the assessment of the CO_2 and lampenflora corrosion on speleothems and MPs pollution in cave sediment should be done with the aim to give back an indirect index of cave conditions and different indexes useful for cave management and protection.

The integrated use of environmental parameters monitoring, geomatic survey and laboratory analysis will define the proper methodology to assess the tourism impact and the threshold value to minimize pollution in caves and the speleothems decay, and to preserve natural heritage in show caves.

References

Antonellini, M., Nannoni, A., Vigna, B., De Waele, J., 2019. *Structural control on karst water circulation and speleogenesis in a lithological contact zone: The Bossea cave system (Western Alps, Italy)*. Geomorphology, 345, pp. 106832. https://doi.org/10.1016/j.geomorph.2019.07.019

Avanzini, M., Romano, M., Citton, P., Salvador, I., Arobba, D., Caramiello, R., Firpo, M., Rellini, I., Negrino, F., Clementi, L., 2018. *Icno-archeology of a human palaeolithic ecosystem: the human and animal footprints in the Grotta della Basura (Toirano, northern Italy)*. Alpine and Mediterranean Quaternary, 31, pp. 39-42. https://doi.org/10.26382/AIQUA.2018.AIQUAconference

Balestra, V., Bellopede, R., 2021. *Microplastic pollution in show cave sediments: First evidence and detection technique*. Environmental Pollution. pp. 118261.

Ballent, A., Corcoran, P. L., Madden, O., Helm, P.A., Longstaffe, F.J., 2016. *Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments*. Marine pollution bulletin, 110(1), pp. 385-395. https://doi.org/10.1016/j.marpolbul.2016.06.037

Baquedano Estevez, C., Moreno Merino, L., de la Losa Román, A., Duran Valsero, J.J., 2019. *The lampenflora in show caves and its treatment: an emerging ecological problem*. International Journal of Speleology, 48(3), pp. 4. https://doi.org/10.5038/1827-806X.48.3.2263

Blumenröder, J., Sechet, P., Kakkonen, J.E., Hartl, M.G., 2017. *Microplastic contamination of intertidal sediments of Scapa Flow, Orkney: a first assessment*. Marine pollution bulletin, 124(1), pp. 112-120. http://dx.doi.org/10.1016/j.marpolbul.2017.07.009

Breda, M., 2015. *The early Middle Pleistocene fallow deer Dama roberti: new insight on species morphology from a complete postcranial skeleton from Valdemino (northwestern Italy)*. Geological Journal, 50(3), pp. 257-270. https://doi.org/10.1002/gj.2624

Calaforra, J., Fernández-Cortés, A., Sánchez-Martos, F., Gisbert, J., Pulido-Bosch, A., 2003. *Environmental control for determining human impact and permanent visitor capacity in a potential show cave before tourist use*. Environmental Conservation, 30(2), pp. 160-167.

Casella, V., Franzini, M., 2016. *Modelling steep surfaces by various configurations of nadir and oblique photogrammetry*. ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences, 3(1). https://doi.org/10.5194/isprsannals-III-1-175-2016

Chang, S.J., Jeong, G.Y., Kim, S.J., 2008. *The origin of black carbon on speleothems in tourist caves in South Korea: Chemical characterization and source discrimination by radiocarbon measurement*. Atmospheric Environment, 42(8), pp. 1790-1800. https://doi.org/10.1016/j.atmosenv.2007.11.042

Chelius, M.K., Beresford, G., Horton, H., Quirk, M., Selby, G., Simpson, R.T., Horrocks, R., Moore, J.C., 2009. *Impacts of alterations of organic inputs on the bacterial community within the sediments of Wind Cave, South Dakota, USA*. International Journal of Speleology, 38(1), pp. 1-10.

Christman, A., 2019, Cave Dwelling Dust Bunnies: Lint Accumulation and Microplastics in Lewis and Clark Caverns State Park.

Cigna, A.A., 2016. *Tourism and show caves*. Zeitschrift für Geomorphologie, 60(Suppl 2), pp. 217-233. https://doi.org/10.1127/zfg_suppl/2016/00305

Cigna, A.A., Burri, E., 2000. *Development, management and economy of show caves*. International Journal of Speleology, 29(1), pp. 1.

Cigna, A.A., Forti, P., 2013. *Caves: the most important geotouristic feature* *in the world*. Tourism and Karst areas, 6(1), pp. 9-26.

Columbu, A., Audra, P., Gázquez, F., D'Angeli, I.M., Bigot, J.-Y., Koltai, G., Chiesa, R., Yu, T.-L., Hu, H.-M., Shen, C.-C., 2021. *Hypogenic speleogenesis, late stage epigenic overprinting and condensation-corrosion in a complex cave system in relation to landscape evolution (Toirano, Liguria, Italy)*. Geomorphology, 376, pp. 107561. https://doi.org/10.1016/j.geomorph.2020.107561

Cuevas-González, J., Fernández-Cortés, A., Muñoz-Cervera, M., Andreu, J., Cañaveras, J., 2010, *Influence of daily visiting regime in tourist cave at different seasons*, in: Springer (eds.), advances in research in karst media, pp. 475-481.

De Freitas, C.R., 2010. *The role and importance of cave microclimate in the sustainable use and management of show caves*. Acta carsologica, 39(3).

Dominguez-Villar, D., Fairchild, I.J., Carraasco, R.M., Pedraza, J., Baker, A., 2010. *The effect of visitors in a touristic cave and the resulting constraints on natural thermal conditions for palaeoclimate studies (Eagle Cave, central Spain)*. Acta Carsologica, 39(3).

Faimon, J., Štelcl, J., Sas, D., 2006. *Anthropogenic CO2-flux into cave atmosphere and its environmental impact: A case study in the Císařská Cave (Moravian Karst, Czech Republic)*. Science of the Total Environment, 369(1-3), pp. 231-245. https://doi.org/10.1016/j.scitotenv.2006.04.006

Fernandez-Cortes, A., Cuezva, S., Sanchez-Moral, S., Cañaveras, J.C., Porca, E., Jurado, V., Martin-Sanchez, P.M., Saiz-Jimenez, C., 2011. *Detection of human-induced environmental disturbances in a show cave*. Environmental Science and Pollution Research, 18(6), pp. 1037-1045. https://doi.org/10.1007/s11356-011-0513-5

Giacobini, G., D'Errico, F., 1985. *La fauna. Atti della tavola rotonda "La grotta preistorica della Basura". Toirano, 11-13 novembre 1983.* Rivista di Studi Liguri, 51, pp. 345-352.

Havlena, Z., 2019, Lighting and Substrate Effects on Lampenflora Microbial Communities in Carlsbad Cavern: New Mexico Institute of Mining and Technology.

Jablonsky, P., Kraemer, S., Yett, B., *Lint in caves*, in: Proceedings National Cave Management Symposium1993, Carlsbad, NM, pp. 73-81.

Kurniawan, I.D., Rahmadi, C., Ardi, T.E., Nasrullah, R., Willyanto, M.I., Setiabudi, A., 2018. *The impact of lampenflora on cave-dwelling Arthropods in Gunungsewu Karst, Java, Indonesia*. Biosaintifika: Journal of Biology & Biology Education, 10(2), pp. 275-283. https://doi.org/10.15294/biosaintifika.v10i2.13991

Lang, M., Faimon, J., Ek, C., 2015a. *A case study of anthropogenic impact on the CO2 levels in low-volume profile of the Balcarka Cave (Moravian Karst, Czech Republic)*. Acta Carsologica, 44(1), pp. 71-80.

Lang, M., Faimon, J., Ek, C., 2015b. *The relationship between carbon dioxide concentration and visitor numbers in the homothermic zone of the Balcarka Cave (Moravian Karst) during a period of limited ventilation*. International Journal of Speleology, 44(2), pp. 7. http://dx.doi.org/10.5038/1827-806X.44.2.6

Lang, M., Faimon, J., Pracný, P., Kejíková, S., 2017. *A show cave management: anthropogenic CO2 in atmosphere of Výpustek Cave (Moravian Karst, Czech Republic)*. Journal for nature conservation, 35, pp. 40-52. http://dx.doi.org/10.1016/j.jnc.2016.11.007

Lobo, H.A.S., Boggiani, P.C., Perinotto, J.A.d.J., 2014. *Speleoclimate dynamics in Santana Cave (PETAR, São Paulo State, Brazil): general characterization and implications for tourist management*. International Journal of Speleology, 44(1), pp. 6. http://dx.doi.org/10.5038/1827-806X.44.1.6

Martini, S., 2008. *Studio delle fasi minerali calcite e aragonite della grotta di santa lucia inferiore (Toirano, SV) e loro interpretazione nel quadro dell'evoluzione ambientale dell'ipogeo*, Toirano e la Grotta della Bàsura: Bordighera, p. 185-204.

Mathalon, A., Hill, P., 2014. *Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia*. Marine pollution bulletin, 81(1), pp. 69-79. http://dx.doi.org/10.1016/j.marpolbul.2014.02.018

Mulec, J., Kosi, G., 2009. *Lampenflora algae and methods of growth control*. Journal of cave and karst studies, 71(2), pp. 109-115.

Naji, A., Esmaili, Z., Mason, S.A., Vethaak, A.D., 2017. *The occurrence of microplastic contamination in littoral sediments of the Persian Gulf, Iran*. Environmental Science and pollution research, 24(25), pp. 20459-20468. https://doi.org/10.1007/s11356-017-9587-z

Notti, D., Giordan, D., Cina, A., Manzino, A., Maschio, P., Bendea, I.H., 2021. *Debris Flow and Rockslide Analysis with Advanced Photogrammetry Techniques Based on High-Resolution RPAS Data. Ponte Formazza Case Study (NW Alps)*. Remote Sensing, 13(9), pp. 1797. https://doi.org/10.3390/rs13091797

Peano, G., Fisanotti, G., 1994. *Valorisation et développement touristique de la" Grotta di Bossea"(Frabosa Soprana, Cuneo, Italie)*. International Journal of Speleology, 23(1), pp. 7.

Phuong, N.N., Poirier, L., Lagarde, F., Kamari, A., Zalouk-Vergnoux, A., 2018. *Microplastic abundance and characteristics in French Atlantic coastal sediments using a new extraction method*. Environmental Pollution, 243, pp. 228-237. https://doi.org/10.1016/j.envpol.2018.08.032

Piano, E., Bona, F., Falasco, E., La Morgia, V., Badino, G., Isaia, M., 2015. *Environmental drivers of phototrophic biofilms in an Alpine show cave (SW-Italian Alps)*. Science of the Total Environment, 536, pp. 1007-1018. https://doi.org/10.1002/gj.2624

Pulido-Bosch, A., Martin-Rosales, W., López-Chicano, M., Rodriguez-Navarro, C., Vallejos, A., 1997. *Human impact in a tourist karstic cave (Aracena, Spain)*. Environmental geology, 31(3), pp. 142-149.

Qiu, Q., Peng, J., Yu, X., Chen, F., Wang, J., Dong, F., 2015. *Occurrence of microplastics in the coastal marine environment: First observation on* *sediment of China*. Marine Pollution Bulletin, 98(1-2), pp. 274-280. http://dx.doi.org/10.1016/j.marpolbul.2015.07.028

Rellini, I., Firpo, M., Arobba, D., Starnini, E., Romano, M., Citton, P., Salvador, I., Negrino, F., Avanzini, M., Zunino, M., 2021. *Micromorphology and origin of an unusual bear fur-bearing deposit in Bàsura Cave (Toirano, NW Italy)*. Quaternary International. https://doi.org/10.1016/j.quaint.2021.05.025

Romano, M., Citton, P., Salvador, I., Arobba, D., Rellini, I., Firpo, M., Negrino, F., Zunino, M., Starnini, E., Avanzini, M., 2019. *A multidisciplinary approach to a unique Palaeolithic human ichnological record from Italy (Bàsura Cave)*. Elife, 8, pp. e45204. https://doi.org/10.7554/eLife.45204

Šebela, S., Miler, M., Skobe, S., Torkar, S., Zupančič, N., 2015. *Characterization of black deposits in karst caves, examples from Slovenia*. Facies, 61(2), pp. 6. https://doi.org/10.1007/s10347-015-0430-z

Šebela, S., Prelovšek, M., Turk, J., 2013. *Impact of peak period visits on the Postojna Cave (Slovenia) microclimate*. Theoretical and applied climatology, 111(1), pp. 51-64. https://doi.org/10.1007/s00704-012-0644-8

Singh, M., 2011. *Microclimatic condition in relation to conservation of cave no. 2 murals of Ajanta*. Current Science, pp. 89-94.

Teppati Losè, L., Chiabrando, F., Giulio Tonolo, F., 2020. *Are measured ground control points still required in UAV based large scale mapping? assessing the positional accuracy of an RTK multi-rotor platform*. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, pp. 507-514. https://doi.org/10.5194/isprs-archives-XLIII-B1-2020-507-2020

Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. *Microplastic pollution in deep-sea sediments*. Environmental pollution, 182, pp. 495-499. http://dx.doi.org/10.1016/j.envpol.2013.08.013

Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. *Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification*. Estuarine, Coastal and Shelf Science, 130, pp. 54-61. http://dx.doi.org/10.1016/j.ecss.2013.03.022

https://hxgnsmartnet.com/it-it/, Hexagon, geosystem division (accessed in 26-04-2021)

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Validation of numerical D.E.M. modelling of geogrid reinforced embankments for rockfall protection

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The adoption of reinforced embankments for rockfall and landslide protection purposes is an effective intervention for the reduction of risk and damages to civil facilities. These earth structures are manufactured with layers of compacted soil alternated with geosynthetics (e.g. geogrids and geotextiles) that are anchored to the outer quarterdeck frame or wrapped around it. This paper discusses the results obtained with a numerical simulation of the reinforced embankment carried out by means of a distinct element commercial (D.E.M.) code as particle code (P.F.C.). Several types of rock impacts on an embankment were simulated, varying block speeds, energies and geometrical impact conditions. Data from practical experiences of the authors and data from full-scale impact tests gathered from relevant literature, were used for the validation of the model. The main result of the work is the development of design operative suggestions that can support the selection of the design parameters of an embankment for rockfall protection purposes: its preliminary size based on impact energy level and induced damages can be outlined. The results of this provide guidance to designers and relevant stakeholders in the evaluation of risk scenarios arising from potential rock falls on infrastructures.
Keywords: *reinforced embankment, rockfall, risk reduction, geogrids, D.E.M. modelling.*

Validazione di modellazione numerica D.E.M. di rilevati rinforzati con geogriglie per protezione da caduta massi. *L'impiego di rilevati rinforzati per la protezione dai fenomeni franosi e di caduta massi costituisce una efficace opzione per la riduzione del rischio e dei danni alle strutture civili. Queste opere in terra sono generalmente costituite da strati di materiale sciolto alternato con geosintetici (quali geogriglie o geotessili), i quali sono ancorati al parti di gabbie metalliche del paramento oppure risvoltate attorno ai corsi sovrapposti. Questo articolo propone i risultati ottenuti da una modellazione del rilevato sviluppata attraverso un codice commerciale agli elementi distinti (D.E.M.) di tipo particellare (P.F.C.). Diversi tipi di impatti sono stati simulati, variando la velocità dei blocchi, le energie e le condizioni geometriche di impatto. Dai dati derivanti da strutture reali esaminate direttamente dagli autori e da quelli presenti in letteratura tecnica in merito a prove di impatto in vera grandezza, si è potuto procedere a una calibrazione del modello numerico. Il principale risultato dello studio consiste nello sviluppo di indicazioni operative che possono agevolare la scelta dei parametri di progetto di un rilevato rinforzato con scopi di protezione passiva: il predimensionamento basato sui livelli energetici di impatto e i danni indotti dallo stesso sono quindi esplicitati. I risultati costituiscono un ausilio progettuale e di verifica per gli addetti alla valutazione degli scenari di rischio derivanti da eventi potenziali di caduta mi massi sulle infrastrutture.*
Parole chiave: *rilevato rinforzato, caduta massi, riduzione del rischio, geogriglie, modellazione D.E.M.*

1. Introduction

Earth reinforced embankments are extensively used in several engineering applications. The reinforcement is aimed at increasing the structural performances of compacted soil embankments in terms of strength, stiffness, and durability (Oggeri, 2011).

Different kinds of reinforcement elements are currently commercially available. In the case of reinforced embankment for rockfall protection, geogrids, geotextiles or metallic elements are adopted, usually embedded as horizontal layers within the soil structure (Figure 1). These structures are designed for absorbing repeated impacts at high energy levels (> 5000 kJ). The adoption of reinforcing elements can allow the reduction of the embankment size, which is advantageous in complex situations like mountainside locations, where usually limited space is available. When geogrid reinforced embankments are subjected to an impact, the structure receives and redistributes the load following a non-linear behaviour. Part of the kinetic energy transmitted by the impact is dissipated through the yielding and the relative sliding between geogrids and soil layers.

A fundamental parameter that drives the behaviour of the structure is the interaction between the geogrids and the soil. This interaction depends on the shear strength available at the soil/mesh interface, on the shear strength of the soil and on the additional strength supplied by the transverse elements of the geogrids.

Different approaches have been developed in order to understand the behaviour of a rockfall embankment during the impact of a rock block, mainly analytical methods, numerical models with different codes, and full scale tests. This latter represents the more reliable approach for the acceptance of the design, but due to the time and

Fig. 1 – Example of a huge earth reinforced embankment, extended parallel the mountainside, for road and houses rockfall protection. Viewpoint is downward: in the uphill wall geogrids and lateral wire mesh adopted for the construction are still visible. Additional protective works against surface runoff have been done by means of local rock fragments and wood element for environmental sustainability (credits, structural testing and approval by C.Oggeri, Northern Italy).

the costs required for setting up the test, usually only a limited set of experiments can be realistically carried out. Analytical approaches have been developed in the literature, but the complexity of the system (mechanical and physical properties of the materials, impact variables and kinetic effects) does not allow good estimations of impact forces and block penetration (Lambert *et al*. 2013).

Numerical modelling has the clear advantage of allowing the analysis of a wider range of parameters at reasonable time and costs, and can therefore provide meaningful preliminary guidance and design charts for assessing the effects of several design parameters. However, the simplifications implicitly included in the numerical modelling might lead to results that deviate from the reality, and experimental validation is required (Brinkgreve and Engin, 2013). Due to the number of parameters affecting the behaviour of the structure in the event of a rock impact, the available literature on numerical modelling validation is still disperse and fragmentary.

This paper discusses the results obtained with numerical models carried out with the Itasca PFC2D (2-dimension Particle flow code), version 3.0 (Potyondy, 2015). The embankment behaviour under impact was simulated and geogrid deformation, as well as and soil compaction, were observed and commented.

Numerical models were calibrated on full-scale test results and the outcomes were compared with results available in the literature and applied to real construction site (Figure 1). The validation exercise confirmed the reliability of the proposed design tool. The results discussed in this paper also represent a contribution to the debated issue of determining the required input parameters for reliable design and modelling of embankment for rockfall protection, as discussed by Agliardi *et al.* (2009).

2. Background

Many Authors have carried out researches and testing since the early 90's: full scale tests have been carried out to understand the behaviour of reinforced embankments subjected to distributed and point forces. These tests highlighted the range of variation of the kinetic energy released during typical impacts and allowed to interpret the behaviour of this type of structure in a qualitative way. After these experiences, both analytical and numerical approaches have been developed, also in the stream of Eurocodes requirements.

2.1. Relevant references

Burroughs *et al.* (1993) studied the behaviour of a geosynthetic reinforced embankment with vertical walls. Blocks of different weight (190 ÷ 8170 kg) and pseudo cubical size were dropped against the embankment. After rolling, the impact energy values were ranging between 8 and 1500 kJ with a velocity of about 5.5 ÷ 19.2 m/s. The recorded penetration and extrusions on the embankment were about 90 cm and 70 cm on the two opposite embankment faces respectively.

Hearn *et al.* (1995) tested three rockfall embankment prototypes made of compacted granular soil, using non-woven geotextile bags wrapped around the walls (which were covered with wood panels). Tests allowed the assessment of the amount of kinetic energy released by the impact that led to the collapse of the structure, and therefore of the critical size of impacting blocks. Yoshida (1999) and Nomura *et al.* (2002) studied the effect of the impact of different blocks against an embankment, whose core was made of horizontal layers reinforced with geosynthetic materials, whilst the impact side was made of two layers of sand bags. The tests were aimed to verify the behaviour of soft and deformable soil. The penetration values were 2.6 ÷ 30 cm, under an impact energy ranging from 60 to 2700 kJ.

Plassiard *et al.* (2008) assessed the shear strength on the soil/reinforcement interface by means of a distinct element simulation of independent soil layers and embedded reinforcing elements. Plassiard and Donzé (2010) studied the shape of the embankment in order to optimise the structure design. Their main conclusion was that the geometry is the key factor in establishing the dissipative capacity, whereas the filling material properties are less relevant. Lambert *et al.* (2009) investigated the role of a surface reinforcement with filled geocells in order to homogenise the overall stress distribution after impact. Lambert and Bourrier (2013) proposed a comprehensive review of current embankment design, in which achievements and limitations for a proper design were pointed out. The impact of a boulder, whose typical velocity ranges from 5 to 30 m/s and for which the mass is limited to tens of thousands of kilograms, results in a dynamic localised stress whose duration is generally less than 0.2 s, thus generating a strain velocity rate in the direction of the impact. Various mechanisms are involved during the impact: compressive wave propagation in a finite volume, soil compaction, friction and crushing of granular particles leading to plastic deformation and large displacements of the embankment, etc. The related effects vary drastically in space and time while depending on the embankment size and geometry as well as on the properties of adopted materials. For these reasons, the analytical models that have been developed to date fail to give good representation of the impact effects on the embankment (Lambert *et al.* 2013).

Cellular rockfall protection embankments were also proposed, with the advantage of adapting the properties of the filling material to the cell position in the structure. Different types of filling materials were tested with the aim of optimizing the behaviour of structure under the impact. Numerical modelling was also carried out to simulate the behaviour of the structure at different scales, from material to full structure (Lambert *et al.* 2014).

Recent contributions have been given on modelling the effects of geosynthetic contacts with reinforcing mesh (Bertrand *et al.*, 2008), investigating the interaction between geogrid and ballast using the discrete element method (Fellerec *et al.*, 2012), and on experimental and numerical methods for the study of soil–geosynthetic interaction (Palmeira, 2009). The load transfer behaviour between geogrid elements and sand was tested and modelled with PFC code providing a detail of the mechanism at a microscopic scale (Wang *et al.*, 2014). The modelling of geocells using 3D finite difference software was used to investigate the load distribution and the interface behaviour of the reinforcement (Hegde *et al.*, 2015). Bourrier *et al.* (2011) investigated a multiscale approach, for studying the dynamic impact on embankment. Vieira *et al.* (2013) characterised the soil-geotextile interface through direct shear tests. Results from physical model studies carried out on reinforced soil walls compacted in different ways are reported in Ehrlich *et al.* (2012), whilst large-scale plane-strain compression tests were carried out on loose and dense sand using four types of geogrids as described in Liua *et al.* (2014). Eventually, Villard *et al.* (2009) and by Li *et al.* (2015) investigated earth reinforced structures under dynamic loading by comparing results from different numerical approaches and physical testing.

Cuomo *et al.* (2019) modelled barriers conceived as a multilayered embankment, reinforced by geogrids wrapped around the facing. In this work both static and dynamic stress–strain analyses have been performed through a FEM code (Plaxis v. 8.5) to simulate the deformation mechanisms and the ultimate limit states. Within the obtained results, the displacement of the reinforced layers along the geogrids with an acceptable performance of the whole barrier have been emphasized.

Relevant evidences from full scale tests were reported in the works carried out by the Politecnico of Torino research group at the Meano test site about two decades ago (extensively cited and in origin developed with reinforcing systems described in Peila *et al.* 2002, Oggeri *et al.* 2004, Peila *et al.* 2007, Ronco *et al.* 2009 and Ronco *et al.* 2010), where a cableway able to drop blocks with a ballistic trajectory was set up. Four series of tests were carried out, varying the embankment reinforcement features, the mechanical characteristics of the fill, and the impact energy.

Lambert and Kister (2018) published a useful summary of the relationship between the block kinetic energy and the displacement of the downhill side of the embankment, obtained by collecting available data from real size tests.

2.2. Interpretation of literature data

While results can be found in the published cited works, a brief summary of test setup and outcomes is presented hereafter, having the results from those tests been used for the validation of the numerical simulation presented in this paper.

Worked case. Step 1): The embankment had the following geometrical features: height 4.2 m; base width 5 m, side inclination referring to the horizontal 67°. The reinforcement was made of high-density polyethylene extruded geogrids with unit weight 350 g/m^2 and tensile strength 50 kN/m. The backfilling was made of coarse and well graded soil, mainly composed of gravel and sand with a silt fraction, with friction angle ϕ = 34° ÷ 36°, cohesion c = 8 ÷ 12 kPa and unit weight γ = 19.0 ÷ 20.5 kN/m^3.

Step 2): The impact tests were carried out by dropping a concrete block with a certain initial speed against the embankment. Different blocks were used, thus obtaining different levels of kinetic energy from impact. Typical block mass was in the order of 3000 ÷ 5000 kg and impact speed was in the range of 28 ÷ 30 m/s.

In order to observe the progressive damage of the structure, multiple impacts were also performed. Typically, the structure was able to absorb at least 2-3 impacts before collapsing or becoming unsuitable for standing further impacts. The block impacting the upper part, where the embankment had a thickness of about 1.2 m, created a footprint with a maximum depth of 0.6 m (measured at right angles to the face), while the extrusion on the opposite downstream side was of about 0.17 m. No relevant geometric changes in the shape were observed outside the area directly affected by the impact, whilst a tension crack was formed in the backfilling soil along the layer affected directly by the impact, with a maximum opening of 140 mm. A plastic deformation of the geogrid was also observed. Cracks or yielding strain are common in reinforced embankments for different geosynthetics (Figure 2).

Step 3): A series of tests was carried out where the geometry of the embankment was kept constant and the impact kinetic energy was gradually increased, in order to assess the ultimate strength condition of the structure.The embankment showed a failure of the reinforcements and extended yielding of the fill after two consecutive impacts characterised by a kinetic energy of at least 4200 kJ.

Fig. 2 – Typical tension cracks formed inside the disassembled body of the embankment: on the left woven geogrids elongated in collapsed earth support structure; on the right extruded geogrid elongated after the impact of the block in a protection embankment. Same graphical scale. (credits personal archive C.Oggeri).

Step 4): In order to assess the contribution of the reinforcement, an unreinforced embankment, i.e. made of compacted soil only, was built with the same geometry and maintaining the kinetic energy equal to 4200 kJ, as for the previous test. The embankment collapsed after the first impact, even though the block was still stopped.

3. Preliminary F.E.M. and new D.E.M. numerical models

DEM and FEM represent two different modes for discretization, both valid. Advantage of FEM is the comprehensive definition of material properties, for DEM the possibility to better follow kinematics. Disadvantages in FEM is the lack of stability for large displacements, for DEM the computational limits in particle size reduction.

3.1 Preliminary F.E.M. modelling

An extensive and original numerical modelling of reinforced embankment was developed by Ronco (2010, unpublished) as a design tool. The model was developed with Abaqus/Explicit code (which is a F.E.M. model) in the dynamic field, running stress-strain analyses related to dynamic changes in parameters. Obtained results were verified against the Eurocode prescriptions for the optimisation of the design parameters. The simulation allowed to assess the relationship between the impact energy and the block penetration/extrusion when the geometrical features of the embankment and the impact point were varied. Results from the numerical simulation with Abaqus code were used as a base for the validation of the numerical simulation method proposed in this paper.

The F.E.M. numerical approach was developed in three phases:

1) The back-analysis of dynamic compaction tests performed on compacted soils, for the assessment of the mechanical and physical input parameters.
2) The study of the behaviour of the reinforced and unreinforced embankments under the impact of blocks.
3) The analysis of the behaviour of the reinforcing elements during impact within the embankment.

The embankments layers were modelled as independent elements, according to the actual construction procedure. The boundary conditions for the model were represented by a rigid bond for the base layer. The Drucker-Prager yield criterion was adopted and appropriate strength parameters were assessed after the preliminary phases. The impacting block was simulated as a rigid element with a regular shape (Figure 3, left and right). Drucker-Prager is a good choice as it if fitting pressure acting problems and it is well implemented in the code settings.

Lateral diffusion in a consequence of the impact and it develops also in static. Construction features drive the shape and the extension of this parameter, and also the local kinematic and reaction: homogeneous filling, strata separation, type of interface (contact or interlocking), scale effect between stratum and block, compaction level of filling (dilatant or contracting behavior) are all factors that can modify the expected results.

The modelled results compared well to the penetration/extrusion values along the two embankment sides, which were measured during full-scale tests. The modelling was then developed considering four types of embankments with different geometries. The impact kinetic energy was also increased until collapse of the embankments, represented by the condition of a deformed shape of the layers which are no longer self-supporting.

Results in terms of block penetration and extrusion distances for the two opposite walls of the embankments, taking into account parameters such as the impact energy and the ratio of the embankment thickness and elevation in correspondence to the impact point (sp/h), are shown in Figure 4 left. When the ratio sp/h ratio was increased, a reduction of the critical impact energy was observed for the ultimate state of the embankment, see Figure 4 right (Oggeri, 2011).

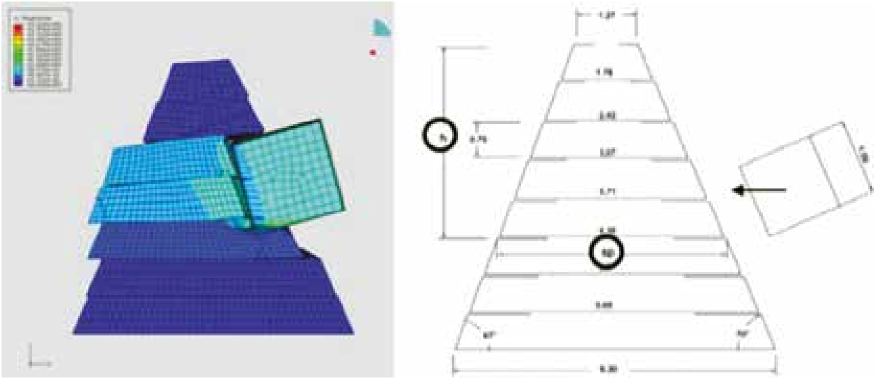

Fig. 3 – Left: Embankment model with the Abaqus/Explicit code (Ronco, 2010, unpublished). Right: Embankment scheme, with the indication of "*h*" and "*sp*" geometric parameters and ideal position of block at impact.

3.2 New D.E.M. modelling and calibration

In order to understand the behaviour under impact, and the displacement measured uphill and downhill, it is useful to have a precise scheme of the design and of the materials adopted during the construction. A sector of embankment has been built for experimental site validation of operative behaviour, following requirements and testing operated by the Authors. New modelling has been done by means of internal computational resources (code) provided by C.Oggeri academic funds, and compared with the behavior of an embankment on a real construction site followed by C.Oggeri for professional expertise (Figure 1).

Controls on the soil parameters during construction, on the geosynthetic installation and on the obtained compaction are of great influence because these aspects are essential in order to avoid excessive scattering of expected adsorbed energy at impact: e.g., stiffness of each soil stratum is measured by means of a plate loading test.

Itasca PFC2D is a distinct element method, where the elements are modelled as spherical particles

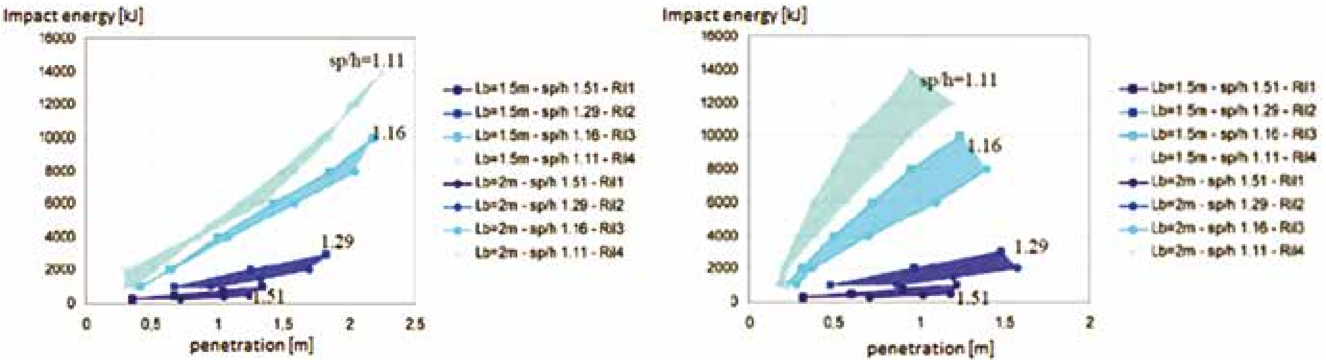

Fig. 4 – Penetration on the uphill wall (left) and bulging on the downhill wall (right) for different values of the impact energy and sp/h ratio. Results were obtained from the F.E.M. numerical modelling of impacts with 1.5 and 2 m wide cubic blocks.

able to move and interact according to their physical and mechanical properties, interface properties and acting force field. These spheres can represent the granular nature of the ground and can simulate the deformation of soil as a result of a stress variation. Each element is described by its intrinsic properties (stiffness, density, radius, velocity and friction) and by contact properties.

The modelled embankment is composed of seven layers. Each layer is built inside a formwork that contains the granular backfilling compacted during the embankment construction. A layer of geosynthetic is then added and anchored at both ends. Each layer interacts with the neighbour elements. Layers can absorb the kinetic energy of the impacting block through two main mechanisms: (a) the soil compaction beneath and around the block impact area, and (b) the sliding of a layer in respect with the neighbour layers.

The main components of the embankment are represented by the external formwork (usually a stiff steel wire mesh), the granular soil, the reinforcement element (a geogrid in this case), which is represented as a chain of connected elements, and the block, which is simulated with solid spheres with high connection strength.

The code elaborates the initial condition, during which gravity (or other field stress state) and material properties are applied. Appropriate initial conditions can be determined by applying external forces, removing boundaries or elements in certain regions, or changing some of the physical and mechanical properties of the elements. The aim of this simulation was to study the effects of an impact originating from a block hitting the reinforced embankment. An initial speed was applied to the block with a defined mass in order to obtain the desired impact energy. The code ran on a cyclic basis, by recalculating the position and forces of the elements at each iteration, until a convergence state was reached. The main output was the stress state and the arrangement of the elements, including the failure of the overloaded ones, at the end of each cycle. Among physical and mechanical properties to be determined, a particular attention was required for the contact properties, i.e. "contact bond" properties. These are defined in the code by the normal strength *n_bond* (which is equivalent to the real tensile strength between the particles) and the shear strength *s_bond* (which is equivalent to the dilatancy that develops between two sliding particles). Contact conditions control the slipping mechanisms between the spheres (preventing or modulating them). The deformation of the model is calculated according to the parameters assigned to the interfaces where the spheres physically interact, as each singular sphere is infinitely stiff (i.e. it cannot deform).

The main model parameters of the constituents are listed in Table 1.

The soil used as filling material was modelled as cohesionless and it is characterised by a friction angle of 35°. In order to take into account the presence of fine soil particles, a suitable contact bond was adopted among the soil particles for achieving convergence of a high number of elements within an acceptable time. The compaction of the soil was simulated through a sequence of drops under gravity stress field, until the desired porosity (n = 12÷16 %) was obtained.

The geogrid was simulated with an alignment of spheres, whose initial position was defined by a code function. In order to account for the flexibility of the geogrid and the roughness of the soil underneath, the bond between the spheres was defined with parallel bond contact only. The friction coefficient for the soil – geogrid interface was assumed equal to 0.46, according to previous work (Ronco *et al.*, 2009). Calibration of geogrid was done simply by simulating a pull out test by using stress strain curve of the geogrid and applying an external force. A further reduction factor of 0.65 applied to the friction coefficient was included for the full scale model. Reduction factor is linked to the physical interface working mode: each geotextile has its own way to interact with different soils and compaction. Palmeira (2009) and Wang *et al.* (2014) have widely studied this key factor and it is reported on available textbooks. Value of 0.65 is reasonable for the worked model. Eventually, the upper end of all the formworks was anchored to the relevant geogrid, in order to avoid an immediate pull-out failure during the impact. The anchoring was simulated by a contact bond between the adjacent spheres of formwork and geogrid

Tab. 1 – Main parameters used in the model.

Component	Unit weight [kg/m^3]	Sphere diameter [m]	Normal stiffness [N/m]	Shear stiffness [N/m]	Normal parallel/contact bond [N/m]	Shear parallel/contact bond [N/m]
Soil	2000	0.02;0.04	$0.8x10^5$	$0.8x10^5$	-	-
Wire mesh	3000	0.04	$0.3x10^6$	$0.3x10^6$	$45x10^3$	$36x10^3$
Geogrid	1000	0.04	$0.3x10^6$	$0.3x10^6$	$50x10^3$	$7.5x10^3$

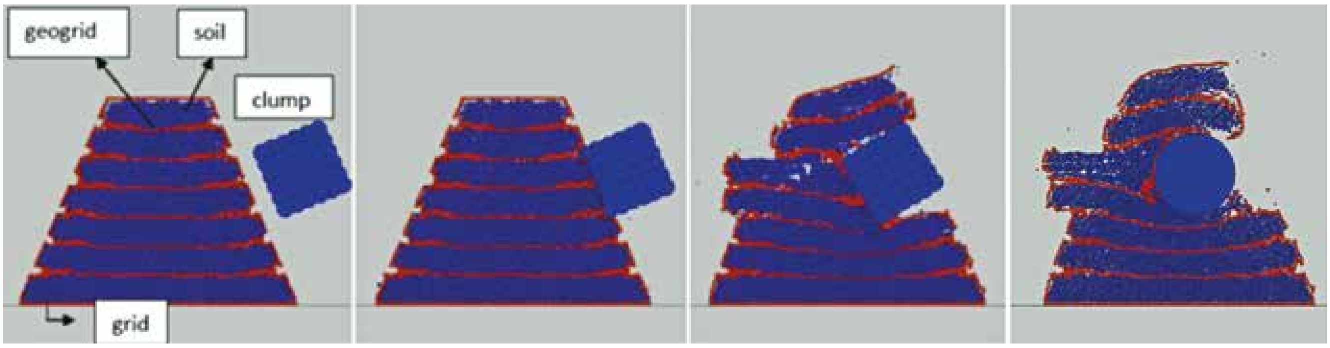

Fig. 5 – Impact modelling with PFC2D, for cubic (left) and spherical (right) blocks. Foot prints from models are embedding the block shape.

respectively, assigning the same strength properties as the geogrid.

The impacting block was simulated with a "clump", i.e. a rigid body with deformable boundaries, with a velocity vector applied to the centre of the block mass (Figure 5).

The impact of a 1.17 m wide cubic block, with a mass of 5000 kg was simulated. The block landed on the fifth and sixth layers of the embankment with a velocity of about 31 m/s. When assuming an overall stiffness of $0.3x10^3$ N/m, the penetration of the block into the upstream wall (measured orthogonally to the face) was 0.7 m, while the maximum bulging off the downstream wall was 0.17 m. The results obtained by the model matched those measured in the cited full scale tests with a satisfactory precision (Ronco *et al.*, 2010).

3.3. Parametric analysis with the calibrated model

After the calibration analysis, further impact conditions were modelled. Thanks to the fine dimension of discrete elements simulated with the model, it was possible to observe the behaviour of the reinforcing elements and soil fill, even in the case of the formation of tension cracks. A close agreement with the results obtained with the previous numerical modelling carried out with Abaqus code was observed. Table 2 summarises the obtained results.

For all cases, energy at impact has been verified with fine scanning of video frames for velocity detection. The scope of the various model types is to recognise separately the effects of each main input parameter (mass, velocity, shape) on the final behaviour of the embankment under impact, in terms of wall displacements. Parametric modelling has examined eight different conditions: effects of block velocity, effects of increased block velocity, effect of increased block mass, effect of increased velocity and block mass, effect of increased velocity, effect on unreinforced soil, effect of the change of block shape to a sphere, effect of the different discretisation of modelled soil.

4. Discussion

The non-homogeneous behaviour of the embankment can be attributed to its layered structure and to the stress distribution after the impact, which is concentrated on a limited surface of the structure.

The kinetic energy is dissipated within the layers by the mechanisms of reciprocal layer sliding and of soil rearrangement, this latter inducing soil plasticisation and compaction. Spherical failure surfaces are often observed under the block on unreinforced embankment, while geogrid levels in a reinforced embankment can control the deformation process.

The relationship between the impact kinetic energy and the calculated displacement is shown in Figure 6. When the impact is applied in the same point on the embankment, a linear trend of the displacements vs. energy data points can be observed.

It was observed that, keeping the impact energy constant, an increased weight of the block resulted in higher damage of the embankment. This outcome should be considered in the general evaluation of performance capabilities

Tab. 2 – Impact conditions and deformation outputs from D.E.M. modelling.

Block shape	Mass [kg]	Impact kinetic energy [kJ]	Impact velocity [m/s]	Uphill penetration [m]	Downhill sliding [m]
cubic	8700	1000	15.2	0.42	0.22
cubic	8700	4000	30.3	1.00	0.50
cubic	20000	1000	10.0	0.80	0.40
cubic	20000	3000	20.0	1.15	0.90
cubic	20000	9000	30.0	2.40	1.80
spherical	8700	8000	42.9	2.40	1.00

of embankments when evaluating the "reference block" in the design stage. However, this behaviour is less important for larger widths of the embankment, due to the inertia of the structure.

The increase in impact energy resulted in upstream penetration values slightly higher than the corresponding downstream sliding movements, due to the compaction of the soil beneath the block developing on the impact side and not on the opposite wall.

When comparing the block shapes (spherical or cubic), it can be observed that: a) layer sliding on the downstream wall was not influenced by the shape of the block; b) the same kinetic energy and impact velocity led to a deeper footprint of the block in case of spherical shape impact; c) the embankment reached the limit state condition for lower impact energy, since a sphere impact involves a greater volume of soil in the collision. This outcome was already observed by the Abaqus model simulation (Ronco, 2010, unpublished).

As far as the adoption of different sphere diameters for modelling the soil is concerned, it was observed that, with the applied refinement, the specific surface area of the spheres was increased. Consequently, it was necessary to reduce the corresponding "fictitious" cohesion of the soil in order to obtain similar deformation values, as the structure response was stiffer in the refined model. This result is in agreement with the expected effect of a well graded grain size distribution of the soil (i.e. porosity reduction and compaction increase).

Geogrid deformation was evaluated at the interfaces between sliding layers as a rupture of the anchoring points. As the model spherical elements cannot deform, the strain is simulated as an increase in the space between the elements. In this way, it is possible to consider the stress/strain relationship of the geogrid, which is fundamental for appreciating the performance of the structure. Spheres modelling the geogrid, even though no longer physically in contact, were able to maintain their alignment and connections until the failure of the structure. This condition is represented in the model by the creation of separate alignments. If several contacts fail, a random dispersion of spheres occurs.

5. Conclusions

A numerical model of geogrid reinforced structures for rockfall protection was set up after a consistent back analysis of both full scale tests and new on site evidences on worked structures. After an initial F.E.M. modelling approach carried out by the Authors, a new code has been adopted to compare and assess the available results and in order to apply it at a new construction site. Both modelling activities allowed for the prediction of the performances of different embankment geometries, under different impact conditions and with the adoption of different reinforcements.

The D.E.M. modelling approach described in this paper is based on the application of Itasca PFC2D. The obtained results compared well with the old F.E.M. modelling with Abaqus.

The output of the code consists of graphical diagrams in which displacements and damage (failures, tension cracks) can be highlighted. As these are among the most important concerns of rockfall protection devices, the PFC2D modelling can be considered satisfactory. Since the embankment is a linear structure, the two-dimensional approach is relevant. The effects of different block mass, kinetic energy, and block geometry were assessed on a model of reinforced embankment. A model simulating the impact on unreinforced embankment was also developed for comparison purposes.

The main outcomes from this research were the following.

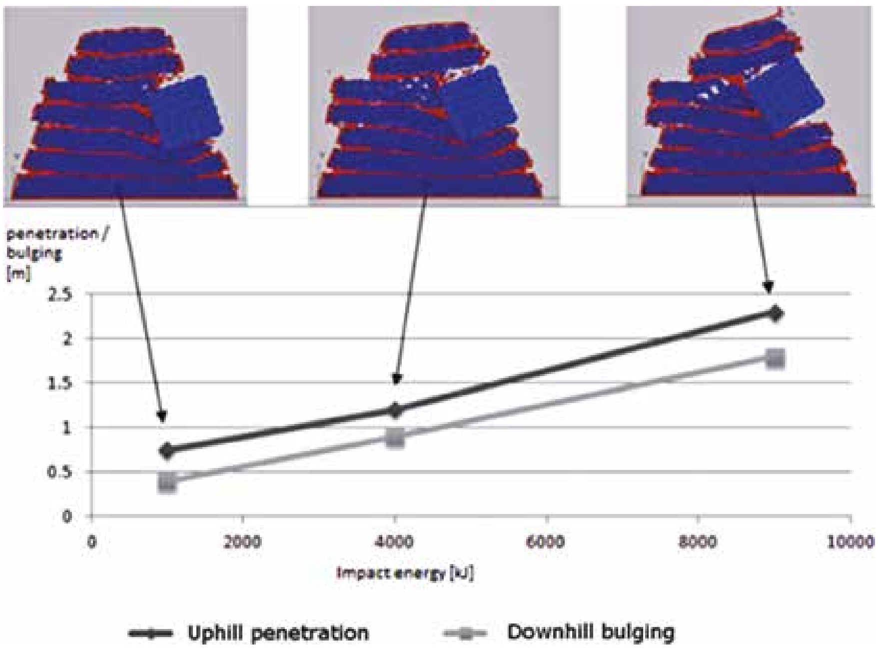

Fig. 6 – Calculated D.E.M. wall displacement of the reinforced embankment.

a) The relationship between the impact kinetic energy and the calculated displacement followed a linear trend.
b) The mass of the block had an influence on the displacement development: a bigger block showed a higher deformation on the embankment than a smaller block with the same kinetic energy.
c) The shape of the block had an influence on the displacement development as well. Spherical blocks caused higher deformation in the embankment than cubic blocks with the same kinetic energy.
d) 2D model is exhibiting a challenging displacement because it is focusing on planar strain, as geometrical model of the embankment is claiming for.
e) The size and the number of the model elements, i.e. the "ball" dimension, had an effect on the stiffness of the structure. Higher fineness of elements (i.e. smaller and more graded soil particles) led to reduced deformation when the fictitious cohesion was kept the same utilised for coarser model. This effect reflects the different porosity and compaction level that can be reached with better graded grain distribution.

Possible adaptation of the model includes a more accurate soil simulation by using small spheres characterised by different diameters, while the adoption of a three dimensional code would be useful for the understanding of the local behaviour of the geogrids, which work as a 3D reinforcing structure, and for assessing the geogrid – soil interaction more accurately, through an analysis of the interlocking phenomenon of the soil grains inside the mesh. The last step, at a practical design level, consists of the analytical verification of structural details and geometrical compatibility.

References

Agliardi, F., Crosta, G.B., Frattini, P., 2009. *Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques*. Natural Hazards and Earth System Sciences, 9(4), 1059.

Bertrand, D., Nicot, F., Gotteland, P., Lambert, S., 2008. *Discrete element method (DEM) numerical modeling of double-twisted hexagonal mesh*. Canadian Geotechnical Journal.

Bourrier, F., Lambert, S., Heymann, A., Gotteland, P., Nicot, F., 2011. *How multi-scale approaches can benefit cellular structure design*. Canadian Geotechnical Journal.

Brinkgreve, R.B.J., Engin, E., 2013. *Validation of geotechnical finite element analysis*. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

Burroughs, D.K., Henson, H.H., Jiang, S.S., 1993. *Full scale geotextile rock barrier wall testing, analysis and prediction.* Proceeding Conference Geosynthetics, Vancouver 1993, 959-970.

Cuomo, S., Moretti, S., Frigo, L., Aversa, S., 2020. *Deformation mechanisms of deformable geosynthetics-reinforced barriers (DGRB) impacted by debris avalanches.* Bulletin of Engineering Geology and the Environment.

Ehrlich, M., Mirmoradia, S.H., Saramago, R.P., 2012. *Evaluation of the effect of compaction on the behaviour of geosynthetic – reinforced soil walls*. Geotextiles and Geomembranes, vol. 34, Oct. 2012, pp. 108-115.

Ferellec, J.-F., McDowell, G.R., 2012. *Modelling of ballast–geogrid interaction using the discrete-element method*. Geosynthetics International, Vol.19 Issue 6, Dec. 2012, pp. 470-479.

Hearn, G., Barrett, R.K., Henson, H.H.,1995. *Testing and modelling of two rockfall barriers*, Transportation research record n° 1504, National Research Council, Washington DC, 1995.

Hegde, A., Sitharam, T.G., 2015. *3-Dimensional numerical modelling of geocell reinforced sand beds.* Geotextiles and Geomembranes, Volume 43, Issue 2, April 2015, pag. 171-181.

Heymann, A., 2012. *Approche expérimentale du comportement mécanique des géo-ouvrages à technologie cellulaire. Application aux ouvrages pare-blocs*. (Doctoral dissertation). University Joseph Fourier, Grenoble (in French).

Lambert, S., Gotteland, P., Nicot, F., 2009. *Experimental study of the impact response of geocells as components of rockfall protection embankments*. Natural Hazards and Earth System Sciences, 9, 459-467.

Lambert, S., Bourrier, F., 2013. *Design of rockfall protection embankments: a review*. Engineering Geology 154, 77-88.

Lambert, S., Heymann, A., Gotteland, P., Nicot, F., 2014. *Real-scale investigation of the kinematic response of a rockfall protection embankment*. Natural Hazards Earth Systems Sciences.

Lambert, S., Kister, B., 2018. *Efficiency assessment of existing rockfall protection embankments based on an impact strength criterion*. Engineering Geology 243, 2018, 1-9.

Li, M., Yu, H., Wang, J., Xia, X., Chen, J., 2015. *A multiscale coupling approach between discrete element method and finite difference method for dynamic analysis*. International Journal Numerical Method in Engineering. 102:1-21.

Liua, C.N., Yang, K.H., Nguyenc, M.D., 2014. *Behaviour of geogrid–reinforced sand and effect of reinforcement anchorage in large-scale plane strain compression*. Geotextiles and Geomembranes, Vol. 42, Issue 5, October 2014, pp. 479-493.

Maegawa, K., Tajima, T., Yokota T.and Tohda, M., 2011. *Slope-rockfall tests on wall embankments reinforced with geosynthetics.* In Proceedings of the 6th International Structural Engineering and Construction Conference, Zürich, Switzerland (pp. 641-646).

Nomura, T., Inoue, S., Fuchigami, M., Yokota, Y., Kubo, T., Tatta, N., Arai, K., 2002. *Experimental research of reinforced soil wall for rock-fall protection*. Proceedings 7th International conference on geosynthetics, 303-308.

Oggeri, C., Peila, D., Recalcati, P., 2004. *Rilevati paramassi*. In Proceedings Convegno Bonifica di versanti rocciosi per la protezione del territorio, GEAM, pp. 191-232 (In Italian).

Oggeri, C., 2011. *Impact features on reinforced embankments used for rockfall protection on the base of Eurocodes and national technical law*. Proceedings. Rocexs2011, Interdisciplinary Rockfall Workshop 18 May 2011, Innsbruck-Igls.

Palmeira, E.M., 2009. *Soil – geosynthetic interaction: Modelling and analysis*. Geotextiles and Geomembranes, vol. 27, Issue 5, Oct. 2009, p. 368-390.

Peila, D., Oggeri, C., Castiglia, C., Recalcati, P., Rimoldi, P., 2002. *Testing and modelling geogrid reinforced soil embankment to high energy rock impact*. Proceedings of 7th I.C.G.International Conference on Geosynthetics, Nice, 133-136.

Peila, D., Oggeri, C., Castiglia, C., 2007. *Ground reinforced embankments for rockfall protection: design and evaluation of full scale tests*. Landslides, Springer Verlag, Vol. 4, ISSN: 1612-510X.

Plassiard, J.P., Donzé, F.V., Lorentz, J., 2008. *Simulations of rockfall impacts on embankments using a discrete element method*. Proceedings of Interdisciplinary Workshop on Rockfall Protection, 84-86.

Plassiard, J.P., Donzé, F.V., 2010. *Optimizing the design of rockfall embankments with a discrete element method*. Engineering Structures, 3817-3826.

Potyondy, D.O. 2015. *The Bonded-Particle Model as a Tool for Rock Mechanics Research and Application: Current Trends and Future Directions*. Geosystem Engineering, 18 (1), 1-28.

Ronco, C., 2010. *I rilevati in terra rinforzata utilizzati per la protezione dei versanti: verifiche numeriche e analitiche di supporto alla progettazione*. Doctoral dissertation, DIATI Politecnico of Torino (in Italian).

Ronco, C., Oggeri, C., Peila, D., 2009. *Design of reinforced ground embankment used for rockfall protection.* Natural Hazards Earth Systems Sciences, 9, 1189-1199.

Ronco, C., Oggeri, C., Peila, D., Bertolo, P., Ferraiolo, F., Giacchetti, G., 2010. *Numerical modeling of ground reinforced embankments used for rockfall protection*. In Advances in Geomaterials and Structures, 3rd Euro-Mediterranean Symposium on Advances in Geomaterials and Structures, Djerba, 269-276.

Vieira, C.S., Lopes, M.L., Caldeira, L.M., 2013. *Sand-geotextile interface characterisation through monotonic and cyclic direct shear tests*. Geosynthetics International, Vol. 20 Issue 1, Feb. 2013, pp. 26-38.

Villard, P., Chevalier, B., Le Hello, B., Combe, G., 2009. *Coupling between finite and discrete element methods for the modelling of earth structures reinforced by geosynthetic*. Computer Geotechnics. DOI:10.1016/j.compgeo.2008.11.005.

Yoshida, H., 1999. *Recent experimental studies on rockfall control in Japan*. Proceedings. Joint Japan-Swiss Scientific Seminar on Impact load by rock fall and design of protection structures, 69-78.

Wang, Z., Jacobs, F., Ziegler, M., 2014. *Visualization of load transfer behaviour between geogrid and sand using PFC2D*. Geotextiles and Geomembranes, vol. 42, Issue 2, Apr. 2014, pp. 83-90.

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Urban sustainability: the role of ecosystem services provided by an italian green infrastructure

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Current population growth, climate change and the increase in derived pollution represent a significant threat to the delicate balance that governs the exploitation of resources on Earth. In recent decades, this balance has been undermined, coming to an over-exploitation condition, or a growing demand for natural raw materials that the planet is no longer able to satisfy, with impacting consequences on human well-being and the health of natural ecosystems. Cities represent the main collectors of such reactions: it is necessary to analyze which mitigation actions can be the best in order to counter their uncontrolled development. This work focuses on a specific tool aimed at achieving the goal: green infrastructures constitute a valid source of sustainability in the urban environment, slowing down the processes derived from climate change and intensifying the recovery of ecological functions. Specifically, the role of the "Le Vallere" park was analyzed, a green area of about 35 hectares that is part of the metropolitan context of the Municipality of Turin, in collaboration with the related management institution ("Ente di gestione delle Aree Protette del Po piemontese", ex "Ente di gestione delle aree del Po torinese"). The main purpose was to quantify the ecosystem services offered by the green infrastructure to the surrounding urban area, through the use of i-Tree, a specific software suite able to evaluate benefits offered by vegetation. Reduction of atmospheric pollutants, carbon storage and sequestration, avoided surface water runoff, improvement of water quality are the main aspects investigated, obtaining an estimate of these parameters also from a monetary point of view. The survey carried out has, therefore, made it possible to obtain an assessment of the sustainability produced by the infrastructure, providing essential information to the related management institution, in view of a future territorial planning.
Keywords: green infrastructure, ecosystem services, urban scale.

Sostenibilità urbana: il ruolo dei servizi ecosistemici forniti da un'infrastruttura verde italiana. *L'attuale crescita della popolazione, il cambiamento climatico e l'aumento dell'inquinamento atmosferico rappresentano una sensibile minaccia al delicato equilibrio che governa lo sfruttamento delle risorse sulla Terra. Negli ultimi decenni, tale equilibrio è stato minato, tanto da poter parlare di sovra-sfruttamento, ovvero una crescente domanda di materie prime naturali che il Pianeta non è più in grado di soddisfare, comportando conseguenze impattanti sul benessere umano e sulla salute degli ecosistemi naturali. Le città rappresentano i principali collettori di tali reazioni: risulta necessario, dunque, analizzare quali azioni di mitigazione possano risultare efficaci al fine di contrastare il loro sviluppo incontrollato. Il presente lavoro si concentra su uno specifico strumento volto al raggiungimento dell'obiettivo: le infrastrutture verdi costituiscono una valida fonte di sostenibilità in ambito urbano, rallentando i processi derivati dai cambiamenti climatici e intensificando il recupero delle funzionalità ecologiche. In modo specifico, si è analizzato il ruolo del parco "Le Vallere", un'area verde di circa 35 ettari che si inserisce all'interno del contesto metropolitano del Comune di Torino, in collaborazione con l'Ente di gestione delle Aree Protette del Po piemontese (ex Ente di gestione delle Aree Protette del Po torinese). Lo scopo principale è stato quello di quantificare i servizi ecosistemici offerti dall'infrastruttura verde all'area urbana circostante, attraverso l'utilizzo di i-Tree, una suite di programmi specifici per la valutazione dei benefici offerti dalla vegetazione. Riduzione di inquinanti atmosferici, stoccaggio e sequestro di carbonio, deflusso idrico superficiale evitato, miglioramento della qualità idrica sono i principali aspetti approfonditi, ottenendo una stima di tali parametri anche da un punto di vista monetario. L'indagine ha consentito di realizzare una valutazione integrata della sostenibilità che l'infrastruttura fornisce all'ambiente circostante, fornendo informazioni fondamentali all'ente suddetto che si occupa della sua gestione, in funzione di una futura pianificazione territoriale.*
Parole chiave: infrastruttura verde, servizi ecosistemici, scala urbana.

1. Introduction

The current population growth, climate change and the consequent increase in pollution levels raise a series of questions related to both human health and the state of natural and man-made ecosystems. The exploitation of resources has now become over-exploitation, an unsustainable demand for natural raw materials that determines a condition of global deficit, so that the Global Footprint Network currently estimates a use equal to 1,75 times the size of the Earth (W1). This is calculated through the ecological footprint of the various countries of the world and measured in equivalent hectares of productive land necessary to supply demand and absorb the waste generated.

Unfortunately, the consequences of this consumption model are not only the impoverishment of the environmental matrix, but also its damage due to various phenomena: (i) decrease in the ozone layer, (ii) loss of integrity of the biosphere, (iii) chemical pollution, (iv) climate change, (v) ocean acidification, (vi) freshwater consumption and global water cycle, (vii) land use, (viii) nitrogen and phosphorus flows in the biosphere and in the oceans, (ix) atmospheric aerosol load (W2).

In response to the progressive elimination of the role of the environment from economic considerations, both as recipient of damage and as a source of irreplaceable wealth, the Ecosystem Services

(ES) model was introduced in the 1970s; the quantification of Ecosystem Services, i.e. the benefits that an ecosystem (natural or man-made) provides and which are directly or indirectly linked to well-being and to the quality of human life, appears particularly important (de Groot *et al.*, 2012). From a first pedagogical purpose aimed at underlining the risks represented by the loss of biodiversity, the ES have become a fundamental political and economic tool (Gómez-Baggethun and Martín-López, 2015). This turning point, which took place at the beginning of the new millennium, was marked in particular by the Millennium Ecosystem Assessment (MA), an international research carried out from 2001 to 2005 in order to identify the state of global ecosystems, assess the consequences of changes in ecosystems on human well-being and provide a scientific basis for formulation of actions necessary for conservation and sustainable use (Reid *et al.*, 2005). MA states that: "Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions. For simplicity, we will refer to ecosystem goods and services together as ecosystem services" (Costanza *et al.*, 1997). The MA, together with the literature subsequently developed (Brauman *et al.*, 2007), has identified four categories of services: (i) supply, i.e. consumer goods that can be directly taken from ecosystems such as food, raw materials, fresh water, (ii) regulation: linked to the regulation of the hydrological cycle, climate and hydrogeological instability, (iii) cultural, related to the intangible benefits offered as inspiration for art, music, architecture and, finally (iv) support, necessary for the realization of all other services (creation of soil, support for reproduction).

In the broad panorama just outlined (Montoya-Tangarife *et al.*, 2017), the present work focuses on the urban environment and on the Ecosystem Services related to land use (land use changes in urban residential areas) and water (the mitigation of damage caused by flood events and the containment of pollutant concentrations in surface, sub-surface and groundwater flows). Nowadays urban environments and ecosystems have particular importance due to global demographic changes: the percentage of the population living in urban areas is 55% globally and is projected to increase to 68% by 2050 (W3). This trend of increasing urbanization is visible with respect to all continents, expect for Oceania. In particular, in Italy there was an increase in its percentage from 51% to 71% since 1950 to today. The urban environment is also peculiar from an environmental point of view as, unlike other systems, it is a "functionally incomplete ecosystem", defined by the consumption of ES and by the presence of human beings and their activities (Reid *et al.*, 2005). By virtue of the strong exploitation of the ES, cities represent a major source of ecological pressures that cause changes to the entire earth's ecosystem through resource consumption, greenhouse gas emissions and pollution (Hodson and Marvin, 2010). According to the IPCC (Intergovernmental Panel on Climate Change), cities consume 67% to 76% of global energy and generate about three quarters of global carbon emissions (IPCC, 2014).

To achieve the sustainability of urban areas, a deeper understanding of the relationships with ecosystems, although mainly anthropogenic in nature, is necessary; in particular a study of ES, not derived from the outside but obtained from ecosystems within the wide context of cities, could be instrumental in emphasizing the relationship that man has with these functions: in this sense, urban green infrastructures offer a possibility of study. Nevertheless, in the area of scientific studies, a lack of sufficient research in the field of urban ecology is reported: on a quantitative level, an analysis of the literature in 2014 reported only 217 publications relating to UES (Urban Ecosystem Services), mainly carried out in North America, Europe and China (Haase *et al.*, 2014). Similarly, Caprioli *et al.* (2020) focused the gap in research on urban-type ecosystems compared to others, such as wetlands or forests. In light of these considerations, many authors underlined the importance of broadening the study of cities as ecosystems and as a cause of changes to ecosystems themselves, in order to guarantee urban ecological safety (Hodson and Marvin, 2010; Solecki *et al.*, 2013, McDonnell, 2015; Jennings *et al.*, 2017).

In particular, urban parks are important repositories of urban biodiversity and supplier of UES. The latter are certainly secondary to those obtained from global ecosystems, but offer various educational, moral and practical advantages thanks to their local nature, and allow to better evaluate the direct benefits obtained by the community and to improve cities, integrating ecological considerations into their design (Bolund and Hunhammar, 1999). Furthermore, the type of ES and the quantity of their supply are strongly influenced by the context in which the parks themselves are located and by community use, especially as regards the cultural ES. These can be negatively impacted by a general neglect or dirt of the places, and by the culture of the population in terms of values represented by green areas. Bolund and Hunhammar (1999) highlight how the size of the park is an important factor: larger parks generally offer more regulation services while smaller parks offer more cultural services.

The aim of this work is to highlight the enormous potential of a green infrastructure located in the suburbs of Turin, “Le Vallere” park, justifying numerically (and monetarily) the multiple benefits that the area silently generates on the surrounding city environment, through a recently developed tool, little used in Europe. At the Italian level, few *i-Tree* applications have been implemented and, more generally, scientific research in Italy has so far devoted little attention to the issue of quantifying ecosystem services.

This scientific article is divided into several chapters: chapter 2, called Methodology, contains a presentation of the two *i-Tree* tools (*Eco* and *Hydro*) implemented in the project, with the related equations; chapter 3 presents a description of the considered green area and of the main input data entered into the programs; in chapter 4 the main results obtained are reported and explained, through tables and figures; finally, chapter 5 reports the conclusions drawn from the work carried out, emphasizing the importance of results but also the future developments of the project; in chapter 6 and 7, thanks to the institutions involved in the project and the bibliography of the article are respectively reported.

2. Methodology

A complete assessment of ecosystem services can be based on various tools: interviews with inhabitants of the neighborhood, on-site inventories of vegetation but, above all, the use of specific softwares. In the following case study, a quantitative analysis of the environmental benefits generating by “Le Vallere” Park has been carried out, through a specific SE assessment tool for vegetation. The suite *i-Tree* is a collection of analysis and assessment tools designed and developed by the United States Forest Service, part of United States Department of Agriculture (USDA), to quantify the ES provided by a green area (i.e. street-lined, park, neighborhood, city or whole region). The choice fell on this software, born in the current century, although there are several tools, more popular and born earlier, designed to carry out a SE evaluation; the reason is related to the specificity of *i-Tree* on vegetation, with an appropriate approach to the purpose of this work.

The project is particularly focused on *Eco* and *Hydro* functionality, two flagship tools of *i-Tree* supported by *Database* and *Canopy* respectively. While *Hydro*, based on urban hydrology model, allows to simulate the effects of changes in tree cover at the urban level on local hydrology, *Eco* provides information on the urban green structure and its environmental effects (Treeconomics and Trädkonsult, 2019). Both tools base the ES assessment on the collection (and often on-site retrieval) of different types of data: geographic location information, topographic data, precipitation time series, species information, pollution data, hydrological parameters and more.

2.1. i-Tree Eco

Table 1 provides a summary of the main input data required and output that the program is able to furnish. Regarding the input data, they vary according to the size of the studied area: for small areas, a “complete inventory” methodology is applied, through a precise inventory of tree species and shrubs, defining land use and cover. On the other hand, the analysis of larger areas can be carried out through a statistical sampling of the parameters and characteristics, that is called “plot-based sample inventory”.

The purpose of *i-Tree Eco* is to analyze and quantify the benefits offered by the green area to the context in which it is located, in terms of CO_2 storage and sequestration, atmospheric pollutants removal, Volatile Organic Compounds (VOC) emissions and avoided water runoff. The precision with which these outputs are provided by the program depends, in turn, on the quantity and quality of the input data, many of which are not necessarily mandatory and which require a site inspection for their retrieval. The monetary evaluation associated with each ecosystem service allows to estimate an overall impact value of the area and derives from the definition, in the input phase, of unitary benefit prices, as shown in Table 1. For each category considered (electricity, eating, carbon and avoided runoff) an unitary benefit price is defined: *Eco* includes default values, linked to an average condition in US but the user can enter their own, relatively to the place where such analysis is carried out.

Eco is based on a mathematical model, validated by countless experiments and with which the tool has been programmed: the Urban Forest Effects (UFORE) model. It allows to monitor urban forest structure and to estimate its ES, using a random sampling technique, with known standard deviation, integrating local environmental data such as pollutant concentration and hourly meteorological data to return estimates of the aforementioned outputs. The greater the knowledge of the forest structure, the greater the accuracy of the benefits estimate.

Five modules make it up: (i)

Tab. I – Summary of *i-Tree Eco* (a) input and (b) output data.

(a) Input		(b) Output
Weather station	CO_2, NO_2, O_3, SO_2, PM 2.5 concentration [ppm] PAR [W/m^2] Rainfall [cm/h] Temperature [°C]	Dry deposition of pollutants per canopy cover unit [g/m^2/h] DBH distribution: - Leaf area [ac] - Leaf biomass [ton] VOC [lb/yr]: - Monoterpene - Isoprene
Inventory	Specie DBH Land Use/Ground Cover Tree Height/Height to crown base Tree crown dimension and condition Crown light exposure GPS coordinates	Stored carbon [ton] Gross sequestered carbon/Equivalent in CO_2 [ton/yr] Potential evapotranspiration, Evaporation, Transpiration, Intercepted rainfall [m^3/yr] Monetary values [€]: - stored carbon - gross sequestered carbon - avoided runoff - pollutants removal
Benefit prices	Electricity [€/kWh] Eating [€/therm] Carbon [€/ton] Avoided runoff [€/m^3]	

UFORE-A: Anatomy of the Urban Forest; (ii) UFORE-B: Biogenic Volatile Organic Compound (VOC) Emissions; (iii) UFORE-C: Carbon Storage and Sequestration; (iv) UFORE-D: Dry Deposition of Air Pollution; (v) UFORE-E: Energy Conservation (Nowak, 2008).

Nowak (1996) states "Accurate estimates of tree leaf area and leaf biomass in both urban and surrounding natural areas are critical in assessing evapotranspiration, atmospheric deposition, biogenic volatile organic emissions, light interception, and other ecosystem processes". On this principle UFORE-A, fundamental model for the implementation of a *Eco* project, is based trough the Equations (1) and (2). These regression equations were produced to calculate total leaf area and total leaf dry-weight biomass of "open-grown urban trees" (Nowak, 1996): Eq. 1 is a function of the DBH (Diameter at Breast Height) while Eq. 2 varies according to the height (H) and width (D) of the crown.

$$\ln(Y) = b_0 - b_1 \cdot DBH + b_2 \cdot S \qquad (1)$$

$$\ln(Y) = b_0 - b_1 \cdot H + b_2 \cdot D + b_3 \cdot S + b_4 \cdot C \qquad (2)$$

where Y is leaf area (m^2) or leaf dry-weight biomass (g); b_0, b_1, b_2, b_3, b_4 are regression coefficients; S is a species-specific shading factor defined as the percentage of light intensity intercepted by the canopy of trees; C is the canopy external surface (Gacka-Grzesikiewicz, 1980) calculated as:

$$C = \pi \cdot D(h + D))/2 \qquad (3)$$

A further important variable for the *Eco* simulations is the leaf area index (LAI)

$$\mathrm{LAI} = -\ln (I/(I_0)/k \qquad (4)$$

where I is the light intensity under the canopy while I_0 is the light intensity above it; k is the light extinction coefficient (0.52 for conifers, 0.65 for hard woods). The ratio between I and I_0 represents the shading factor. The LAI is a dimensionless index that represents the leaf area (m^2) per surface unit (m^2) and that is defined on the basis of Beer-Lambert law (Nowak, 1996).

The parameter on which UFORE-D is based, fundamental for the analysis carried out, is the flow of atmospheric pollutants removed (g/m^2/s^1), (Hirabayashi *et al.*, 2011).

$$\mathrm{F} = V_d \cdot C \qquad (5)$$

where V_d is the deposition rate (m/s) and C is the pollutant air concentration (g/m^3). The deposition rate for CO, NO_2, SO_2 and O_3 is calculated as the reciprocal of the sum of resistances to pollutant transport (s/m), (Baldocchi *et al.*, 1987).

$$V_d = 1/(R_a + R_b + R_c) \qquad (6)$$

where R_a is the aerodynamics resistance, that is the resistance opposed by the air to the passage of the pollutant molecules; R_b the quasi-laminar layer resistance, or the resistance encountered by the particles at the air-leaf interface surface; R_c is the canopy resistance, or rather the resistance opposed by the plant tissues and the stomal openings. In Baldocchi *et al.* (1987) an insight into how these three resistance types can be calculated is present.

2.2. *i-Tree Hydro*

As mentioned at the beginning of the chapter, *i-Tree Hydro* is a flagship tool based on urban hydrology model specific for vegetation and allows to simulate the effects of changes in tree cover at the urban level on local hydrology. In other words, it is a desktop-based program aimed at studying the hydrogeological impact of different type of coverage. It is based on a hydrological topographically-based model, UFORE-*Hydro*, still in development, composed by the division into *Hydro* and *Hydro*+; the latter is a new advanced version subjected to research. UFORE-*Hydro* has been developed through the OBJTOP (Object-oriented, Topographic) structure and it is based on algorithms which work with interception, storage, infiltration, evaporation and runoff data, modifying them slightly. It is an easy-to-use model for researchers, urban planners or environmental technicians, who are required to insert minimal input data (Wang *et al.*, 2008). The version used, on which all the model updates depend, involves the use of an urban scheme of soil-vegetation-atmosphere exchanges represented by vertical layers. Furthermore, the surface is recognized as permeable or impermeable and coverage percentage due to the presence of albedo is quantified.

The flow model provides, as inputs, NED (National Elevation Data) as raster with each pixel corresponding to an area with a user-definable size and NLCD (National Land Cover Data). Therefore, from these two data sets, the following information can be obtained: Topographic Index (TI) from NED and estimates of Impermeable Cover (IC) and Tree Crown (TC) from NLCD (Yang *et al.*, 2003). TI is calculated as the quotient between the area by the length of the contour and the tangent to the slope of the local pixel; IC and TC are defined for each block of TI, i.e., groups of pixels with the same Topographic Index. Other input data are: (i) initial groundwater level, (ii) chemical composition of soil and its physical parameters, (iii) meteorological data, required with hourly time interval or less and (iv) potential evapotranspiration.

Then, main output data are: (i) amount of precipitation intercepted by the vegetation, (ii) infiltration, (iii) evapotranspiration, (iv) surface runoff and (v) lateral flows of the aquifer.

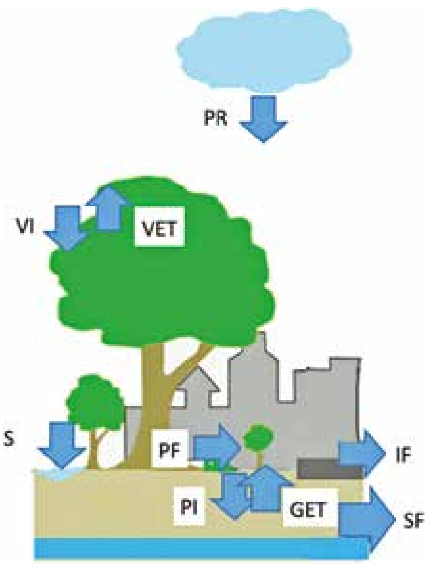

Fig. 1 – *i-Tree Hydro* water balance.

Equation 7 represents the water balance taken as model in *Hydro*, whose components are represented in Figure 1.

$$PR = VET + VI + S + PI + PF + IF + SF + GET \quad (7)$$

with mm as unit of measure for all terms and where, in particular, PR is the precipitation; VET and GET are respectively vegetation and soil evapotranspiration; VI is vegetation interception; S is storage in soil depressions; PI is infiltration on permeable soil; PF, IF and SF are respectively permeable, impermeable and subsurface runoff.

3. Study Area and Data

The proposed i-Tree tools have been applied to an urban park located in Moncalieri, in the Metropolitan City of Turin (Italy N O). The city covers a surface of 4753 hectares and has a population of 57528 inhabitants (W5). It is located at 262 meters above the sea level and it has a warm and temperate climate. Moncalieri receives annual precipitation of 700-750 mm spread in 75 days with a minimum in winter and a maximum in spring and autumn. The average temperature is 12°C with the warmest month in July. According to Köppen and Geiger this climate is classified as Cfa (Humid subtropical climate) (W6).

The selected area is “Le Vallere” park, an extensive semi-urban green space located at the confluence of two rivers, Po River and Sangone Torrent with an extension of 130 ha. “Le Vallere” term was given by French to the embankments built in 1541 during the first French occupation of Piedmont. In 1960s this area was partially saved from the urbanization and the overbuilding which led to the construction of the main street “Corso Trieste” and the residential neighborhood located west of it. Subsequently, “Le Vallere” park became Piedmont Region’s property and in 1990’s the large eighteenth-century farmhouse became the headquarters of the park management institution, ex “Ente di gestione delle aree protette del Po torinese”. On 29th June 2009, Piedmont Region enacted a regional law with which the park was protected as Nature Reserve; nowadays it is open to the public and available with regulation. The regional law n.11/2019 established that all individual protected areas along the Po river in Piedmont, in the section from Casalgrasso to the border with Lombardy, constituted a single protected area: the “Piedmontese Po Natural Park” (“Parco Naturale del Po Piemontese”) (W7).

The designed land use has been turned from a merely agricultural use to an alternation of intensive forage cultivation and clearings with groves. The coexistence of

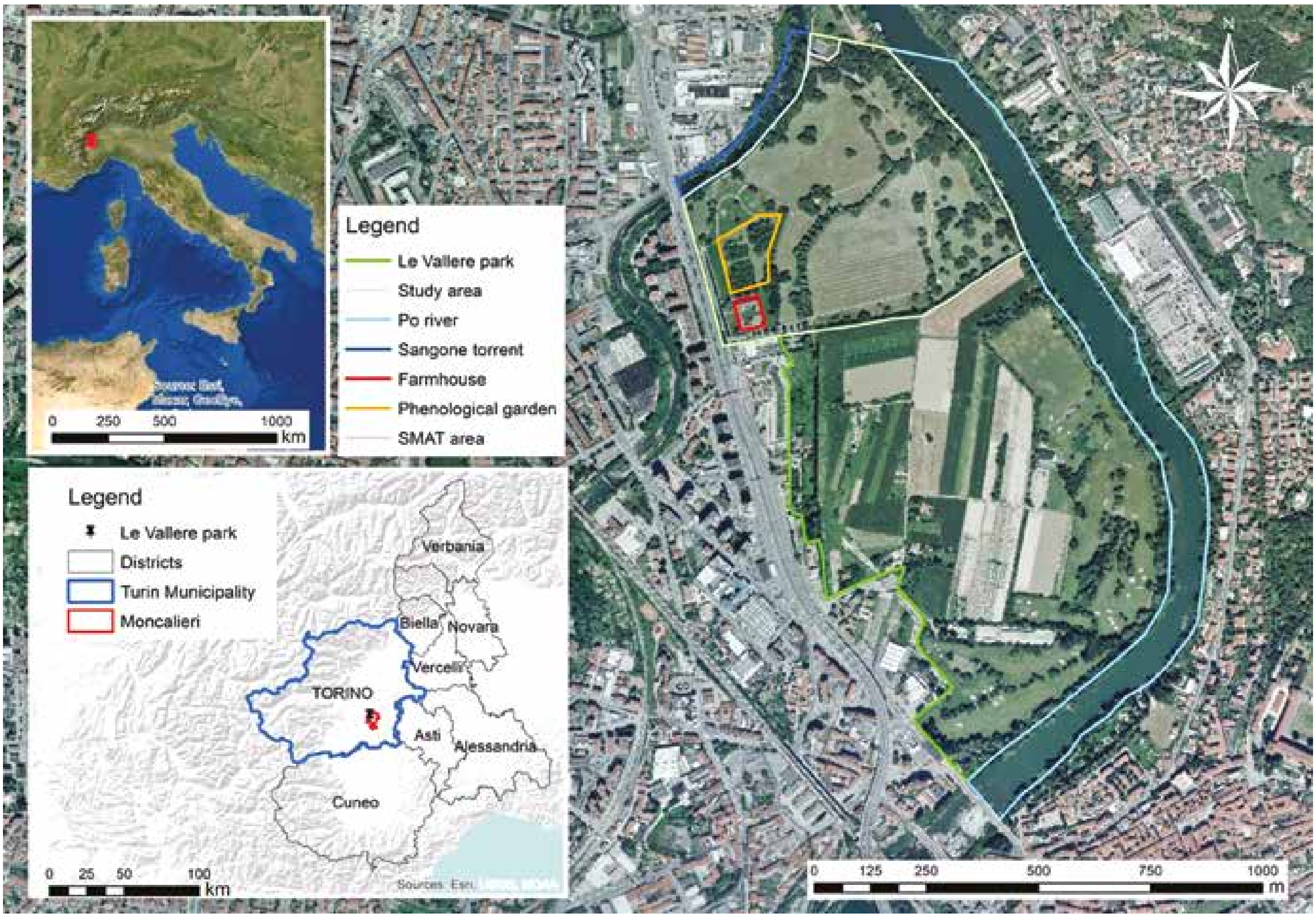

Fig. 2 – Geographical framework of case study "Le Vallere" park.

agricultural landscape and public park and the environmental and landscape recovery measures of Po River's banks allowed to re-enact a section of ecological network of Turin metropolitan area, underling its important role as an element of biodiversity conservation and for migratory flows. The alternance of agricultural activities and public park represents the distinguishing feature between "Le Vallere" park and the other green areas located in the surrounding urban context, increasing the environmental quality of the city.

The present work has been developed on a portion of park managed by "Ente di gestione delle aree protette del Po torinese" (now become part of "Ente di gestione delle aree protette del Po piemontese) which covers a surface of 34 hectares (Fig. 2). Within this area, recreational activities are common: it includes children playground, sport area, picnic areas, two plots for dogs, a botanical-phenological garden and different paths for mountain biking, walking and horse riding. The botanical-phenological garden has been created between 2000 and 2002, it is named in honour of Carlo Allioni and it aims to evaluate the impact that thermal anomalies, parasites and air and soil pollution have on typical species of a continental climate regions (W8). "Le Vallere" park also encloses a building managed by SMAT S.p.A., the water management society of the metropolitan city of Turin.

The partnership with the aforementioned institution has allowed to get reliable and up-to-date technical data. A measurement campaign has been conducted in July 2020 in order to retrieve datasets on tree population required by *Eco* and *Hydro* tools such as arboreal species, tree diameters, health crown condition, land use and land cover. The entire study area has been subdivided into 192 circular plots fixed grid distributed; the plot size is one twentieth of a hectare with a radius of 12.62 m. It has been decided to sample a single tree for each plot, since mostly plants falling within each plot had similar dimensional characteristics; 102 trees have been analyzed.

Concerning meteorological and air quality data, we gathered them from sources provided by regional authorities. In particular, for *Eco* simulation, we had to refer to data collected by "Bric della Croce" weather station (ID 160610-99999) located in Turin (45°02'N 07°44'E) because it was the only station close to study area with validated datasets from USDA Forest Service. Conversely, *Hydro* simulation has allowed to customize climate data selecting a weather station that was representative of the entire study area: we referred to "Torino Vallere" weather station (ID 249) located inside the park itself, run by ARPA Piemonte, and to datasets surveyed by the "Observatory of Carlo Alberto College, Italian Metrological Society" in Moncalieri. All weather and air quality data implemented in *Eco* simulation refer to 2015, while those used in *Hydro* simulation refer to 2019. Table 2 shows input data required to carry out *Eco* and *Hydro* simulations.

4. Results and discussion

4.1. i-Tree Eco

4.1.1. Tree population and carbon storage and sequestration

The first output provided by *i-Tree Eco* is a valuation of composition and structure of the urban forest based on field data. Concerning "Le Vallere" park, it assesses a number of 487 (±29) trees belonging to 25 different species, covering about 31% of park's surface. The most common species are (i) *Tilia x europaea* (67), (ii) *Salix alba* (62), (iii) *Tilia cordata* (43) and (iv) *Populus nigra* (38) which present a percentage distribution of tree stem diameters in 45.7-61 class (50% *Tilia x europaea,* 66.7% *Tilia cordata*), in 30.5-45.7 class (53.8% *Salix alba*) and in 106.7-121.9 class (37.5% *Populus nigra*).

Based on previous results, *i-Tree Eco* estimates leaf area and leaf biomass for each species (see Paragraph 2.1, Eq. 1 and Eq. 2) and, according to those factors, assesses the contribution of carbon storage and gross carbon sequestration of trees by species. Total estimates of the first one are 437 metric tons with a leaf biomass of 14 kilograms and a monetary value of about 40 thousand euros, while the gross carbon sequestration amounts to about 13 metric tons compared to a leaf area of 21.3 hectares, economically equivalent to about 1.2 thousand euros. The monetary value refers to benefit prices in Table 2, according to the Italian context.

The most performing species for the ES evaluation is *Populus nigra* due to the unusually large diameter structure and to the fair crown health. As expected, *Tilia* and *Salix* genus also concur positively to the process of carbon fixation in plant tissues and to the removal of carbon dioxide from the atmosphere through chlorophyll photosynthesis. Although plants belonging to *Tilia* and *Salix* genus hold a higher number of individuals than *Populus* genus (approximately twice), it results they have less influence on carbon storage and carbon sequestration quantification.

4.1.2. Air quality

Another interesting output produced by *i-Tree Eco* is the quantification of annually atmospheric pollutants removed by tree population

Tab. 2 – *I-Tree Eco* and *i-Tree Hydro* input data for case study "Le Vallere" park.

	Eco	Hydro
Project configuration	Plot – based sample inventory, unstratified sample	Non – watershed
n. of plots sampled	192 (one tree for each plot)	-
n. of trees sampled	102	-
Weather data	Bric della Croce (2015)	Torino Vallere, Observatory of Carlo Alberto College (2019)
Air quality data	Bric della Croce (2015)	-
DTM	-	CTRN 1:10000
Land cover parameters	-	Grass/herbaceous (57.1%), Impervious ground (3.8%), Tree impervious (1.6%), Tree pervious (33.9%), Soil/bare ground (3.5%), Water (0%)
DCIA (Directly Connected Impervious Area)	-	10.1%
LAI	-	1.74
Annual average flow of project area	-	$9.98 \cdot 10^{-3}$ m^3/s
National pooled EMCs and NURP EMCs	-	As default
Benefit prices	Energy (0.17 €/kWh), Heating (2.87 €/therm), Carbon (91.92 €/ton), Avoided runoff (1.902 €/m^3)	-

and the resulting improvement in air quality. Ozone (O_3), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) removal made by the green area turns out to be much larger compared to particulate matter (PM2.5), as reported in Table 3. It also points out the non-linear relationship between pollutants quantities removed and their monetary value. One possible reason for that disparity can be the impact that each pollutant have on environment quality and human health, taken into account by *i-Tree Eco*.

In order to correctly quantify ES provided by "Le Vallere" park, it is necessary to take into account the emission of biogenic volatile organic compounds (BVOCs) produced by plants. They significantly affect atmospheric chemistry and climate, especially monoterpene e isoprene emissions that represent a possible source of atmospheric pollution through the formation of O_3, CO and other tropospheric aerosols. Therefore, it has been necessary to consider these compounds in the overall balance of pollutants removal provided by the study area. What has been deduced is that the pollutants removal process strongly depends on trees' intrinsic characteristics, their size and vegetative cycle, not only on their numerical quantity. The economic value assigned to air pollution removal is equal to 95 thousand euros, resulting from a pollutants quantity equal to 437 kilograms per year.

Eco tool provides other hydrological outputs (such as evaporation, evapotranspiration, flows interception by vegetated covers and avoided runoff) intentionally not examined as they have been evaluated with *Hydro* tool as it is based on more robust hydrological models that allow greater precision in runoff calculation and in plant-specific hydrological processes.

4.2. i-Tree Hydro

Concerning *i-Tree Hydro*, outputs provided by simulation assess the effects of changes in urban tree cover and impervious surface on stream flows and water quality. In order to compare different scenarios, the current configuration of park has been defined as *Base case*, while it has been assumed an increase in impermeable surface of 25%, 50% and 75%, respectively as *Alternative case S1, S2, S3*. It has been taken 25% of these percentages out of "Pervious under tree cover" class and the remaining percentage out of "Herbaceous" class, assuming that the reduction of permeable soil involves a decrease in tree cover. Percentages of "Impervious under tree cover" and "Bare soil" have been kept unchanged.

The first output belongs to *water quantity* results: more specifically, it has compared the analyzed scenarios in total flows generated by precipitation fallen in 2019, subdivided into (i) base flow, (ii) pervious flow and (iii) impervious flow. As expected, the comparison has shown an important increase in impervious runoff component related to *Alternative cases*, especially in *S3* in which it represents the 72% of the total flow (Tab 4). Quantities related to Base flow show a decrease of about 225 m^3 per year each 25% increase in impermeable cover.

The second output provided by *Hydro* is related to *water quality*, examined through ten different type of pollutants: total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), soluble phosphorus (soluble P), total Kjeldahl nitrogen (TKN), nitrite and nitrate (NO_2, NO_3), copper (Cu), lead (Pb). As shown in Figure 3, the more impermeable surface increases, the more runoff quality gets worse.

Finally, as *i-Tree Hydro* is a vegetation-specific urban hydrology model, it has been possible to make a few general observations on results from sub-routines such as interception by vegetation, storage on vegetation surfaces and throughfall from them (*Vegetation Hydrology* outputs). The simulation has shown a strong correlation between processes that occur at tree canopy level, intensity and duration of precipitation events and vegetative period of arboreal individuals. In terms of soil hydrology, the program refers to quantities that reach the ground exceeding the maximum accumulation capacity of the leaf cover: some of these volumes seep into subsurface zones, others evaporate from root zone. The comparison conducted between *Base case* and *Alternative cases* has shown that both components decrease as permeable cover decreases.

Tab. 3 – Removed pollutants quantity with related monetary benefit (*i-Tree Eco*).

	NO_2	O_3	PM 2.5	SO_2
Removed quantity (kg/year)	89.3	305.6	8.9	32.2
Monetary value (€/year)	2040.6	46747.6	47432.8	268.2

Tab. 4 – Water quantity outputs (*i-Tree Hydro*).

	Total flow m^3/year	Base flow m^3/year	Pervious flow m^3/year	Impervious flow m^3/year
Base case	217763,2	852,5	215357,4	1517,4
S1	233829,3	627,2	197332,3	35833,8
S2	250383,0	401,9	148645,2	101299,9
S3	267187,5	176,7	74845,0	192129,8

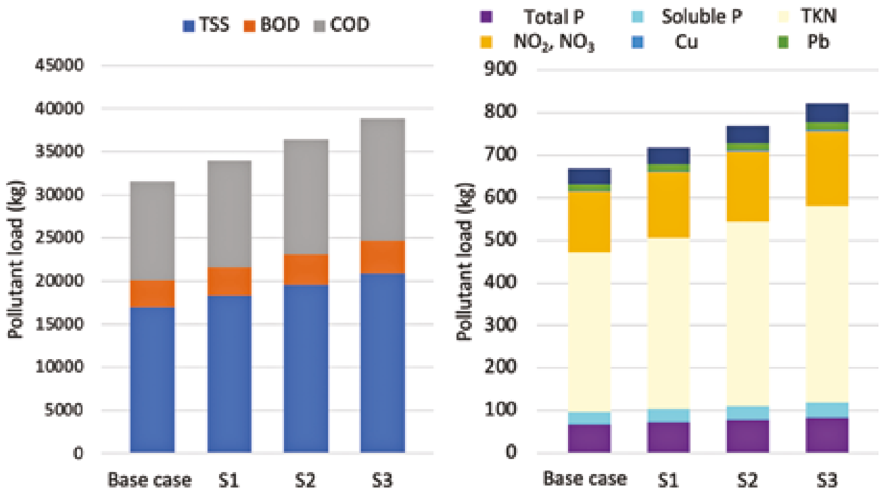

Fig. 3 – Yearly water quantity outputs: on the left, main pollutants; on the right, secondary pollutants (*i-Tree Hydro*).

The results proposed by *Eco* and *Hydro* tools highlight the importance role of the "Le Vallere" park as permeable area, underling the avoided runoff and the improved water quality of surface runoff compared to a waterproofed land cover with same size.

5. Conclusions

The project is part of the complex theme of ES, analyzed through an application on an urban green area with the aim of investigating whether and how the presence of the aforementioned area can contribute to make the surrounding metropolitan environment more resilient and sustainable.

In particular, through the use of i-Tree software suite, the ES offered by "Le Vallere" park, the green lung of the urban area between the municipalities of Moncalieri and Turin, were quantified. The methodology used is based on the availability of data, in part already accessible and in part detected on site, while the accuracy of the analysis is inextricably linked to the quantity and quality of such data. The results proposed by *Eco* and *Hydro* tools highlight the role of the green infrastructure as permeable area, underlying the avoided surface runoff and the improvement of water quality compared to an impervious area with same size. Furthermore, the green area has a significant impact on improving air quality and carbon storage.

The quantified benefits provide a useful tool to guide the future planning and planting choices of the management institution "Ente di gestione delle Aree protette del Po piemontese", with which a pleasant collaboration was held. In this regard, in the future it will be crucial to analyze more specifically the role that each species could play in determining each ecosystem service. The project is in progress to analyze a further fundamental aspect for future urban environmental sustainability: the role of climate change. A *i-Tree* project is being implemented on "Le Vallere" park, in order to take into account the effects that future climate changes (temperature and precipitation) will entail, analyzing two possible scenarios: RCP 4.5 and RCP 8.5, respectively the scenario for which it is planned to implement mitigation actions and the scenario for which it is not planned to fight climate change. As a mitigation action hypothesized in this work, a detailed future planting plan is being defined, in agreement with the park technicians, which can be implemented through the "Forecast" function of *i-Tree Eco*. Through such a study, it is expected to obtain a valid tool for evaluating the evolution of the ES system offered by the park and on this basis, possibly, proceed with some changes.

Bibliography

Baldocchi, D.D., Hicks, B.B., Camara, P., 1987. *A canopy stomatal resistance model for gaseous deposition to vegetated surfaces*. Atmospheric Environment. 21(1), pp. 91-101.

Bolund, P., Hunhammar, S., 1999. *Ecosystem services in urban areas*. Ecological Economics. 29(2), pp. 293-301.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. *The nature and value of ecosystem services: An overview highlighting hydrologic services*. Annual Review of Environment and Resources. 32(1), pp. 67-98.

Caprioli, C., Bottero, M., Mondini, G., 2020. *Urban Ecosystem Services: a Review of Definitions and Classifications for the Identification of Future Research Perspectives*. Computational Science and Its Applications – ICCSA 2020, 20th International Conference. Cagliari, Italy, July 1-4, 2020. Proceedings, Part V.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. *The value of the world's ecosystem services and natural capital*. Nature. 387, pp. 253-260.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P., 2012. *Global estimates of the value of ecosystems and their services in monetary units*, Ecosystem Services. 1(1), pp. 50-61.

Gacka-Grzesikiewicz, E., 1980. *Assimilation surface of urban green areas*. Ekologia poslka, 28(4), pp. 493-523.

Gómez-Baggethun, E., Martín-López, B., 2015. *Ecological economic perspectives on ecosystem services valuation*. Handbook of Ecological Economics. Eds. J. Martínez-Alier and R. Muradian. U.K, pp. 260-282.

Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, A., Breuste, J., Gómez-Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Lorance Rall, E., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., Wurster, D., Elmqvist, T., 2014. *A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation*, AMBIO. 43, pp. 413-433.

Hirabayashi, S., Kroll, C.N., Nowak, D.J., 2011. *Component-based development and sensitivity analyses of an air pollutant dry deposition model*. Environmental modelling & Software. 26, pp. 804-816.

Hodson, M., Marvin, S., 2010. *Urbanism in the anthropocene: Ecological urbanism or premium ecological enclaves?*, City. 14(3), pp. 298-313.

IPCC, 2014, *Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx J.C. (eds.)]. Cambridge University Press. Cambridge. United Kingdom and New York. NY. USA.

Jennings, V., Floyd, M.F., Shanahan, D., Coutts, C., Sinykin, A., 2017. *Emerging issues in urban ecology: implications for research, social justice, human health, and well-being*. Population and Environment. 39(1), pp. 69-86.

McDonnell, M.J., 2015. *Journal of Urban Ecology: Linking and promoting research and practice in the evolving discipline of urban ecology*. Journal of Urban Ecology. 1(1).

Montoya-Tangarife, C., de la Barrera, F., Salazar, A., Inostroza, L., 2017. *Monitoring the effects of land cover change on the supply of ecosystem services in an urban region: A study of Santiago-Valparaíso, Chile*. PLoS ONE. 12(11): e0188117.

Nowak, D.J., 1996. *Estimating leaf area and leaf biomass of open-grown deciduous urban trees*. Forest Science. 42(4), pp. 504-507.

Nowak, D.J., Crane, D.E., Stevens, J.C., Hoehn, R.E., Walton, J.T., Bond, J., 2008. *A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services*. Aboriculture & Urban Forestry. 34(6), pp. 347-358.

Reid, W.V., Mooney, H.A., Cropper, A., Capistrano, D., Carpenter, S.R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A.K., Hassan, R., Kasperson, R., Leemans, R., May, R.M., McMichael, A.J., Pingali, P., Samper, C., Scholes, R., Watson, R.T., Zakri, A.H., Shidong, Z., Ash, N.J., Bennett, E., Kumar, P., Lee, M.J., Raudsepp-Hearne, C., Simons, H., Thonell, J., Zurek, M.B., 2005. *Ecosystems and human well-being – Synthesis;A Report of the Millennium Ecosystem Assessment*. Island Press. Washington D.C.

Solecki, W., Seto, K.C., Marcotullio, P.J., 2013. *It's Time for an Urbanization Science*. Environment Science and Policy for Sustainable Development. 55(1), pp. 12-17.

Treeconomics and Trädkonsult. *Second European i-Tree Conference*. Malmö. 03/10/2019.

Wang, J., Endreny, T.A., Nowak, D.J., 2008. *Mechanistic simulation of tree effects in an urban water balance model*. JAWRA Journal of the American Water Resources Association. 44(1), pp. 75-85.

Yang, L., Huang, C., Homer, C.G., Wylie, B.K., Coan, M.J., 2003. *An approach for mapping large-area impervious surfaces: Synergistic use of Landsat-7 ETM+ and high resolution imagery*. Canadian Journal of Remote Sensing. 29(2), pp. 230-240.

Website

https://www.overshootday.org/newsroom/press-release-july-2019-italian/ Last accessed: 18/03/2021

https://www.co2.earth Last accessed: 19/03/2021

https://www.who.int Last accessed: 26/04/2021

https://www.itreetools.org Last accessed: 23/03/2021

https://www.amministrazionicomunali.it/piemonte/moncalieri Last accessed: 04/04/2021

https://it.climate-data.org/europa/italia/piemonte/moncalieri-13527/ Last accessed: 06/04/2021

http://www.parcopopiemontese.it/index.php Last accessed: 03/04/2021

http://www.parks.it/parchi.po.collina/giardino.fenologico.html Last accessed 06/04/2021

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Smart cooperation during CoVID-19 Pandemic: a case study in Nosy Mitsio Island (Madagascar)

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The majority of rural areas in developing countries live in a state of chronic emergency, due for the most part to the lack of sanitary assistance and food. Covid-19 aggravates this situation, complicating the action of International Cooperation in these countries. To this extent, the case study of the Nosy Mitsio island (Madagascar) is presented. The partnership between H4O, Kukula and Politecnico di Torino aimed to develop the design of a water supply system on the island, providing water for vegetable gardens and thus allowing the local population to achieve food self-sufficiency. The project was supposed to be implemented in 2020 before the Covid-19 pandemic happened. However, despite this major obstacle, the design started with a literature review and the data analysis of soil and water samples collected from the island. The relationship between the Covid-19 pandemic and the project development highlights the central role of smart cooperation: i.e., engagement, inclusion and participation of local communities and their professional training is essential for remote working of NGOs projects during the pandemic.
Keywords: Covid-19, international cooperation, Madagascar, WASH, agriculture, water resources, irrigation.

La cooperazione internazionale ai tempi della Pandemia da Covid-19: il caso studio dell'isola di Nosy Mitsio (Madagascar). *I paesi in via di sviluppo vivono in un continuo stato di emergenza, prevalentemente per la mancanza di cibo e assistenza sanitaria. La pandemia legata alla diffusione del Covid-19 ha aggravato tale situazione, complicando l'azione della Cooperazione Internazionale in questi paesi. A questo proposito viene presentato il caso studio dell'isola di Nosy Mitsio (Madagascar) sulla quale, attraverso la collaborazione tra H4O, Kukula e il Politecnico di Torino, era prevista la progettazione di un sistema di approvvigionamento idrico destinato all'irrigazione di orti per il sostentamento della popolazione. La situazione pandemica ha rallentato lo sviluppo del progetto di fatto permettendo unicamente una ricerca bibliografica e l'analisi di campioni di suolo e acqua provenienti dall'isola. La situazione ha messo in luce la necessità di adottare nuovi strumenti e nuove modalità di cooperazione, basati in primis sulla smart cooperation. Una buona relazione con i locali, la loro formazione e l'adozione, fin dalle fasi iniziali del progetto, di strumenti utilizzabili autonomamente dai locali, dovranno diventare, nel futuro, aspetti essenziali soprattutto nei progetti di Cooperazione Internazionale di piccola e piccolissima scala.*
Parole chiave: Covid-19, cooperazione internazionale, Madagascar, WASH, agricoltura, risorse idriche, irrigazione.

1. Introduction

The global Covid-19 pandemic and the consequent health emergency is particularly exacerbating the precarious pre-existing conditions of developing countries (Patel *et al.*, 2020). Indeed, most of the low-income countries already live in a chronic health emergency and the Covid-19 pandemic is only part of it. This scenario also affects the work and the impact of international cooperation, especially in rural areas where community development still relies on NGOs (Non-Governmental Organizations) and aid organizations actions. In those areas, the main constraint for the projects is that most of them are entirely led and run by expat staff. At present, due to the current impossibility for most of the expat staff to reach the spot where the oversea interventions take place, new considerations have to be taken into account.

For development projects, the importance of the local community engagement is undeniable. However, the success of the projects is often related to the output construction rather than the participatory approach according to which the projects are designed, implemented, and the way beneficiaries manage it in the long term. However, in a period like the Covid-19 pandemic, the capability of local communities to autonomously carry out the projects, together with the ability of the "western staff" to support them from remote are key factors for the project outcomes to be achieved.

Academic literature still lacks a set of indicators to measure a sustainable implementation of the projects and a protocol to follow in order to carry out the activities only with the remote support of the expat staff. This piece of research aims to gather relevant data from a Water Cooperation case study in northern Madagascar. In particular, the article aims to assess the methodologies that have been used to carry out a feasibility study for the design of a water irrigation system for a number of household vegetable gardens in a village of rural Madagascar. The research team wants to understand the main constraints, difficulties and also advantages and usefulness of the so-called *smart cooperation*. The result is a set of observations that may also be useful for similar projects.

2. Materials and methods

2.1. The Nosy Mitsio island

Nosy Mitsio is an island located 20 miles off the northwest coast of Madagascar in the Mozambique Channel (12° 54′ 0″ S, 48° 36′ 0″ E). The island covers a surface of less than 30 km^2 and the landscape is mostly hilly, its highest point is Mt. Ankarana, 206 m a.s.l. Nosy Mitsio is the only inhabited island of the Mitsio archipelago, with approximately 2,500 inhabitants (Antakarana ethnic group) distributed within 5 main villages: Bevaoko, Marimbè, Ampanitsoha, Ratapenjiky and Ampasindava (Figure 1).

Largely due to its off-grid location, the island lacks essential services and infrastructures. This makes the population highly vulnerable, especially with regards to health. The economic situation of its population is in line with the national trend: 77.6% of the inhabitants live below the poverty threshold, the Human Development Index (HDI) reaches only 0.521 and is ranked #162 out of 189 countries (UNDP, 2020). The villages lack basic services, such as access to drinking water and sanitation facilities. The only available water sources are few stagnant ponds located far away from the inhabited area. The only exceptions are the villages of Ampanitsoha and Bevaoko, which have access to drinking water since 2018 thanks to the *Tany Vao Project* (see next section). However, the whole population still practises open defecation, leading to a high morbidity and mortality rates for faecal-oral diseases (Nyoni and Nyoni, 2020).

The island economy is based mainly on fishing and goat/zebu farming. Livestock, instead of being consumed, are for the most part sold on the Madagascar mainland. Food availability strongly depends on weather conditions; when fishing is not possible, people only rely on rice and corn crops. The total lack of vegetables and the very low fruit availability has led to an unbalanced diet, with severe cases of malnutrition across the whole population. The households are very basic with no improved areas for food preparation and storage. Meals are prepared indoors on three stone open fires, which increase health risks especially for women and children due to their prolonged exposure to combustion fumes. In addition to the increased risk of respiratory diseases, open fires also represent a safety hazard and contribute to deforestation due to the large amount of firewood required.

Fig. 1 – Nosy Mitsio Island.

Agriculture in Nosy Mitsio is small-scale, subsistence farming. It is based on traditional know-how and exclusively rain-fed. Most of Nosy Mitsio households directly depend on agriculture for their livelihood, however, their limited capacity to cope with shocks threatens food security and general well-being (Hertel *et al.*, 2010). Malagasy farmers generally lack basic services to be sufficient, such as a reliable water distribution for irrigation, which make them chronically affected by food insecurity (Harvey *et al.*, 2014).

The scarce availability of agricultural inputs, chemical fertilizers and improved varieties of seeds, along with the fact that only few farmers have ever received any technical training on crop production, make the entire community highly vulnerable. In Madagascar, small farms are exposed to a number of risks such as pests, disease outbreaks and extreme weather events, which undermines the owners' food and income security (Morton, 2007). Nosy Mitsio is no exception and local farmers face food insecurity and are vulnerable to external shocks.

In Nosy Mitsio agriculture activities follow the seasons: rainfalls are concentrated between October and April (rainy season) while are scarce from May to September (dry season). Each farming family usually owns several plots of slash-and-burn flat land for rice production and for few other agricultural crops, such as maize, manioc, vegetables, or fruit (e.g., coconut). Owing to the unsustainable land-use, almost all of the agricultural fields are severely eroded. On average, the slash-and-burn fields are cultivated for 3 years and are subsequently abandoned because of the soil depletion, weed invasion and a consequential low crop yield. As a direct result, new areas are regularly cleared from the primary forest for agricultural use, causing significant deforestation (Gaydes-Combes *et al.*, 2017).

The global temperature rising could be also a relevant risk for the local agriculture. Recent studies based on regional and global simulation models indicate that even moderate increases in temperatures will negatively impact on rice and maize cultivations (Rosenzweig *et al.*, 2014), which are the main cereal crops for Nosy Mitsio farmers. The low food security of Nosy Mitsio farmers due to the high exposure to a number of different risks, highlight the urgent need of permanent vegetable gardens with an efficient water distribution, which make them operative throughout the entire year.

2.2. Rainfall and weather data analysis

Madagascar has a tropical maritime climate that is influenced by the proximity to the sea, the altitude and the monsoons. Two main seasons are present: a hot season (from November to April) with heavy rainfalls and high levels of humidity, and a cool and dry season (from May to October). The average temperature along the coasts is between 23-27 °C, while in the internal area is between 16-19 °C (World Bank Group, 2021). In particular, the zone where the Nosy Mitsio island is located is characterized by a tropical climate (Köppen-Geiger classification Am – tropical monsoon climate).

Since a weather station is not located in Nosy Mitsio, rainfalls, rainy days and temperature data have been collected from different web sources (e.g., Cecchini, 2021; Merkel, 2020; WWCI, 2020). After a careful check of the source reliability and the possible presence of biases, the average monthly temperature, the rainfalls and rainy days have been calculated (Figure 2).

The maximum temperature ranges from 31°C in November to 29°C in August. The minimum temperature goes from 22°C in December to 18°C in June and July. Due to the sea presence, temperatures in Nosy Mitsio are generally higher than the average temperatures in Madagascar, but they show the same trend during the year. The monthly rainfall peak is in January (480 mm), while the minimum (34 mm) is in August. In Nosy Mitsio rainfalls follow Madagascar national trends, but they are more intense during the rainy season, and more moderate in the dry season. The total amount of rainfall in a year is about 2000 mm, even if there is a great variability between years: for this reason, a conservative and precautionary approach has been adopted, considering a variation of ±20% in the rainfall volume.

The frequency of rainy days follows the rainfall trend. The annual rainy days are 128 with 15-20 rainy days per month during the rainy season, and 0-5 rainy days per month during the dry season. Compared to the mainland of Madagascar, meteorological events in Nosy Mitsio are accentuated.

2.3. Hydrogeological characterization

The geological composition of Nosy Mitsio (as well as the whole Mitsio archipelago) consists of a volcanic bedrock. The lithological composition is made of acid and basic plutonic rocks and mixed sedimentary rock with a lateritic coverage (Roig, 2012). Ferralsol, also known as ferralitic or lateritic soil, covers around 10% of Africa and it is widespread in Central, Eastern, and Southern Africa, besides the

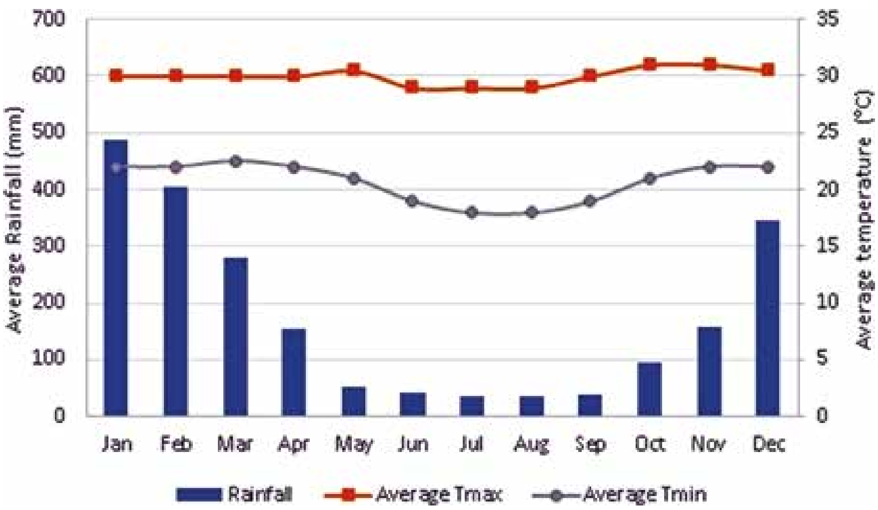

Fig. 2 – Nosy Mitsio Island: temperature and average monthly rainfall. Köppen-Geiger classification: Am – tropical monsoon climate.

north and east coast of Madagascar. Because of weathering, ferralsol is a leached soil with a very low content of nutrients, as calcium and magnesium, and a high content of aluminium and iron oxides (Dewitte *et al*., 2013). Quartz is the only primary mineral present and as secondary minerals, there is a combination of kaolinite, gibbsite, goethite, and hematite. This type of soil has a low cation exchange capacity and a high anion absorptive capacity. The ferralsol appears red and patchy yellow-red, but in the upper layer is present a humus horizon, thanks to luxuriant vegetation, with a percentage of humus in the range from 1-1.15 to 8-10. This confers a black colour to the soil. In general, the structure of the middle zone shifts from the humus to the parent rock (Chesworth, 2008). In this soil fluorine and arsenic are commonly found in high quantities, which can be transferred to the water. Ferralsol is a good soil for the growth of local vegetation, as coconut palms, but the soil low pH, which combines iron and aluminium oxides, fixes the phosphorus fertiliser, and does not allow the phosphorus plant consumption. The natural vegetation grows thanks to a self-sustaining nutrient cycle, recognised by traditional agricultural practice as shifting agriculture. If the cycle is modified (e.g. deforestation or exportation of agricultural products), the soil loses its fertility and can be subjected to degradation as erosion (European Commission, 2013).

The aquifer is an igneous extrusive rock composed of basalt (MacDonald, 2012; British Geological Survey, 2019). This aquifer type is common in the north of Madagascar. The basalts compose fractured aquifers, usually unconfined, and can support very large springs. The approximated productivity is moderate to high, which means productivity is in the range of 2-20 l/s. The borehole yield depends on the local distribution of fractures, but generally, the maximum yield observed is 7 l/s. Volcanic groundwater is typically low in mineralisation, but occasionally can be brackish to salty. From geological maps of the British Geological Survey (2019), it is possible to collect data for the different aquifer types. Nosy Mitsio is a little island and very often is not represented in the maps. For this reason, information about the aquifer was given by the near Antsiranana area (north of Madagascar), which has the same type of aquifer as Nosy Mitsio. The groundwater storage is about 10-25 m water depth. The estimated depth of the aquifer is 7-25 m b.g.l., and its saturated thickness is about 25-100 m (Sethi and Di Molfetta, 2019).

3. Project evolution during Covid-19 pandemic

In Nosy Mitsio the H4O intervention started in 2017. Before then, the hygienic-sanitary conditions were critical: public services were absent, and 100% of the population was practicing open-defecation (Nyoni and Nyoni, 2020). There was no access to potable water and the local population used to consume untreated water from natural pools and wells. Water was often contaminated by animal carcasses that stumbled trying to reach the water sources. Bevaoko and Ampanitsoha, (400 and 300 inhabitants, respectively) were the two villages selected for the interventions. From the water catchment, the water was conveyed to a water tank and, then, to several taps dislocated within the villages through a pipeline. This has allowed safe and potable water from the springs to the residential yards, the schools, and the Bevaoko's hospital. Two schools with hygienic services were also built in Bevaoko and Ampanitsoha, and the hospital in Bevaoko was upgraded. Water from taps was used by the population to cook, do housework, and as drinking water.

3.1. The "Tany Vao Project"

Tany Vao ("New Land'' in Malagasy) is a people-centred and cross-sectoral project, which aims to improve the living conditions of the inhabitants of Ampanitsoha and Bevaoko. The lack of basic services exposes the Nosy Mitsio inhabitants to health-related risks such as faecal-oral and respiratory diseases mainly due to the absence of WASH infrastructures and the use of indoor open fires. The project, which is a two-year continuation of the Water, Sanitation and Hygiene (WASH) programme initiated in 2018, entails a holistic approach focusing on safe water, toilets and good hygiene, food and nutrition and clean cooking. The project therefore aims to provide access to clean drinking water, improved sanitation facilities and improved cookstoves. However, in order to improve public-health conditions, the project will focus on reducing malnutrition by identifying the criticisms of the local diet and using them to shape the development of climate-smart agricultural practices. Thanks to training and awareness-raising activities, the project promotes community development and empowers the population to be self-sufficient. The direct beneficiaries of the project will be 700 out of 2.500 inhabitants of the island, with a strong focus on children and women.

The project is carried out by H4O in partnership with Kukula and Associazione ELPIS Nave Ospedale. In particular, Kukula is responsible for agricultural and clean cooking activities, while Associazione ELPIS Nave Ospedale undertakes the epidemiological study and medical assistance. Moreover, academic partners will provide technical and scientific support to the project (H4O, 2021; Kukula, 2021).

Within the project framework, the WASH component is the basis for the implementation of further activities. The water supply system will be upgraded by widening the catchment basins and by installing new taps for drinking water. The enhancement of the water supply network will allow for a greater availability of clean water by reducing the length of the round-trip for its collection. Furthermore, a new water supply system will be built to irrigate the vegetable gardens. The irrigation system will maximise water efficiency, reducing water consumption and related environmental impacts.

3.2. Expedition in Nosy Mitsio

At the beginning of December 2020 there was an expedition in Nosy Mitsio by a volunteer of Kukula. The original reason for the expedition was to conduct a census of the local population in Bevaoko and Ampanitsoha, collecting data on age, gender, height, and weight, in order to establish if the population is malnourished and to assess some criteria to select the future beneficiaries of the vegetable gardens.

The expedition also represented the opportunity to collect more information about Nosy Mitsio. The altitude was recorded following the pipeline of the existing water supply system (Figure 3), from the water catchment (WS01) to the village (continuous line).

To supply the gardens with water a source was identified (WS02). The GPS data were taken also from WS02 to the village (dashed line) and around the area where the gardens could be settled. Water samples were also collected in four strategic points in Ampanitsoha where villagers are used to collect water: WS01, WS02, VMM (a pristine well actually not in use) and VMASK (a private well used by a local family). For each point, two samples (0.5 l) were collected, and pH, temperature and Total Dissolved Solids (TDS) were recorded three times to obtain a mean value. Soil samples were also collected taking 0.5 kg of the first 20-30 cm of soil in four points: two in Ampanitsoha (Figure 3: AMP01 and AMP02) and two in Bevaoko.

3.3. Water and soil analysis

Water samples were brought to Antananarivo ensuring the cold-chain and then analysed at the Institute Pasteur de Madagascar: the temperature of conductivity was analysed with a probe, whereas the electrical conductibility and nitrite were analysed following the French standard NF EN 27888 and NF EN 26777, respectively. Chloride, iron, fluorides, calcium, magnesium, potassium, and sulphite were measured with the method of spectroscopy. Hydrogen carbonates were derived through calculations (Table 1). The parameters were compared with well-known threshold values. The only values that overcome the limits are the fluorides at VMM, although for monsoon climate (i.e., high precipitations) the guidelines restrictions are very strict (Ayers and Westcot, 1994). In conclusion, on the basis of the parameters considered, it can be assumed that the water analysed does not fully comply with drinking water standards due to pH and fluoride values, whereas for irrigation use there are no problems (Bortolini *et al.*, 2018). A more complete and accurate assessment requires further analysis taking into account seasonal variability.

Soil samples were brought to Italy and analysed at the DIATI laboratory (Politecnico di Torino). Soil composition was assessed through a granulometric analysis of dry and wet samples (Table 2). For the dry sieve, a mechanical shaker has been used for 10 minutes.

The results of dry and wet sieves are different. If the soil is dry, it can be classified as a sandy soil with a fine material fraction lower than 10%. On the contrary, if the soil is wet, the fine fraction, com-

Fig. 3 – Ampanitsoha village: existing water supply pipe (continuous line) and projected system (dashed line).

Tab. 1 – Results of water sample analysis.

		WS01	WS02	WMM	VMASK
T of conductivity	°C	20.50	20.50	20.70	20.50
EC at 25°C	μS/cm	307	258	599	676
TDS	ppm	180.83	10.38	10.65	10.59
Chloride	meq/l	0.584	0.327	0.623	1.416
Iron (Fe)	mg/l	<0.05	<0.05	<0.05	<0.05
Fluorides (F)	mg/l	1.1	1.0	2.5	1.1
Hydrogen carbonates (in HCO_3^-)	meq/l	2.099	1.400	3.999	3.899
Nitrite	mg/l of NO_2	0.2	0.4	<0.1	<0.1
Arsenic	mg/l	<0.01	<0.01	<0.01	<0.01
Calcium	mel/l of Ca	1.337	0.938	3.833	4.851
Magnesium	meq/l of Mg	0.576	0.004	2.386	0.576
Sulphite	mg/l of SO_3	11.3	8.2	9.5	5
Potassium (K)	mg/l	1.5	3.6	0.2	3.4
pH (mean value)	-	8.86	9.21	8.30	8.09

posed of clay and silt, is over 90%. This happens because the soil has a high amount of fine fraction, which tends to aggregate and form particles with a bigger size. During the wet sieve, thanks to water and the manual mechanical action, the biggest particles disaggregate in the fine fraction. The soil in contact with water shows a muddy texture and becomes very compact due to the high amount of silt and clay. For this reason, it is possible to say that water leaks into the soil for a short time, until the fine fraction absorbs the water, and the soil becomes impermeable. This behaviour explains the great occurrence of mud flow during the rainy season.

4. The struggle with Covid pandemic

The Covid-19 pandemic is the greatest challenge since World War II and the major global health, social, economic and educational crisis of our time. The situation we are living in has proven that modern society is scarcely prepared for sudden negative events. High-income countries are no exception, although economic resources are larger for coping with sudden and unexpected events (Lambert, 2020). Moreover, the pandemic made human beings aware that many personal, social and environmental key aspects were overlooked or taken for granted. For instance, personal basic hygiene practices as well as the relationship between environment and health and the consequences of human actions on nature and environment. This situation highlights the need of reflecting on how the pandemic affects our society through the twelve issues proposed by Shek (2021): "economic development versus saving lives, consumption versus environmental protection, health inequality, economic disadvantage, family well-being, gender inequality, impact on holistic well-being, digital divide, individual rights versus collective rights, international collaboration versus conflict, prevention of negative well-being, and promotion of positive well-being".

Therefore, the time has come to focus on the short and long-term effects of Covid-19 on the environment, health (European Environment Agency, 2020) and each field of work, including international cooperation (Brown and Susskind, 2020). Global uncertainty carried by Covid-19 made a large number of small-scale international cooperation projects in rural areas at risk due to poor NGOs' local structure and the difficulties faced by the remote project management. Covid-19 preventive measures have stopped the displacement from nation to nation for expat staff as well as most of the interactions between the international stakeholders and local beneficiaries. Concerning our case-study, despite the Covid-19 pandemic and all the related difficulties, the Tany Vao feasibility phase has been carried out. It has been possible thanks to the close collaboration between NGOs' we-

Tab. 2 – Passing percentage for wet (W) and dry (D) sieve of four samples 1 (dimension of sieves in mm).

		Sieves						
		0.075	0.106	0.250	0.425	0.85	2.0	4.75
AMP01	Wet	91.80	92.45	95.78	97.46	98.95	99.69	100
	Dry	4.37	5.49	12.32	18.75	35.40	61.60	91.25
AMP02	Wet	86.43	89.37	93.01	94.26	96.21	98.45	100
	Dry	0.59	1.15	5.68	12.13	27.94	53.02	80.21
BVK01	Wet	91.72	92.72	93.85	94.36	95.70	97.40	100
	Dry	1.44	2.13	5.45	9.24	17.45	37.29	73.01
BVK02	Wet	90.25	92.03	94.12	94.95	96.50	97.66	100
	Dry	2.40	3.66	9.24	14.58	25.37	51.29	86.45

Fig. 4 – Photos taken on Nosy Mitsio island. From top left: a local man measures the well depth; the source WS01 at its natural state; locals engaged in the construction of the water catchment at source WS01.

stern staff and local inhabitants and thanks to the in-depth knowledge of local dynamics.

During the feasibility study, the fundamental activities carried out by the local beneficiaries mainly consisted in helping the expat staff member (who went on the field for his first time) during the data collection (Figure 4).

Local inhabitants helped him to identify the natural resources, to assess and perform the data collection and to make him aware of social dynamics within the village. The activities highlighted how local inhabitants have an integrated in-depth knowledge of the natural and social context, which is crucial to carry out the project since its feasibility study. Moreover, local communities have proven the willingness to participate in the Tany Vao project and to make their local know-how open source, for the benefit of the entire community and the environment.

On the other hand, the international staff member brought on the field all the tools and instruments to technically assess the resources, the expertise in using them, and the capability to process the collected data. This phase was also the opportunity for the project to select the key informants within the community and to perform training sessions for the local staff. These activities will be crucial for the locals to be autonomous and to carry out future tasks, only supported from remote.

The success of international cooperation projects is often evaluated based on the achievements of the expected outputs in terms of building facilities or infrastructures, while some other projects are focused on training and awareness-raising activities to be achieved at the end of the project (EuropeAID, 2004). However, Covid-19 highlights the need of carrying out the projects based on the engagement of the direct beneficiaries and local staff. The NGO's expat staff duty turns into supporting local staff from remote, enabling them to carry out most of the project activities. We call this approach "*Smart Cooperation*", which consists in considering and trying to answer the over mentioned twelve issues proposed by Shek (2021) at each phase of the project. The answers often suggest setting a strong collaborative network with local people and to define the role played by each stakeholder, starting from the problem identification and the feasibility study.

With regards to the Tany Vao case study, the *Smart Cooperation* approach is making the project more resilient and participative, mitigating risks of any kind, as is the case of Covid-19 challenge. An effective management and the local inhabitants' engagement allowed the project to keep going and the Smart Cooperation to come true since its feasibility study. Indeed, without this approach it would have been complicated to collect relevant data and information for the project move forward. Based on the Tany Vao case study, the *Smart Cooperation* approach is indispensable to keep the project going and it should definitely be part of the Project Cycle Management for each Cooperation Project.

5. Future vision

The future of Tany Vao, based on the activities carried out during the feasibility study, will definitely follow the Smart Cooperation

Approach. In order to put this approach in place, the local communities will be provided with both the communication devices and the specific training activities for certain project tasks. Nevertheless, some specific activities throughout the whole project will require the supervision and the presence of technical experts on the field to ensure the proper accomplishment of each task.

The first aim of this paper is to enable the scalability and replicability of the projects such as the Tany Vao one. In fact, the goal is to understand the main drivers of the Smart Cooperation Approach success to extend it to other similar contexts. Nosy Mitsio Island, in which the Tany Vao project takes place, has certain peculiar characteristics that shaped the tailor-made design used for the Tany Vao project during its course. That being said, there are some important features in common with many other developing countries all over the world such as geographical isolation, lack of infrastructures, lack of governance, lack of support from public authorities and a number of other aspects that can be found in many other rural and tropical areas. Therefore, we can consider the teachings learned during this study as something applicable in many contexts with similar characteristics in other developing countries.

References

Ayers, R.S., and Westcot, D.W., 1994. *Water quality for agriculture*, Vol. 29-1, pp. 174. Rome: Food and Agriculture Organization of the United Nations. ISBN 92-5-102263-1.

Bortolini, L., Maucieri, C., and Borin, M.A., 2018. *Tool for the Evaluation of Irrigation Water Quality in the Arid and Semi-Arid Regions*. Agronomy. 8(2), pp. 23.

British Geological Survey, 2019. *User Guide: Africa groundwater atlas country hydrogeology maps*, version 1.1. doi: OR/19/035.

Brown, G., and Susskind, D., 2020. *International cooperation during the COVID-19 pandemic.* Oxford Review of Economic Policy. 36, Issue Supplement_1, pp. S64-S76.

Chesworth, W. (ed.), 2008. Ferralitic, Springer Netherlands, Dordrecht, pp. 237-237.

Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Thiombiano, L., Van Ranst, E., Yemefack, M., Zougmore, R., 2013. *Harmonisation of the soil map of Africa at the continental scale*. Geoderma, 211-212, 138-153.

EuropeAID, 2004. Aid Delivery Options Project Cycle Management (PCM) – Project Approach Guidelines, Project Cycle Management Guidelines, vol. 1, pp. 158. Brussels: EuropeAid Cooperation Office, European Commission.

European Commission, 2013. *Soil Atlas of Africa (Part 1),* FAO, Rome, Italy and IIASA, Laxenburg, Austria. doi: 10.2788/52319.

European Environment Agency, 2020. *COVID-19 and Europe' s environment: impacts of a global pandemic,* Briefing no. 13/2020, Copenhagen, doi: 10.2800/223351.

Gay-des-Combes, J.M., Robroek, B.J.M., Hervé, D., Guillaume, T., Pistocchi, C., Mills, R.T.E., Buttler, A., 2017. *Slash-and-burn agriculture and tropical cyclone activity in Madagascar: Implication for soil fertility dynamics and corn performance*, Agriculture, Ecosystems & Environment, 239, pp. 207-218.

Harvey, C.A., Rakotobe, Z.L., Rao, N.S., Dave, R., Razafimahatratra, H., Rabarijohn, R.H., Rajaofara, H., MacKinnon J.L., 2014. *Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar*. Philosophical Transactions of the Royal Society B: Biological Sciences 369.1639: 20130089.

Hertel, T.W., Rosch, S.D., 2010. *Climate change, agriculture, and poverty*. Applied Economic Perspectives and Policy 32.3: 355-385.

Lambert, H., Gupte, J., Fletcher, H., Hammond, L., Lowe, N., Pelling, M., Raina, N., Shahid, T., Shanks, K., 2020. *COVID-19 as a global challenge: towards an inclusive and sustainable future*, The Lancet Planetary Health, 4 (8), pp. e312-e314.

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O., and Taylor, R.G., 2012. *Quantitative maps of groundwater resources in Africa*, Environ. Res. Lett., 7, 024009.

Morton, J.F., 2007. *The impact of climate change on smallholder and subsistence agriculture*: Natural Resources Institute. University of Greenwich, UK. 6pp.

Nyoni, S.P., Nyoni, T., 2020. *Open Defecation in Madagascar: A Box-Jenkins ARIMA Approach*. International Journal of Advance Research and Innovative Ideas in Education (IJARIIE), 6(4), 546-556.

Patel, J.A., Nielsen, F.B.H., Badiani, A.A., Assi, S., Unadkat, V.A., Patel, B., Ravindrane, R., Wardle, H., 2020. Poverty, inequality and COVID-19: the forgotten vulnerable, Public Health, 183, pp. 110-111, doi: 10.1016/j.puhe.2020.05.006.

Roig, J.Y., Tucker, R.D., Delor, C., Peters, S.G., Théveniaut, H., 2012. *Carte géologique de la République de Madagascar à 1/1 000 000*. Ministère des Mines, PGRM, Antananarivo, République de Madagascar.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones J.W., 2014. *Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison.* Proceedings of the National Academy of Sciences 111.9: 3268-3273.

Shek, D., 2021. *COVID-19 and Quality of Life: Twelve Reflections*. Applied Research in Quality of Life, 16, pp. 1-11.

Sethi, R., Di Molfetta, A., 2019. *Groundwater Engineering: A Technical Ap-*

proach to Hydrogeology, Contaminant Transport and Groundwater Remediation. Springer Ed.

UNDP (2020) *Human Development Report 2020*. The Next Frontier: Human Development and the Anthropocene. New York.

Website

Cecchini, M., 2019. *World climate guide*. Available at: https://www.climatestotravel.com/climate/madagascar / nosy-be (last accessed 05/10/2020).

H4O, 2021. *Help for Optimism*. Available at http://helpforoptimism.org/ (last accessed 03/05/2021).

Kukula, 2021 Kukula: Growing a Sustainable Future. Available at https://kukula.it/ (last accessed 03/05/2021).

Merkel, A., 2020. *Climate Data for Cities Worldwide*. Available at https://en.climate-data.org/africa/madagascar-177/ (last accessed 17/04/2021).

World Bank Group, 2020. *Climate Change Knowledge Portal*. Available at: https://climateknowledgeportal.worldbank.org/country/madagascar/climate-data-historical (last accessed 15/12/2020).

WWCI, 2020. *World Weather & Climate Information*. Available at: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Hall-Ville,Madagascar (last accessed 05/10/2020).

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How underground systems can contribute to meet the challenges of energy transition

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The paper provides an overview of the several scientific and technical issues and challenges to be addressed for underground storage of carbon dioxide, hydrogen and mixtures of hydrogen and natural gas. The experience gained on underground energy systems and materials is complemented by new competences to adequately respond to the new needs raised by transition from fossil fuels to renewables. The experimental characterization and modeling of geological formations (including geochemical and microbiological issues), fluids and fluid-flow behavior and mutual interactions of all the systems components at the thermodynamic conditions typical of underground systems as well as the assessment and monitoring of safety conditions of surface facilities and infrastructures require a deeply integrated teamwork and fit-for-purpose laboratories to support theoretical research. The group dealing with large-scale underground energy storage systems of Politecnico di Torino has joined forces with the researchers of the Center for Sustainable Future Technologies of the Italian Institute of Technology, also based in Torino, to meet these new challenges of the energy transition era, and evidence of the ongoing investigations is provided in this paper.
Keywords: *hydrogen, underground storage, energy transition, well testing, reservoir modeling, microfluidics, offshore facilities, monitoring, biochemistry.*

Il contributo dei sistemi sotterranei alle sfide della transizione energetica. *L'articolo fornisce una panoramica dei numerosi aspetti tecnici e scientifici e delle sfide che devono essere affrontate per effettuare lo stoccaggio sotterraneo di anidride carbonica, idrogeno e miscele di idrogeno e gas naturale. L'esperienza acquisita sui sistemi energetici sotterranei e sui materiali viene integrata con nuove competenze per rispondere adeguatamente alle necessità connesse alla transizione dai combustibili fossili alle fonti rinnovabili. La caratterizzazione sperimentale e la modellizzazione delle formazioni geologiche (inclusi gli aspetti geochimici e microbiologici), il comportamento dei fluidi e del flusso e le reciproche interazioni tra tutti i componenti del sistema alle condizioni termodinamiche tipiche degli stoccaggi sotterranei nonché la valutazione e il monitoraggio delle condizioni di sicurezza degli impianti e delle infrastrutture di superficie richiedono una squadra di lavoro profondamente integrata e laboratori dedicati per supportare la ricerca teorica. Il gruppo del Politecnico di Torino che si occupa di sistemi di stoccaggio di energia a larga scala ha messo a sistema le sue competenze con quelle dei ricercatori del Center for Sustainable Future Technologies dell'Istituto Italiano di Tecnologia, sempre con sede a Torino, per rispondere a queste nuove sfide della transizione energetica. Nell'articolo viene fornita evidenza delle attività di ricerca attualmente in corso.*
Parole chiave: *Idrogeno, stoccaggio sotterraneo, transizione energetica, prove di pozzo, modellistica di giacimento, microfluidica, piattaforme offshore, monitoraggio, biochimica.*

1. *Introduction*

According to the 2030 climate & energy framework defined in the Paris Agreement (https://ec.europa.eu/clima/policies/strategies/2030_en), the key targets for 2030 are to cut greenhouse gas emissions by at least 40% compared to the 1990 levels and to achieve at least a 32% share of renewable energy and at least a 32.5% improvement in energy efficiency.

Renewable sources are considered key to decarbonize energy systems and reduce dependency on fossil fuels, as stated by the Mission Innovation Program (http://mission-innovation.net/). However, despite the availability of solar energy and wind power, technologies relying on these sources are not fully viable yet due to their unstable and intermittent nature (Rodrigues *et al.*, 2014; Benetatos *et al.*, 2019). Therefore, solutions to match the high-frequency variation of renewable energy production with the electricity demand are fundamental for energy transition. In this view, large-scale energy storage can provide means for balancing supply and demand, increasing energy security, promoting a better management of the grid and allowing convergence towards a low carbon economy. To this end, both electrical storage technologies – such as rechargeable batteries and supercapacitors (Scalia *et al.*, 2021; Lamberti *et al.*, 2015) – and chemical storage are currently under investigation.

Chemical storage implies transforming electrical power into chemical energy in the form of H_2, which can then be used as such or combined with captured CO_2 to produce green CH_4 (referred to as the gas-to-power technology), thus it is very versatile. One way to ensure large-scale storage of chemical energy is to use the storage capacity of underground reservoirs, since geological formations have the potential to store large volumes of fluids with minimal impact to the environment and society (Matos *et al.*, 2019).

Furthermore, strategies for CO_2 capture and permanent storage have been developed to compensate for CO_2 emissions from burning fossil fuels and to meet the challenge of drastically reducing CO_2 emissions in the next future. While long-term CO_2 underground storage is often regarded as an essential mitigation option to reduce greenhouse gases into the atmosphere and contrast climate change, temporary underground storage could be a strategy to match the quantity of captured CO_2 and the quantity of CO_2 that can be transformed into value-added fuels and chemicals.

Based on the above, it is evident that underground storage systems can play a fundamental role in the transition to a decarbonized and more sustainable energy future. To this end, the Underground Energy Systems group of Politecnico di Torino has teamed up with the researchers of the Center for Sustainable Future Technologies of the Italian Institute of Technology (IIT), also based in Torino, to work together and tackle these new challenges. By joining forces, we can complement expertise on rocks and fluids characterization, CO_2 capture and reduction, hydrogen, materials, conversion and safety of offshore facilities, numerical modeling and underground gas storage to address the issues posed by energy transition. New laboratory facilities within the Competence Center SEASTAR – Sustainable Energy Applied Sciences, Technology & Advanced Research have also been established to carry out experimental investigations in support of the ongoing research. Research on H_2 and CO_2 underground storage is under development.

2. Well testing: more than 20 years' experience in geo-energy

Pressure transient analysis to characterize underground formations from a production/shut-in sequence applied to a well began in the early 1930's both within and peripheral to petroleum engineering. Over the years, the technological improvement of pressure gauges and the mathematical development of interpretation models made these tests an oil industry standard methodology for well performance and reservoir characterization for various physical reservoir concepts and flow conditions (Gringarten *et al.*, 1979; Bourdet *et al.*, 1983; Agarwal, 1980; Coelho *et al.*, 2005).

Conventional well testing consists of analyzing the pressure transient recorded down-hole during production of the reservoir fluids at either a constant or variable rate, and subsequent shut-in phase. Typically, during exploration activities there are no infrastructures to collect the hydrocarbons produced during well tests, thus it is common practice to flare them; this involves emissions of unburned hydrocarbons, carbon monoxide and nitrogen oxides. Over the last twenty years, significant evolution in HSE's policies, driven by technological advancements and a societal push toward sustainability, allowed alternative well testing methods to gain increased consideration. Alternative technologies fit into the sustainable path in different ways (Verga *et al.*, 2016): injection tests, suited for reservoir characterization without surface production and thus eliminating greenhouse gases emissions (they can be complemented with Wireline Formation Testing for reservoir fluid sampling) (Levitan, 2003; Beretta *et al.*, 2007); harmonic pulse testing, suited for well monitoring in production and storage fields without interruption of ongoing operations (which could compromise conventional well test interpretation) and for well and thermal front monitoring in geothermal systems.

2.1. Injection Testing

An injection test consists in injecting a fluid (commonly brine, diesel or nitrogen) in a reservoir zone and monitoring the pressure response during the injection period and the subsequent fall-off period, in which the well is shut-in and the pressure tends to return to the initial equilibrium value. If the hydrocarbons originally in place and the injected fluid are not miscible, the physics of injection tests is characterized by the presence and movement of two phases in the reservoir. Along with analytical solutions (Levitan, 2003; Ramakrishnan & Kuchuck, 1993; Boughrara *et al.*, 2007; Habte & Onur, 2014) and numerical simulation (Verga *et al.*, 2008; Azarkish *et al.*, 2006; Verga *et al.*, 2011), an interpretation approach leveraging consolidated interpretive tools is presented in the technical literature (Beretta *et al.*, 2007; Verga *et al.*, 2012).

Examples of successful injection tests were published in the scientific literature: test of a naturally-fractured light-oil carbonate reservoir using brine as the injection fluid (Beretta *et al.*, 2007); test of a light oil reservoir in Algeria where diesel was injected (Tripaldi *et al.*, 2009); and, test of a depleted dry gas (i.e., methane) field, which could potentially be converted into an underground gas storage, where the injection fluid was nitrogen (Azzarone *et al.*, 2011).

2.2. Harmonic Pulse Testing (HPT)

HPT is a well testing technique in which the injection or production rate is varied periodically. The pressure response to the imposed rates, both in the pulser wells and in the observer well(s), can be analyzed in the frequency domain to evaluate the reservoir properties. Although harmonic testing entails a much longer rate sequence than conventional testing to obtain the same information (Hollaender *et al.*, 2002), the main advantage of this approach is that it does not require the interruption of production nor the knowledge of the previous rate history. In storage scenarios, well monitoring is essential to guarantee market delivery targets (gas volume and rate) but interrupting the production before and during a test is often unfeasible for the very same reasons.

The concept of harmonic testing was first proposed by Kuo (1972) and later developed by several authors (Rosa & Horne, 1997; Hollaender *et al.*, 2002; Ahn & Horne, 2010; Fokker & Verga, 2011; Fokker *et al.*, 2012; Fokker *et al.*, 2013; Sun *et al.*, 2015, Salina Borello *et al.*, 2016, Fokker *et al.*, 2017, Viberti *et al.*, 2018). In Fokker *et al.* (2018) analytical models are presented for HPT interpretation on a graph analogous to the log-log diagnostic plot for the most common scenarios (I.A.R.F., single boundary, partial penetration, horizontal well, closed reservoir).

Real applications of HPT are documented in the literature for hydrocarbon reservoirs, aquifers, storage fields, and geothermal systems. Rochon *et al.* (2008) characterized single and multilayer reservoirs. Fokker *et al.* (2013) characterized heterogeneities of a sandstone aquifer (Renner & Messar, 2006). Salina Borello *et al.* (2016) assessed the deliverability of a gas well in a storage field and identified turbulence effects. Well deliverability estimation is provided by Shoaib *et al.* (2018). Recently, the application of harmonic pulse testing was successfully extended to geothermal systems (Salina Borello *et al.*, 2019; Fokker *et al.*, 2020).

3. Integrated multiscale static and dynamic modeling of underground porous media

The ability to predict the future performance of an underground system for different development, production or storage strategies mainly depends on the possibility to reliably describe the system – be it a reservoir, aquifer or storage – by integrating all the available geological, geophysical, petrophysical, testing and production information and simulating the fluid dynamics taking place within it (Benetatos & Viberti, 2010). To this end, it is common practice to rely on a 3D numerical reservoir model. The model is first generated to accurately reproduce the structural and petrophysical properties of the underground system (static modeling) and then implemented to describe the evolution of pressure and fluid saturations in space and time (dynamic modeling). Due to a generally enhanced awareness of environmental and safety issues the same model is often further extended to account for the rock mechanical properties and to simulate potential consequences of the induced variations of the stress conditions. Furthermore, dealing with CO_2 or H_2 storage also demand for including relevant geochemical phenomena such as rock dissolution or salt precipitation, which can alter the rock petrophysical properties.

3.1. Static reservoir modeling

The static model of a reservoir can be considered as the final product of the structural, stratigraphic, lithological and petrophysical modeling activities. A deep integration among them is necessary in order to generate a representative static model (Benetatos & Giglio, 2019).

The construction of a 3D static model begins with the dataset creation and the quality check of all the available well log, geophysical and geological data including sedimentological information. The available 2D seismic sections or 3D high resolution seismic datasets are used for the identification of the main horizons, geological trends and faults if present as well as for the extraction of seismically derived lithological and petrophysical properties. The structural model and the subsequent stratigraphic model are of primary importance for the definition of the internal reservoir architecture and for the continuity and connectivity of the sedimentary bodies.

The volume of interest (i.e., the reservoir) is divided into elements called blocks (or cells). Each block is assigned values of the local petrophysical properties: fluid saturations and porosity dictate the amount of hydrocarbons stored in the reservoir, whereas permeability defines the ease with which fluids can flow through porous media and thus well productivity or injectivity. The values of the petrophysical parameters usually derive from well and core data (Viberti, 2010; Viberti *et al.*, 2012) but their distribution in the model is controlled by deterministic or statistical methods. In the last decades, geostatistics has become a valuable tool in geological modeling, offering techniques for the integration of multiscale data, mapping their uncertainties and distributing properties into 3D reservoir models.

3.2. *Dynamic reservoir modeling*

The objective of reservoir dynamic modeling is to build a 3D numerical model able to simulate the dynamic behavior of a given underground system. The main input data for dynamic reservoir modeling comes from different sources and includes: the static model, fluids thermodynamic behavior (Pressure-Volume-Temperature or PVT data), rock-fluid interaction properties, initial pressure and temperature conditions, well data, production history if any, and forecast targets and constraints. Pressure profiles versus depth are obtained through well measurements. Laboratory routine analyses on cores provide information about horizontal and vertical permeabilities; special core analyses are performed to obtain capillary pressures and relative permeability curves. Fluid samples are collected and analyzed in laboratories to obtain PVT fluid properties. Well testing is a common and powerful tool to get reliable estimates of well productivity, permeability of the formation, and evidence of possible heterogeneities within the test drainage area. The grid cells obtained from the static model are connected through flow equations describing the fluid flow under pressure variations.

The basic workflow consists of five steps: data acquisition, model design, initialization, history matching and forecast. The design of a simulation model is influenced by the type of process to be modeled, the complexity of the fluid-mechanics problem, the objectives of the study, the quality of the data, and the time and budget constraints. Common simulators consider only three fluids (black oil models), namely oil, water and gas, and isothermal conditions, with the temperature depending on the local geothermal gradient; more complex processes require to account for all the fluid components (compositional models) and for the thermal variations of the system. The initialization phase consists in assigning the initial saturation and pressure distributions, verifying the thermodynamic and hydrostatic equilibrium, and double-checking the hydrocarbons volumetric evaluations performed with the static model. In the history matching phase, the model is calibrated based on the available measured pressure and production data, by modifying the input parameters through a manual or assisted back analysis approach. Once the model is properly calibrated, productivity and recovery forecasts are performed for different field development scenarios.

The static and dynamic modeling approach for underground gas storage analysis follows the same workflow as a conventional reservoir study; however, there are issues, which are specifically relevant to gas storage. These include varying gas composition, reservoir temperature (slight) reduction due to repeated injection of “cold” gas, enhanced effects of petrophysical heterogeneities on the pressure response due to the cyclical withdrawal and injection of gas at high rates resulting in rapid and significant pressure variations and hysteresis of gas-water relative permeabilities (Verga, 2018).

The chemical composition of the stored gas can go from natural gas (typically methane with small percentages of heavier hydrocarbon components) to CO_2, to H_2 or any mixture of the above. CO_2 is very distinctive because it exhibits super-critical behavior at reservoir conditions. Obviously, composition variations affect the gas PVT behavior and thus the dynamics of the system, because pore pressure is intrinsically connected to gas compressibility which, in turn, is a function of gas composition. Compositional models are therefore needed to accurately simulate the effects induced by gas composition variations due to injection.

3.3. *Microscale analysis*

In recent years, the availability of new technologies to characterize pore spaces with a high level of detail supported the growing interest in pore-scale modeling. For example, X-ray micro-CT imaging allow reconstruction and visualization of a 3D porous medium with a resolution sufficient to identify grains and pores (Wildenschild & Sheppard, 2013). Thanks to this technique, a realistic representation of the reservoir rock can be obtained and used as an input for further geometrical and hydrodynamic analyses. In addition, algorithms able to reproduce 3D synthetic porous media with given grain size distribution, porosity and anisotropy have become increasingly abundant. The output is a 3D binary image.

At macroscale, fluid flow is modeled by averaging the microscopic continuity and momentum equations over a representative elementary volume (REV) and the porous medium is parameterized mainly by porosity and permeability. The fundamental equation of fluid motion in porous media is Darcy's equation. However, at microscale, porous media are complex materials characterized by a chaotic structure and tortuous fluid flow, with pore and grain dimensions varying over a wide range. To address the crooked fluid paths through the porous structure, the concept of tortuosity (geometrical, which is based on distances, or hydraulic, which is based on the actual flow paths) was introduced. Moreover, to account for pore space interconnections, the concept of effective porosity was introduced. These microscale properties can be estimated through a geometrical investigation of the pore space using specific algorithms, such as medial axis or path-finding algorithms, and by performing hydrodynamic simulations at the pore-scale (Viberti *et al.*, 2020). When fluids saturate the rock pores, the interactions between the different components depend on the physical and chemical properties of fluids and solid boundaries. All displacement phenomena are governed by local capillary pressure and by its instabilities. Fluid displacement on a pore-by-pore basis is composed of a sequence of equilibrium steps, where fluids reach an equilibrium position (energy balance) following Young-Laplace equation. In water-wet permeable media, non-equilibrium capillary pressure conditions can cause water layers to swell and spontaneously fill the pore throats, thus disconnecting and trapping the non-wetting phase (Roman *et al.*, 2017): this is called snap-off, and is very relevant in many processes including CO_2 sequestration.

3.3.1. Microfluidics for pore-scale investigation

Microfluidics has expanded from chemical and biological applications to energy and environmental fields. Unlike traditional core flooding experiments, in which transport properties are indirectly calculated by measuring the pressure drop across a rock sample, microfluidic chips enable direct visualization of the fluid dynamics in synthetic porous media.

A microfluidic chip is a microdevice whose outer dimensions range from hundreds of microns to centimeters. The device is usually constituted of two layers: the lower layer hosts the microfluidic patterns and the optically transparent upper one seals the circuit and allows for the visualization of the fluid flow. For microfluidic devices simulating rocks, the microfluidic patterned core mimics the porous network, and the inlet and outlet channels connect the pore network to the inlet and outlet ports. The internal features range from nanometers to hundreds of microns. The devices can be fabricated with a variety of additive and subtractive manufacturing techniques and all the materials of technological relevance can be selected: glass, silicon, polymers, composites and geomaterials (Jahanbakhsh *et al.*, 2020).

Glass is one of the most commonly employed materials, and historically one of the first to be used, together with silicon. Its optical transparency, hardness, chemical and thermal stability are indeed extremely well suited for applications in the geological and petroleum engineering field. Among the very many types of Si/glass microfluidics fabrication methods (Park *et al.*, 2004; Ciprian *et al.*, 2007; Marasso *et al.*, 2008; Marasso *et al.*, 2011; Henley *et al.*, 2012Ku *et al.*, 2018; Kumar Mishra *et al.*, 2019), micro powder blasting, relying on physical erosion by an abrasive powder jet accelerated towards the substrate, or laser micromachining are technological options enabling cheap, fast and complex three-dimensional micro-structuring. Pore network structures can also be generated on the surface of silicon wafers, using essentially the same methods as for the generation of pore network patterns on glass. Since silicon is opaque in the visible spectrum, direct optical visualization of fluid flow processes inside pore network structures is only possible at the surface of a silicon wafer bonded to a transparent substrate. To this purpose, a glass-silicon-glass architecture is typically used with anodic bonding as the dominant technology enabling complex multi-level microfluidic systems. The main advantage of using silicon over glass substrates is its ability to generate pore network structures with very high (sub-nanometer) resolution and accuracy.

Transparent polymers are also considered valid options for the fabrication of microfluidic devices, being significantly cheaper than silicon or glass (Marasso *et al.*, 2014; Tsao, 2016). Photolithography, 3D printing and/or molding processes are the most common manufacturing techniques (Vitale *et al.*, 2013; Vitale *et al.*, 2015; Bertana *et al.*, 2018). 3D printing is undoubtedly the most recent approach for microfluidics. It allows moving directly from digital design data to manufacturing. Though still limited for large volume needs, it is perfectly suited for microfluidic systems with moderate resolution but high level of complexity, outrunning in this sense more conventional manufacturing techniques. Polymers are generally more versatile than silicon or glass, available in a wide range of compositions and thus of physicochemical properties, cheaper, allow for surface modification, and can easily be bonded. However, this also implies that the surface tends to undergo undesired modifications during processing, which requires additional stabilization. Moreover, polymers can be blended with nanostructured materials to provide composites with improved characteristics and performance (Quaglio *et al.*, 2011). The main drawbacks of polymers are their reduced chemical and mechanical resistances, that limit their application with solvents and make them unsuitable to withstand high temperatures and high differential pressures.

Main applications of microfluidics in the oil and gas field are related to the investigation of water/oil separation (Quaglio *et al.*, 2019), drainage and imbibition processes (Gunda *et al.*, 2011), enhanced oil recovery (Gaol *et al.*, 2020), CO_2 underground storage (Amarasinghe *et al.*, 2021), carbonate reservoirs and dissolution processes (Soulaine *et al.*, 2021) and PVT measurements (Molla and Mostowfi, 2021).

4. Underground storage

4.1. Storage as a discipline

The concept of storing natural gas underground in geologic formations arose from the need to balance the divergence between a constant gas supply and the seasonal and daily variability of gas consumption. The first successful underground storage of natural gas in a depleted gas reservoir occurred in 1915 in Ontario, Canada. Since then, hundreds of facilities have been developed. Underground gas storage (UGS) may be defined as the long-term safe isolation of natural gas within geological formations. Thus, two of the most important characteristics of an underground storage are its ability to hold natural gas for future use and the rate at which that gas can be withdrawn. Depleted gas and oil reservoirs, deep saline formations, salt caverns and un-minable coal beds are the favorable candidates for safe geological storage of natural gas, but several reconditioned mines are also in use as gas storage facilities.

Historically, depleted gas or partially depleted gas reservoirs have been the most sizeable and commonly used formations for natural gas storage. A depleted field typically represents the most suitable option because of its proven ability to contain and trap gas on a geological timescale. Pressure is used to force the gas into and out of the porous and permeable reservoir while a sealing caprock prevents vertical fluid migration. However, if the original formation pressure is exceeded during storage operations to increase the working gas volume (i.e. delta-pressure conditions are applied), there is a risk that the caprock may fail to confine the gas. Thus, both the hydraulic sealing capacity and the mechanical resistance of the caprock must be carefully investigated. Geomechanical analyses are also needed for evaluation of potential subsidence and induced (micro)seismicity. A significant advantage of depleted fields is the level of knowledge already gained and readily available: information about the geological, structural, petrophysical characteristics and fluid-flow properties are inherited from the exploration and production phases. From a commercial standpoint, depleted reservoirs typically provide very good storage efficiency, both in terms of movable gas volume and injection/withdrawal gas rates. Deep saline aquifers represent a common alternative for UGS. The development and management of saline aquifers require that the original formation pressure is exceeded to displace the water initially saturating the pores of the rock to accommodate the gas. Therefore, the sealing capacity of the caprock, the presence of spill points (depths below which the gas may "escape" from the geological structure) as well as the rock mechanical integrity must be assessed in order to prevent gas leakage. Salt caverns and excavated rock caverns (such as coal and granite) are generally developed in regions where reservoirs are not available. They are typically much smaller in volume than either depleted reservoirs or aquifers but can provide high delivery rates (Benetatos *et al.*, 2013).

The successful development of a UGS must include an appropriate site selection based on subsurface information and subsequent performance analysis, preferably based on an integrated geological, geochemical, fluid-dynamic and geomechanical approach. To this end, the same basic sets of information as a typical reservoir study are used: geophysics, geology, well logging and core analysis, well testing and production history, rock compressibility. Furthermore, an adequate monitoring program to satisfy technical and safety regulations together with social and environmental concerns must also be conceived to ensure the long-term feasibility of the project, especially if delta-pressure conditions are applied. However, even though the UGS industry has borrowed much of its knowledge from other industries (primarily oil and gas reservoir engineering and production), it has also needed to develop a technology of its own to meet specific challenges and concerns (Verga, 2018).

4.2. Carbon capture, utilization and storage and hydrogen storage

Underground storage of carbon dioxide and hydrogen is quite similar to the underground storage of natural gas. In fact, most of the past and ongoing underground CO_2 and H_2 storage projects use the experiences of the underground natural gas storage in each and every aspect, such as site specifications, storage techniques, monitoring and even cost life cycle or economic viability. The major difference is represented by the physiochemical properties of CO_2 and hydrogen that require more attention than natural gas especially in terms of leakage, monitoring, chemical affinity and potential chemical, biological or microbial reactions.

Long-term CO_2 underground storage is regarded as an essential mitigation option to reduce greenhouse gases in the atmosphere and contrast climate change. CCUS (Carbon Capture, Utilization and Storage) encompasses all the methods and technologies to remove CO_2 from the industrial flue gas and from the atmosphere, followed by CO_2 recycling or by safe and permanent storage options (IEA, 2020). In this perspective, a dualism exists between CO_2 utilization and storage – as if one technology was alternative rather than complementary to the other. The authors believe that, as opposed to permanent geological sequestration, temporary underground storage should be part of the CCUS process as a strategy to efficiently couple CO_2 capture with CO_2 valorization options, i.e. the storage acts like a "buffer". In this approach, CO_2 storage is fully integrated with valorization technologies leading to a virtuous CO_2 cycle, or the three C's: Capture, Cache and Convert (Bocchini *et al.*, 2017). Each industrial segment could operate independently and optimize its own value chain with an expected significant efficiency enhancement, largely offsetting the cost due to storage. There are several technologies for CO_2 sequestration and re-use; some of them are already available in the market whereas others, at present, still need a further step of development to become industrially appealing, an example being the RECODE EU project (recodeh2020.eu). Furthermore, deploying all of them at the same site still requires significant efforts. The capture process can be attained either from the atmosphere or at the emission source, such as power plants, cement plants or biomass plants where a conversion process – *i.e.* combustion – produces carbon dioxide-rich flue gases. Among the possible separation techniques, the amine scrubbing technology is very mature and has been industrially employed for over 50 years in post-combustion separation. However, amines have major drawbacks: they are toxic/corrosive and require a large amount of energy to be regenerated. Other technologies such as the use of ionic liquids can solve some critical issues (Latini *et al*,. 2019) as they feature negligible vapor pressure, non-corrosiveness and low energy demand (Davarpanah *et al*,. 2020). Following CO2 capture, the valorization process to obtain chemicals and fuels can be exploited both as a direct conversion process, or as the final step of a value chain. Several (bio)chemical approaches can be designed to obtain the desired molecules, and each of them can be valueable in specific application conditions. The biocatalytic route exploits ad-hoc developed microorganism strain to obtain the desired products (Vasile *et. al.*, 2021), electrochemical valorization (Zeng *et al.*, 2018 and 2021; Bejtka *et al.*, 2019, Zeng *et al.*, 2021) exploits renewable energy sources to power the system (Sacco *et al.*, 2020), while thermocatalytic processes, can take advantage of hydrogen from renewables in the power to gas approach. In the chemical catalytic approaches, the challenge is to select and optimize processes and materials highly selective, efficient, inexpensive and environmentally friendly, able to be competitive in the energetic transition (Kamkeng *et al.*, 2020). At present, CO and formic acid are considered to be the most economically viable molecules in electro catalytical processes (Jouny *et al.*, 2020), while thermocatalysis is more efficiently exploited to obtain methane, methanol and more complex C2 molecules (e.g. ethylene).

Currently, hydrogen is generally stored as a gas in very high-pressure vessels, or in liquid form at very low temperatures in heavily insulated vessels. Such vessels are expensive, heavy and inconvenient. Geological storage is a possible option to store large quantities of hydrogen and therefore large amounts of energy over long timescales. This is the reason why underground H_2 storages has been given serious consideration. Hydrogen can be stored using either salt caverns or porous formations like saline aquifers or depleted gas and oil fields. While hydrogen has already been stored successfully in salt caverns for industrial use, experiences with subsurface porous media hydrogen storage are relatively scarce. Although large-scale underground storage of hydrogen is possible thanks to the technology of underground storage of natural gas and carbon dioxide, additional investigations are needed to assess technical feasibility and safety with respect to caprock tightness, diffusivity, interactions with the reservoir rocks with potential subsequent changes of the storage properties, reactions with microbial communities and compatibility with materials. All these aspects are currently being investigated by the PoliTO-IIT research team with equipment suitable to run experiments even at the challenging pressure and temperature conditions typical of deep underground geological formations.

4.2.1. EoS and phase behavior

Hydrogen and methane are in gaseous phase at both reservoir and standard conditions due to their critical constants and phase diagram. When storing H_2 in a depleted reservoir, the description of the interaction between fluids (H_2, hydrocarbons and water) and the volumetric behavior of the resulting gas mixture requires the adoption of a compositional fluid model. The fluid behavior is defined by an Equation of State (EoS) which must be properly selected for the range of pressure and temperature conditions of the physical system under investigation. The two most used EoS implemented in compositional reservoir simulators are the cubic equations called Soave-Redlich-Kwong, originally conceived by Redlich and Kwong in 1949 and subsequently improved by Soave in 1972, and Peng-Robinson, in which a further modification to the Soave-Redlich-Kwong equation was introduced in 1976. The GERG-2008 EoS can also approximate well the thermodynamic properties of natural gases and other mixtures for a wide range of mixture compositions, pressure and temperature.

4.2.2. Diffusion

One of the issues to be addressed for gas storage is the sealing capacity of reservoir caprocks to prevent upward gas migration. In gas reservoirs evidence proves that methane diffusion through caprocks is negligible even over geological times. Conversely, H_2 and CO_2 diffusion through reservoir caprocks has to be properly evaluated as well as diffusion of any gas mixture in the case of storage in aquifers.

Hydrogen diffusivity mainly takes place in the water saturating the caprock (Hemme & Van Berk, 2018; Vinsot *et al.*, 2014); the gas first dissolves in the water and then diffuses through it. Solubility and diffusivity of CH_4, H_2 and CO_2 in pure water are shown in Tab. 1.

Diffusivity coefficient measured at ambient pressure should represent an overestimation of diffusivity at reservoir pressure because theoretical values of free molecular diffusivity coefficient for most gases show a direct proportionality with temperature and an inverse proportionality with pressure (Roberts, 1972). Inverse correlations between diffusion coefficients and pressure were experimentally observed for diffusion of He in rocks (Pandey et al., 1974.), CH_4 in rocks (Schlomer et al., 2004), CH_4 in coal (Wang et al., 2016) and H_2 in clay (Boulin et al., 2008). Diffusion is higher for dry samples because hydrogen diffuses directly in the empty pore spaces: measurements on dried argillites samples were close to 10-7 m^2/s while tests on the same argillite at different water saturation values showed diffusion was two orders of magnitude lower than for dry samples. In water saturated clay rocks, measured H_2 diffusion was found in the range 10-12-10-10 m2/s (Krooss, 2008; Aertsens, 2009; Jacops et al., 2012; Vinsot et al., 2014; Jacops et al., 2015). Water salinity could also have an impact on diffusivity. According to Panfilov (2016) caprocks saturated with water represent an impermeable barrier to hydrogen, and numerical simulations with a hydrogeochemical modeling approach confirmed that the loss of hydrogen by diffusion through the caprock at reservoir conditions is negligible (Carden and Paterson 1979; Krooss, 2008; Hemme et al., 2018). The diffusion values of H2-CH4 mixtures measured by the PoliTO-IIT research team at standard pressure and reservoir temperature are also in the range 10-10-10-11 m^2/s and seem to confirm the sealing capacity of clayey caprocks.

Tab. 1 – Solubility and diffusivity of CH_4, H_2 and CO_2 in pure water (Engineering toolbox, 2008; Wise & Houghton, 1966; Tamimi *et al.*, 1994).

Gas	Solubility in water (g/kg)		Diffusivity in water (m2/s)	
	@ 20°C, 0,1 MPa	@ 60°C, 0,1 MPa	@ 20°C, 0,1 MPa	@ 60°C, 0,1 MPa
CH_4	0.023	0.007	2.4 10^{-9}	6.7 10^{-9}
H_2	0.0016	0.0012	5.0 10^{-9}	13.1 10^{-9}
CO_2	0.16	0.6	1.67 10^{-9}	4.2 10^{-9}

4.2.3. Biochemistry

Biogeochemical analyses need to be carried out with the main aim of assessing the potential changes in the stored gas mixture and in petrophysical properties due to microbial activities within the reservoirs selected for underground storage of CO_2 or H_2. Several studies have estimated that generally between 10^3 and 10^6 microbial cells per milliliter of water can be found in deep underground formations (Ivanova, 2007; Gniese, 2014; Itävaara, 2016) and it is well known that microbial communities can deeply affect the activity of UGS with respect to: (i) loss of stored gas and, as a result, loss of energy value; (ii) damage to plant and technical equipment due to biocorrosion and clogging caused by biofilm formation and biomass accumulation; (iii) safety risks to operators mainly due to the production of hydrogen sulfide, which is highly toxic (West, 2011; Gniese, 2014).

The recent development of powerful molecular biology tools, such as high-throughput Next-Generation Sequencing (NGS) technologies, has allowed for a targeted and detailed study of the deep microbiota, characterized by non-culturable microorganisms that cannot be analyzed by standard laboratory techniques. Samples of formation fluids and sediments can be collected prior to injection for a baseline on microbial composition to be compared with changes induced by the presence of insufflated CO_2 or H_2. In both cases, microbiological analysis is useful to identify and monitor the biogeochemical processes, which can affect the consumption and diffusion of the gas within the reservoir during storage. Numerous studies of microbial communities in the deep biosphere have revealed that – based on their metabolic pathways – four main classes of microorganisms can be distinguished: methanogens, sulphate reducers, homoacetogenic bacteria and iron reducers, with the first two posing the greatest risks to the storage site (Leung, 2014; Heinemann, 2021).

In the case of CO_2 storage, it is extremely unlikely that microorganisms can survive direct exposure to supercritical CO_2. However, it has been proven that, after the injection phase, different microbial classes can be exposed to the gaseous or dissolved phase of CO_2 and metabolize it to proliferate. The direct effect of CO_2 is its potential role as oxidant compound that can be used as an energy source (e.g. for methane production), while the indirect effect is the reduction of the pH level, altering the composition of the microbiota and leading to a reduction in the microbial diversity (Gulliver, 2016).). It has been shown by experimental evidence that resilient microbial populations can have both favourable and unfavourable effects on the capacity, integrity and safety of a storage site (Gniese, 2014). For example, biofilm formation can potentially help to "lock in" the injected CO_2 and prevent its migration as plume. Conversely, the activation of some microbial metabolisms, e.g. methanogenesis, can lead to methane production and potential leakage (Mu & Moreau, 2015). Although the effects related to microbial activity may be small and almost undetectable at the beginning of the storage period, they can become very difficult to control and costly to remediate if autocatalytic reactions are triggered (West, 2011).

The studies needed to ensure safety and efficiency of a H_2 storage are even more complex than those required for CO_2 since the experience and practical applications of underground H_2 storage are to date very limited (Heinemann, 2021). From a biochemical point of view, the insufflation of hydrogen can trigger the proliferation of all the hydrogenotrophic microorganisms, which belong to the four aforementioned metabolic classes. It has been proven that the risks of H_2 loss is higher when more terminal electron acceptors for microbial metabolic activities, like CO_2 and sulfate, are available. Therefore, a detailed mineralogical-petrographic analysis of the reservoir and caprock is needed to assess the content of sulfate- and carbonate-based minerals (e.g. calcite, dolomite and siderite) (Flesch, 2018; Hemme & Van Berk, 2018).

The PoliTO-IIT research team is applying its expertise in microbiology and reactor engineering in order to: (i) carry out the characterization of microbial profile of the microbiota in depleted reservoirs of interest for potential conversion into storages, and (ii) study the microbial metabolic activities by means of a multiphase reactor system (installed in the SEASTAR facilities) that has been specifically designed to reproduce reservoir conditions (max pressure = 200 bar and max temperature = 150°C), with solid rock samples, microfluidic chips, bacteria and flow of gas/liquid mixtures . The microbiological analysis is carried out by means of taxonomic and relative abundances determination of deep microbiota through NGS sequencing of the 16S ribosomal subunit, with specific targets for both bacteria and archaea populations. The study is complemented by the use of functional genes for the characterization of the metabolic activities of methanogenic archaea (*mcrA*) and sulphate-reducing bacteria (*dsrB*) (Ranchou-Peyruse, 2019).

4.2.4. Geochemistry

Geochemistry plays an important role in CO_2 storage. The reactivity of carbonate and silicate minerals is at the heart of porosity and pore geometry changes in rocks injected with CO_2, which ultimately control the evolution of flow and transport properties of fluids in porous (Noiriel & Daval, 2017). Supercritical CO_2 at the pressure and temperature conditions typical of subsurface storage is soluble to a limited degree in water and saline brine but enough to transform the brine into a carbonic acid solution. The acidified brine can dissolve silicate minerals in the rocks, a form of silicate rock "weathering", the extent of which depends on the availability of divalent cations contained in silicate minerals and the kinetics of mineral dissolution. The second part of the weathering cycle, which can also occur in underground reservoirs, is the recombination of released divalent cations like Ca, Mg and Fe with dissolved CO_2 to form solid carbonate minerals. Intuitively, an increase in permeability is likely to occur due to dissolution while carbonation should lead to a permeability reduction by globally decreasing the reservoir porosity. However, the evolution of permeability also depends on how the pore space is affected by reactions, e.g.: non-uniform precipitation patterns emphasize the permeability decrease by increasing the pore roughness; crystallization pressure resulting from precipitation of carbonates or salts could induce fracturing and the creation of new flow paths. Thus the prediction of permeability evolution in reservoirs is somewhat challenging due to the number of factors that can affect the dynamics of flow path enlargement or clogging. In addition, sample-size limitations restrict the ability to predict reliable porosity-permeability relationships at larger scales.

4.3. Geomechanical issues

Pressure changes caused in geological formations by fluid production and/or storage affect the rock stress state. If the variations of the rock stress state are significant, they could jeopardize the formation integrity and induce microfracturing, faults (re)activation and ground movements. Therefore, current regulations and public concerns call for geomechanical analyses to assess safety conditions in terms of stored gas containment, earthquake hazard and subsidence magnitude and extension. Geomechanical models, based on mechanical properties derived from lab and in-situ measurements, are strongly connected to the static and dynamic models. The geomechanical model simulates the stress state variations, verifies rock integrity and potential fault slippage, and calculates the rock deformation, which can propagate to the surface and induce ground movements. If ground movement surveys are available, a back-analysis procedure is carried out: the rock mechanical parameters are calibrated until a satisfactory match is achieved between simulated and measured deformations. The Interferometric Synthetic Aperture Radar (InSAr) acquisition technique is widely adopted for ground movements surveys due to its high accuracy (millimeters) on large areas (Berardino *et al.*, 2003; Ferretti *et al.*, 2001).

In the case of natural gas storage, seasonal ground movements can be correlated with withdrawal/injection operations. Gas pressure changes in the geological formations cause variations of effective stresses; if these variations are significant, they could affect the formation integrity and induce microfracturing, faults (re)activation and ground movements. Therefore, avoidance of these issues calls for geomechanical analyses to assess safety conditions.

The analysis of ground movement surveys induced by the storage systems located in the Po Plain, Italy (depth is in the range 1-1.5 km), shows a consistent relation between pressure variations and corresponding subsidence/rebound at the surface level (Codegone *et al.*, 2016; Coti *et al.*, 2018; Benetatos *et al.*, 2020). This UGS-related pressure variations due to the withdrawal/injection phases affect the formation cyclically and over relatively short periods (typically 5-7 months). The correlation between gas injection/extraction and upward/downward ground movements indicates that the formations behave elastically (Teatini *et al.*, 2011; Ferronato *et al.*, 2013). When a depleted reservoir is converted into a storage, it is initially refilled with gas; this phase generates a pressure increase and thus a decrease of the effective stresses (unloading). The subsequent cycles of gas withdrawal (loading) occur in the elastic field, with a stiffer behaviour than in primary production, where the quasi-monotonic pressure decrease occurring over decades can induce a consistent time-dependent behaviour of the sandy reservoir materials (Musso *et al.*, 2021). The simulation of the deformations induced by gas withdrawal/injection cycles requires an appropriate choice of the relevant parameters by selecting the reference range of strains of the process from lab tests (Marzano *et al.*, 2019, Rocca *et al.*, 2019). Furthermore, the transverse isotropy of the clastic formations can affect their mechanical response during storage cycles, as in the case of wellbores (Deangeli & Omwanghe, 2018; Parkash & Deangeli, 2019; Deangeli *et al.*, 2021).

4.3.1. Microseismicity monitoring

Microseismic monitoring is the passive observation of very small-scale earthquakes (i.e. magnitude less than zero) which occur in the underground because of geothermal operations or gas storage which cause a stress state change. During stress redistribution, sudden slips can occur along pre-existing zones of weakness such as faults or fracture networks, releasing energy in the form of seismic waves which are known as microseismic events. These micro-earthquakes are typically too small to be felt on the surface but can be detected by borehole seismic sensors with an adequate resolution in order to register even very low magnitude events at the depths of the geological formations involved in the injection or withdrawal operations. The spatial and temporal variations in microseismicity can be used to monitor changes in the stress field and hence potentially be used to monitor perturbations in fluid pathways as well as top-seal and well-bore integrity.

The design of a microseismic network for monitoring purposes must be based on a detailed analysis of the local and regional faults systems, especially in areas where infrastructures and/or urban settlements are present. Prior to installation of the instruments, a careful mapping of all the possible sources of noise is necessary as well as a quantitative analysis of the noise levels at the selected locations.

4.4. Conversion of offshore facilities

In the case of an offshore (partially) depleted reservoir to be converted into CH_4-H_2 mixtures or CO_2 storage facility, this also implies the conversion of the platform originally designed for hydrocarbon production. This option is particularly attractive because it allows minimizing the environmental impact that is typical of complete platform decommissioning, in particular for the subsea ecosystem that has grown around the jacket, and because it offers a cost-saving solution for the implementation of the equipment needed for underground gas storage.

The accidental release of dangerous (flammable and/or toxic) high pressure gases are one of the key safety issues for offshore platforms. Thus, an efficient CFD model has been developed (Carpignano *et al.*, 2017; Moscatello *et al.*, 2021) to simulate accidents with the aim of using the simulation results as a driver for effective design choices. The model, called SBAM model, is being validated by experimental activities, where model predictions are compared with the dispersion of a low concentration methane release into a scaled mock-up of an oil&gas platform (scaled 1:10) in the SEASTAR facilities of the PoliTO-IIT research team (Gerboni *et al.*, 2020; Moscatello *et al.*, 2020). The program of the research aims at extending the application of the model for the simulation of potential accidents involving CH_4-H_2 mixtures and CO_2.

Along with CH_4-H_2 or CO_2 storage, other complementary conversion options have been taken into account for the production of photovoltaic (PV) energy and use of this renewable energy for the separation and delivery of desalinated seawater for civil use, and recovery of raw materials such as lithium from the resulting brine.

References

Agarwal, R.G., 1980. *A New Method to Account for Producing Time Effects When Drawdown Type Curves Are Used To Analyze Pressure Buildup and Other Test Data.* Presented at the SPE ATCE, Dallas, Texas, USA, SPE-9289-MS.

Ahn, S., Horne, R., 2010. *Estimating Permeability Distributions From Pressure Pulse Testing.* ATCE, Florence, Italy. SPE-134391-MS.

Amarasinghe, W., Farzaneh, S., Fjelde, I., Sohrabi, M., Guo, Y., 2021. *A Visual Investigation of CO_2 Convective Mixing in Water and Oil at the Pore Scale Using a Micromodel Apparatus at Reservoir Conditions.* Gases, Vol. 1(1), pp. 53-67.

Azarkish, A., Khaghani, E., Rezaeidoust, A., 2006. *Interpretation of Water Injection/Fall Off Test* (Response to M.Levitan,SPE 77532). Conference paper presented at the SPE International Oil & Gas Conference and Exhibition in Beijing, China, 5-7 December.

Azin, R., Mahmoody, M., Jafari Raad, S.M., Osfouri, S., 2013. *Measurement and modeling of CO_2 diffusion coefficient in saline aquifer at reservoir conditions.* Cent Eur J Eng, 3(4), pp. 585-594.

Azzarone, E., Beretta, E., Guglielmelli, A., Nunzi, P., Mariotti, P., 2011. *Gas Injection testing & PLT – Off-shore Eni Experience.* OMC, Ravenna, Italy.

Bejtka, K., Zeng, J., Sacco, A., Castellino, M., Hernández, S., Farkhondehfal, M.A., Savino, U., Ansaloni, S., Pirri, C.F., Chiodoni, A., 2019. *Chainlike Mesoporous SnO_2 as a Well-Performing Catalyst for Electrochemical CO_2 Reduction.* ACS Applied Energy Materials, 2(5), pp. 3081-3091.

Benetatos, C., Codegone, G., Deangeli, C., Giani, G., Gotta, A., Marzano, F., Rocca, V., Verga, F., 2017, *Guidelines for the study of subsidence triggered by hydrocarbon production*, Geoingegneria Ambientale e Mineraria, 152(3), pp. 85-96

Benetatos, C., Codegone, G., Ferraro, C., Mantegazzi, A., Rocca, V., Tango, G., Trillo, F., 2020. *Multidisciplinary Analysis of Ground Movements: An Underground Gas Storage Case Study.* Remote Sensing, 12, 3487.

Benetatos, C., Codegone, G., Rocca, V., 2020. *Subsidence analysis in the Italian Po Plain area: an extended case study.* Proceedings of the 82nd EAGE Conference & Exhibition 2020.

Benetatos, C., Giglio, G., 2021. *Coping with uncertainties through an automated workflow for 3D reservoir modelling of carbonate reservoirs.* Geoscience frontiers, (in press).

Benetatos, C., Málek, J., Verga, F., 2013, *Moment tensor inversion for two micro-earthquakes occurring inside the Háje gas storage facilities*, Czech Republic, Journal of Seismology, 17(2), pp. 557-577

Benetatos, C., Salina Borello, E., Peter, C., Rocca, V., Romagnoli, R., 2019. Considerations on energy transitions. GEAM. Geoingegneria Ambientale e Mineraria, Vol. 158 (3), pp. 26-31.

Benetatos, C., Viberti, D., 2010. *Fully integrated hydrocarbon reservoir studies: myth or reality?* American Journal of Applied Sciences, Vol. 7(11), pp. 1477-1486.

Berardino, P., Costantini, M., Franceschetti, G., Iodice, A., Pietranera, L., Rizzo, V., 2003. *Use of differential SAR* *interferometry in monitoring and modelling large slope instability at Maratea (Basilicata, Italy).* Engineering Geology, Vol. 68, pp. 31-51.

Beretta, E., Tiani, A., Lo Presti, G., Verga, F., 2007. *Value of Injection testing as an Alternative of Conventional Well testing: Field Experience in a Sour-Oil Reservoir.* SPEREE, Vol. 10 (2), pp. 112-121. SPE-100283-PA.

Bertana, V., Potrich, C., Scordo, G., Scaltrito, L., Ferrero, S., Lamberti, A., Perrucci, F., Pirri, C.F., Pederzolli, C., Cocuzza, M., Marasso, S.L., 2018. *3D-printed microfluidics on thin Poly(-methyl methacrylate) substrates for genetic applications*, Journal of Vacuum Science and Technology B, Vol. 36(1), 01A106-1/7.

Bocchini, S., Castro, C., Cocuzza, M., Ferrero, S., Latini, G., Martis, A., Rocca V., Viberti, D., 2017. *The virtuous CO_2 circle or the three Cs: capture, cache, and convert.* Journal of Nanomaterials. DOI: 10.1155/2017/6594151

Boughrara, A.A., Peres, A.M., Chen, S., Machado, A.A.V., Reynolds, A.C., 2007. *Approximate Analytical Solutions for the Pressure Response at a Water-Injection Well.* SPE Journal, Vol. 12 (1), pp. 19-34.

Boulin, P., Angulo-Jaramillo, R., Daıan, J.F., Talandier, J., Berne, P., 2008. *Experiments to estimate gas intrusion in Callovo-oxfordian argillites*. Phys. Chem. Earth A/B/C 33, pp. 225-230.

Bourdet, D., Whittle, T.M., Douglas, A.A., Pirard, V.M., 1983. *A New Set of Type Curves Simplifies Well Test Analysis,* in: WORLD OIL, May 1995.

Boving, T.B., Grathwohl, P., 2001. *Tracer diffusion coefficients in sedimentaryrocks: correlation to porosity and hydraulic conductivity*. Journal of Contaminant Hydrology, 53, pp. 85-100.

Carden, P.O., Paterson, L., 1979. *Physical, chemical and energy aspects of underground hydrogen storage*. Int J Hydrog Energy, 4(6), pp. 559-56.

Carpignano, A., Corti, T., Uggenti, A.C., Gerboni, R. 2017. *Modelling of a supersonic accidental release in Oil&-Gas offshore: Characterisation of a source box.* GEAM. Geoingegneria Ambientale e Mineraria. 152:3, pp. 58-64.

Ciprian I, Bangtao C, Jianmin M, editors, 2007. Deep wet etching-through 1mm pyrex glass wafer for microfluidic applications. IEEE 20th International Conference on Micro Electro Mechanical Systems (MEMS); 2007 21-25 Jan. 2007.

Codegone, G., Rocca, V., Verga, F., Coti, C., 2016. *Subsidence modeling validation through back analysis for an Italian gas storage field*. Geotechnical and Geological Engineering, Issue 6.

Coelho, A.C.D., de Carmargo, C., Kato, E.T., Legrand, V.M., 2005. *Utilizing Mini – DST for Formation Evaluation.* Presented at the SPE Latin American and Caribbean Petroleum Engineering Conference in Rio de Janeiro, Brazil, June. SPE 94963.

Coti, C., Rocca, V., Sacchi, Q., 2018. *Pseudo-Elastic Response of Gas Bearing Clastic Formations: An Italian Case Study*. Energies, 11, 2488.

Davarpanah, E., Hernández, S., Latini, G., Pirri, C.F., Bocchini, S., 2020. *Enhanced CO_2 absorption in organic solutions of biobased ionic liquids*. Advanced Sustainable Systems, 4(1), 1900067.

Deangeli, C., Cardu, M., Martinelli D., 2021. *Analysis of the Stability of Openings Excavated in Anisotropic Rocks*. In: Barla, M., Di Donna, A., Sterpi D. (eds) Challenges and Innovations in Geomechanics. IACMAG 2021. Lecture Notes in Civil Engineering, vol. 126. Springer, Cham. https://doi-org.ezproxy.biblio.polito.it/10.1007/978-3-030-64518-2_43

Deangeli, C., Omwanghe, O., 2018. *Prediction of mud pressures for the stability of wellbores drilled in transversely isotropic rocks*. Energies, 11(8), 1944.

Dobereiner, L., 1984. *Engineering geology of weak sandstones.* University of London, United Kingdom.

Engineering ToolBox, 2008. *Solubility of Gases in Water*. Retrieved from https://www.engineeringtoolbox.com/gases-solubility-water-d_1148.html

European Union. *2030 climate & energy framework.* Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en

Ferretti, A., Prati, C., Rocca, F., 2001. *Permanent scatterers in SAR interferometry*. IEEE Transactions on Geoscience and Remote Sensing, Vol. 39, pp. 8-20.

Ferronato, M., Castelletto, N., Gambolati, G., Janna, C., Teatini, P., 2015. *II cycle compressibility from satellite measurements.* Géotechnique, Vol. 63(6), pp. 479-486.

Flesch, S., Pudlo, D., Albrecht, D., Jacob, A., Enzmann, F., 2018. *Hydrogen underground storage – Petrographic and petrophysical variations in reservoir sandstones from laboratory experiments under simulated reservoir conditions*. International Journal of Hydrogen Energy, Vol. 43(45), pp. 20822-20835.

Fokker, P.A., Renner, J., Verga, F., 2013. *Numerical modeling of periodic pumping tests in wells penetrating a heterogeneous aquifer.* American Journal Of Environmental Sciences, Vol. 9(1), pp. 1-13.

Fokker, P.A., Salina Borello, E., Serazio, C., and Verga, F., 2012. *Estimating reservoir heterogeneities from pulse testing.* Journal of Petroleum Science and Engineering, Vol. 86-87, pp. 15-26.

Fokker, P.A., Salina Borello, E., Verga, F., Viberti, D., 2017. *Harmonic Pulse Testing for Well and Reservoir Characterization.* In Proceedings 79th EAGE/Europec Conference.

Fokker, P.A., Salina Borello, E., Verga, F., Viberti, D., 2018. *Harmonic pulse testing for well performance monitoring.* Journal of Petroleum Science and Engineering, Vol. 162, pp. 446-459.

Fokker, P.A., Salina Borello, E., Viberti, D., Verga, F., van Wees, J.D., 2020. *Pulse Testing for Monitoring the Thermal Front in Aquifer Thermal Energy Storage.* Geothermics, Vol. 89.

Fokker, P.A., Verga, F., 2011. *Application of Harmonic Pulse Testing to Water-Oil Displacement.* JPSE, Elsevier, Journal of Petroleum Science and Engineering, Vol. 79, Issues 3-4, pp. 125-134.

Gaol, C.L., Wegner, J., Ganzer, L., 2020.

Real structure micromodels based on reservoir rocks for enhanced oil recovery (EOR) applications. Lab on a Chip, Vol. 20(12), pp. 2197-2208.

Gerboni, R., Carpignano, A., Gueccia, A., Ledda, G., Moscatello, A., Uggenti, A.C. 2020. *Wind tunnel: a versatile infrastructure for validating gas releases simulations.*. Presented at HYPOTHESIS XV HYdrogen POwer THeoretical and Engineering Solutions International Symposium, pp. 99-100

Gniese, C., Bombach, P., Rakoczy, J., Hoth, N., Schlömann, M., Richnow, H.H., Krüger, M. 2014. *Relevance of deep-subsurface microbiology for underground gas storage and geothermal energy production.* Advances in Biochemical Engineering/Biotechnology, Vol. 142, pp. 95-121.

Gringarten, A.C., Bourdet, D.P., Landel, P.A., 1979. *A Comparison Between Different Skin and Wellbore Storage Type-Curves for Early-Time Transient Analysis.* ATCE, Las Vegas, Nevada, USA. SPE-8205-MS.

Gulliver, D.M., Lowry, G.V., Gregory, K.B., 2016. *Comparative Study of Effects of CO_2 Concentration and pH on Microbial Communities from a Saline Aquifer, a Depleted Oil Reservoir, and a Freshwater Aquifer*. Environmental Engineering Science, vol. 33(10), pp. 806-816.

Gunda, N.S.K., Bera, B., Karadimitriou, N.K., Mitra, S.K., Hassanizadeh, S.M., 2011. *Reservoir-on-a-Chip (ROC): A new paradigm in reservoir engineering.* Lab on a Chip, Vol. 11(22), pp. 3785-3792.

Habte, A.D., Onur, M., 2014. *Laplace-Transform Finite-Difference and Quasistationary Solution Method for Water-Injection/Falloff Tests.* SPE Journal, Vol. 19(3), pp. 398-409.

Heinemann, N., Alcalde, J., Miocic, J.M., Hangx, S.J.T., Kallmeyer, J., Ostertag-Henning, C., Hassanpouryouzband, A., Thaysen, E.M., Strobel, G.J., Schmidt-Hattenberger, C., Edlmann, K., Wilkinson, M., Bentham, M., Haszeldine, R.S., Carbonell, R., and Rudloff, A., 2021. *Enabling large-scale hydrogen storage in porous media – the scientific challenges*. Energy and Environmental Science, Vol. 14, pp. 853-864.

Hemme, C., Van Berk, W., 2018. *Hydrogeochemical Modeling to Identify Potential Risks of Underground Hydrogen Storage in Depleted Gas Fields*. Applied Sciences, 8(11). 2282.

Hemme, C., Van Berk, W., 2018. *Hydrogeochemical modeling to identify potential risks of underground hydrogen storage in depleted gas fields*. Applied Sciences, Vol. 8(11), pp. 2282.

Henley WH, Dennis PJ, Ramsey JM., 2012. *Fabrication of microfluidic devices containing patterned microwell arrays*. Anal Chem. 84(3):1776-80.

Aertsens, M., 2009. *Re-evaluation of the experimental data of the MEGAS experiment on gas migration through Boom Clay*. SCK-CEN ER-100. Mol, Belgium.

Hollaender, F., Hammond, P.S., Gringarten, A.C., 2002. *Harmonic testing for continuous well and reservoir monitoring.* ATCE, San Antonio, Texas, USA. SPE 77692.

IEA, 2020. *CCUS in Clean Energy Transitions*, IEA, Paris. Retrieved from https://www.iea.org/reports/ccus-in-clean-energy-transitions.

Itävaara, M., Salavirta, H., Marjamaa, K., Ruskeeniemi, T., 2016. *Geomicrobiology and Metagenomics of Terrestrial Deep Subsurface Microbiomes*. Advances in Applied Microbiology, Vol. 94, pp. 1-77.

Ivanova, A.E., Borzenkov, I.A., Tarasov, A.L., Milekhina, E.I., Belyaev, S.S., 2007. *A Microbiological Study of an Underground Gas Storage in the Process of Gas Injection*. Microbiology, Vol. 76, 453.

Jacops, E., Volckaert, G., Maes, N., Govaerts, J., Weetjens, E., 2012. *Determination of gas diffusion coefficients in undisturbed Boom clay. Clays in natural and engineered barriers for radioactive waste confinement* – 5. International meeting. Book of abstracts.

Jacops, E., Wouters, K., Volckaert, G., Moors, H., Maes, N., Bruggeman, C. & Littke, R., 2015. *Measuring the effective diffusion coefficient of dissolved hydrogen in saturated Boom Clay*. Applied Geochemistry, 61, pp. 175-184.

Jahanbakhsh, A., Wlodarczyk, K.L., Hand, D.P., Maier, R.R., & Maroto-Valer, M.M., 2020. *Review of Microfluidic Devices and Imaging Techniques for Fluid Flow Study in Porous Geomaterials*. Sensors, Vol. 20(14), 4030.

Jouny, M., Luc, W., Jiao, F., 2020. *Correction to "General Techno-Economic Analysis of CO_2 Electrolysis Systems.* Ing. Eng. Chem, Res. 2020, 59, 16, 8121-8123.

Kamkeng, A.D.N., Wang, M., Hu, J., Du, W., Qian, F., 2021. *Transformation technologies for CO_2 utilisation: Current status, challenges and future prospects.* Chemical Engineering Journal, 409. 128138.

Kanji, M.A., 2014. *Critical issues in soft rocks*. Journal of Rock Mechanics and Geotechnical Engineering, 6(3), pp. 186-195.

Krooss, B., 2008. E*valuation of database on gas migration through clayey host rocks*. Belgian National Agency for Radioactive Waste and Enriched Fissile Material (ONDRAFNIRAS). RWTH, Aachen.

Ku X, Zhang Z, Liu X, *et al.* Low-cost rapid prototyping of glass microfluidic devices using a micromilling technique. Microfluidics and Nanofluidics. 2018 2018/07/21;22(8):82.

Kumar Mishra D, Arab J, Pawar K, *et al.* Fabrication of Deep Microfeatures in Glass Substrate using Electrochemical Discharge Machining for Biomedical and Microfluidic Applications. 2019.

Kunz, O., Wagner, W., 2012. *The GERG-2008 wide-range equation of state for natural gases and other mixtures: an expansion of GERG-2004*. Journal of chemical & engineering data, 57(11), pp. 3032-3091.

Kuo, C.H., 1972. *Determination of reservoir properties from sinusoidal and multirate flow tests in one or more wells*. SPE Journal, Vol. 12(06), pp. 499-507. SPE 3632.

Lamberti, A., Garino, N., Sacco, A., Bianco, S., Chiodoni, A., Gerbaldi, C. 2015. *As-grown vertically aligned amorphous TiO_2 nanotube arrays as* *high-rate Li-based micro-battery anodes with improved long-term performance*. Electrochimica Acta 151, pp. 222-229.

Latini, G., Signorile, M., Crocellà, V., Bocchini, S., Pirri, C.F., Bordiga, S., 2019. *Unraveling the CO2 reaction mechanism in bio-based amino-acid ionic liquids by operando ATR-IR spectroscopy*. Catalysis Today, 336, 148-160.

Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M. 2014. *An overview of current status of carbon dioxide capture and storage technologies.* Renewable and Sustainable Energy Reviews, vol. 39, pp. 426-443.

Levitan, M.M., 2003. *Application of Water Injection/Falloff Tests for Reservoir Appraisal: New Analytical Solution Method for Two-Phase Variable Rate Problems.* SPE Journal, vol. 8(4), pp. 341-349.

Marasso, S.L., Canavese, G., Cocuzza, M., Ferrarini, A., Giuri, E., Lo Bartolo, S., Mantero, G., Perrone, D., Quaglio, M., Vallini, I., 2008. *APEX protocol implementation on a lab-on-a-chip for SNPs detection*. Microelectron. Eng., vol. 85, no. 5-6, pp. 1326-1329, 2008.

Marasso, S.L., Giuri, E., Canavese, G., Castagna, R., Quaglio, M., Ferrante, I., Perrone, D., Cocuzza, M., 2011. *A multilevel Lab on chip platform for DNA analysis*, Biomed Microdevices, vol. 13, no. 1, pp. 19-27.

Marasso, S.L., Mombello, D., Cocuzza, M., Casalena, D., Ferrante, I., Nesca, A., Poiklik, P., Rekker, K., Aaspollu, A., Ferrero, S., Pirri, C.F., 2014. *A polymer Lab-on-a-Chip for genetic analysis using the arrayed primer extension on microarray chips,* Biomed. Microdev., 16(5), pp. 661-670.

Marzano, F., Pregliasco, M., Rocca, V., 2019. *Experimental characterization of the deformation behavior of a gas-bearing clastic formation: Soft or hard rocks? A case study.* Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 6, 10.

Matos, C., Carneiro, J.F., Pereira da Silva, P.P., 2019. Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. Journal of Energy Storage, Vol. 21, pp. 241-258.

Mattax, C.C., Dalton, R.L., 1990. *Reservoir Simulation*, Society of Petroleum Engineers (U.S.), Henry L. Doherty series, vol. 13 SPE monograph series.

Molla, S., Mostowfi, F., 2021. *Novel Microfluidic Device for Dew Point Pressure Measurement of Retrograde Gas Condensates Using a Microfluidic Device*. Energy & Fuels.

Moscatello, A., Uggenti, A.C., Iuso, G., D'Ambrosio, D., Cafiero, G., Gerboni, R., Carpignano, A. 2020. *Scaling procedure for designing accidental gas release experiment*. ENGINEERING COMPUTATIONS.

Moscatello, A., Uggenti, A.C., Gerboni, R., Carpignano, A. 2021. *A novel approach to high-pressure gas releases simulations.* Journal of Loss Prevention in the Process Industries.

Mu, A., & Moreau, J.W. 2015. *The geomicrobiology of CO_2 geosequestration: a focused review on prokaryotic community responses to field – scale CO_2 injection*. Frontiers in microbiology, vol. 6, 263.

Musso, G., Volonté, G., Gemelli, F., Corradi, A, Nguyen, S.K., Lancellotta, R., Brignoli, M., Mantica, S., 2021. *Evaluating the subsidence above gas reservoirs with an elasto-viscoplastic constitutive law. Laboratory evidences and case histories.* Geomechanics for Energy and the Environment. Paper no. 100246 (in press)

Noiriel, C., Daval D. 2017. *Pore-Scale Geochemical Reactivity Associated with CO_2 Storage: New Frontiers at the Fluid−Solid Interface*. Acc. Chem. Res. 2017, 50, 759−768, DOI: 10.1021/acs.accounts.7b00019

Pandey, G.N., Tek, M.R., Katz, D.L., 1974. *Diffusion of fluid through porous media with implications in petroleum geology*. AAPG Bulletin, 58(2), pp. 91-303.

Panfilov, M., 2016. *Underground and pipeline hydrogen storage.* Woodhead Publishing Series in Energy, Compendium of Hydrogen Energy, Woodhead Publishing, pp. 91-115.

Park D-S, Cho M-W, Lee H, Cho W-S. 2004. *Micro-Grooving of glass using micro-abrasive jet machining.* Journal of Materials Processing Technology. 2004 02/01;146:234-240.

Parkash, D., Deangeli, C., 2019. *Wellbore stability analysis in anisotropic shale formations*. SPE/PAPG Pakistan Section Annual Technical Symposium and Exhibition.

Peng, D.-Y., Robinson, D.B., 1976. *A new two-constant equation of state*. Industrial & Engineering Chemistry Fundamentals, 15 (1), pp. 59-64.

Pirri, C.F. 2020, *An Integrated Device for the Solar-Driven Electrochemical Conversion of CO_2 to CO,* ACS Sustainable Chemistry and Engineering, Vol. 8 (20),pp. 7563-7568, 10.1021/acssuschemeng.0c02088

Quaglio, M., Bianco, S., Castagna, R., Cocuzza, M., Pirri, C.F., 2011. *Elastomeric nanocomposite based on Carbon Nanotubes for Polymerase Chain Reaction device*. Microelectronic Engineering, Vol. 88(8), pp. 1860-1863.

Quaglio, M., Frascella, F., Marasso, S.L., Cocuzza, M., Viberti, D., Amendola, A., Carminati, S., & Pirri, C.F., 2019. *Design and Characterization of Microfluidic Devices for Water/Oil Separation*. OMC, Ravenna, Italy.

Ramakrishnan, T.S., Kuchuk, F.J., 1993. *Pressure transients during injection: Constant rate and convolution solutions*. Transport in Porous Media, Vol. 10 (2), pp. 103-136. Kluwer Academic Publishers, The Nederlands.

Ranchou-Peyruse, M., Auguet, J.C., Mazière, C., Restrepo-Ortiz, C.X., Guignard, M., Dequidt, D., Chiquet, P., Cézac, P., Ranchou-Peyruse, A., 2019. *Geological gas-storage shapes deep life*. Environmental Microbiology, vol. 21(10), pp. 3953-3964.

Redlich, O., Kwong, J.N., 1949. *On the thermodynamics of solutions. V. An equation of state. Fugacities of gaseous solutions.* Chemical reviews, 44(1), pp. 233-244.

Reitenbach, V., Ganzer, L., Albrecht, D., Hagemann, B., 2015. *Influence of added hydrogen on underground gas storage: a review of key issues.* Environmental Earth Sciences, Vol. 73, pp. 6927-6937.

Renner, J., Messar, M., 2006. *Periodic pumping tests.* Geophysical Journal international, Wiley-Blackwell, 167, pp. 479-493.

Roberts, R.C., 1972. *Molecular diffusion of Gases*. Gray D.E. (ed.), American Institute of Physics Handbook, Mc-Graw Hill Book Company, New York, pp. 2249-2252.

Rocca, V., Cannata, A., Gotta, A., 2019. *A critical assessment of the reliability of predicting subsidence phenomena induced by hydrocarbon production*. Geomechanics for Energy and the Environment, Vol. 20, 100129.

Rochon, J., Jaffrezic, V., Boutaud de La Combe, J.L., 2008. *Method and application of cyclic well testing with production logging.* ATCE, Denver, Colorado, USA

Rodrigues, E.M.G., Godina, R., Santos, S.F., Bizuayehu, A.W., Contreras, J., Catalão, J.P.S., 2014. *Energy storage systems supporting increased penetration of renewables in islanded systems*. Energy, Vol. 75, pp. 265-280.

Roman, S., Abu-Al-Saud, M.O., Tokunaga, T., Wan, J., Kovscek, A.R., Tchelepi, H.A., 2017. *Measurements and simulation of liquid films during drainage displacements and snap-off in constricted capillary tubes.* Journal of colloid and interface science, Vol. 507, pp. 279-289.

Rosa, A.J., Horne, R.N., 1997. *Reservoir description by well-test analysis by use of cyclic flow-rate variation*. SPE Formation Evaluation, December 1997, Vol. 12 (4), pp. 247-254. SPE 22698.

Sacco A, Speranza, R., Savino, U., Zeng, J., Farkhondehfal, M.A., Lamberti, A., Chiodoni, A.,

Salina Borello, E., Fokker, P.A., Viberti, D., Espinoza, R.V., Verga, F., 2016. *Harmonic-Pulse Testing for Non-Darcy-Effects Identification*. SPE Reservoir Evaluation & Engineering. SPE-183649-PA.

Salina Borello, E., Fokker, P.A., Viberti, D., Verga, F., Hofmann, H., Meier, P., Min, K.-B., Yoon, K., Zimmerman, G., 2019. *Harmonic Pulse Testing for Well Monitoring: application to a fractured geothermal reservoir*, in: Water resources research, Vol. 55 (6), pp. 4727-4744.

Scalia, A., Zaccagnini, P., Armandi, M., Latini, G., Versaci, D., Lanzio, V., Varzi, A., Passerini, S., Lamberti, A., 2021. *Tragacanth Gum as Green Binder for Sustainable Water-Processable Electrochemical Capacitor.*ChemSusChem 14.1, pp. 356-362.

Schlomer, S., Krooss, B.M., 2004. *Molecular transport of methane, ethane and nitrogen and the influence of diffusion on the chemical and isotopic composition of natural gas accumulations*. Geofluids, 4, pp. 81-108.

Shoaib, M., Viberti, D., Salina Borello, E., Verga, F., 2019. *Harmonic pulse testing for gas well deliverability assessment.*, GEAM. Geoingegneria ambientale e mineraria, Vol. 158 (3), pp. 53-60.

Soave, G., 1972. *Equilibrium constants from a modified Redlich-Kwong equation of state*. Chemical engineering science, 27(6), pp. 1197-1203.

Soulaine, C., Maes, J., & Roman, S., 2021. Computational microfluidics for geosciences. Frontiers in Water, Vol. 3, pp. 11.

Span, R., Wagner, W., 1996. *A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa*. Journal of physical and chemical reference data, 25(6), pp. 1509-1596.

Sun, A.Y., Lu, J., Hovorka, S., 2015. *A harmonic pulse testing method for leakage detection in deep subsurface storage formations.* Water Resources Research. AGU.

Tamimi, A., Rinker, E.B., Sandall, O.C., 1994. *Diffusion Coefficients for Hydrogen Sulfide, Carbon Dioxide, and Nitrous Oxide in Water over the Temperature Range 293-368 K.* Journal of Chemical & Engineering Data, 39 (2), pp. 330-332.

Teatini, P., Castelletto, N., Ferronato, M., Gambolati, G., Janna, C., Cairo, E., Marzorati, D., Colombo, D., Ferretti, A., Bagliani, A., 2011. *Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in the Po River basin, Italy.* Journal Geophysical Research, 116, pp. 1-21.

Tripaldi, G., Beretta, E., Bertolini, C., Gorlani, A., Costa, A., Latioui, S., Hachelaf, H., Di Gianvittorio, D., Benayad, N., Uematsu, H., Viberti, D., Verga, F., 2009. *Injection testing: an Innovative Field Application in Berkine Basin, Algeria.* Conference Paper presented at the OMC, Ravenna, Italy, 25-27 March.

Tsao, C.W., 2016. *Polymer Microfluidics: Simple, Low-Cost Fabrication Process Bridging Academic Lab Research to Commercialized Production*. Micromachines, 7, pp. 225.

Vasile, N.S., Cordara, A., Usai, G., Re, A., 2021. *Computational analysis of dynamic light exposure of unicellular algal cells in a flat-panel photobioreactor to support light-induced CO2 bioprocess development*, Frontiers in Microbiology, vol. 12, 1, 639482

Verga, F., 2018. *What's conventional and what's special in a reservoir study for underground gas storage*. Energies, Vol. 11, Issue 5, DOI: 10.3390/en11051245

Verga, F., Salina Borello, E., 2016. *Unconventional well testing: a brief overview*. GEAM. Geoingegneria Ambientale E Mineraria, Vol. 149 (1106), pp. 45-54.

Verga, F., Viberti, D., Salina Borello, E., 2008. *A New 3-D Numerical Model to Effectively Simulate Injection Test.* Europec/EAGE Conference and Exhibition in Rome, Italy. SPE-113832-MS.

Verga, F., Viberti, D., Salina Borello, E., 2011. *A new insight for reliable interpretation and design of injection tests*. Journal of Petroleum Science and Engineering, Vol. 78(1), pp. 166-177.

Verga, F., Viberti, D., Salina Borello, E., Serazio, C., 2015. *Estimation of skin from the interpretation of injection tests in fractured reservoirs.* Geoingegneria Ambientale e Mineraria., Vol. 146, n.3, pp. 45-52.

Verga, F., Viberti, D., Serazio, C., 2012. *Estimation of skin components for a partially completed damaged well from injection tests.* Journal of Petroleum Science and Engineering, Vol. 90-91, pp. 165-174.

Viberti, D., 2010. *A rigorous mathematical approach for petrophysical properties estimation*. American Journal of Applied Sciences, 7 (11), pp. 1509-1516. ISSN 1546-9239. DOI: 10.3844/ajassp.2010.1509.1516

Viberti, D., Peter, C., Salina Borello, E., Panini, F., 2020. *Pore structure characterization through path-finding and lattice Boltzmann simulation.* Advances in Water Resources, Vol. 141.

Viberti, D., Verga, F. 2012. *An Approach for the Reliable Evaluation of the Uncertainties Associated to Petrophysical Properties*. Mathematical Geosciences, vol. 44, Issue 3, pp. 327-341.

Vinsot, A., Appelo, C.A.J., Lundy, M., Wechner, S., Lettry, Y., Lerouge, C., Fernández, A.M., Labat, M., Tournassat, C., De Canniere, P., Schwyn, B., Mckelvie, J., Dewonck, S., Bossart, P., Delay, J., 2014. Geological Society, London, Special Publications, 400, pp. 563-578.

Vitale, A., Quaglio, M., Chiodoni, A., Bejtka, K., Cocuzza, M., Pirri, C.F. & Bongiovanni, R., 2015. *Oxygen-Inhibition Lithography for the Fabrication of Multipolymeric Structures*. Advanced Materials, Vol. 27-31, pp. 4560-4565.

Vitale, A., Quaglio, M., Marasso, S.L., Chiodoni, A., Cocuzza, M., & Bongiovanni, R., 2013. *Direct photolithography of perfluoropolyethers for solvent-resistant microfluidics*. Langmuir, Vol. 29(50), pp. 15711-15718.

Wang, Y., Liu, S., 2016. *Estimation of pressure-dependent diffusive permeability of coal using methane diffusion coefficient: laboratory measurements and modeling*. Energy & Fuels, 30(11), pp. 8968-8976.

West, J.W., McKinley, I.G., Palumbo-Roe, B., Rochelle, C.A., 2011. *Potential impact of CO_2 storage on subsurface microbial ecosystems and implications for groundwater quality*. Energy Procedia, Vol. 4, pp. 3163-3170.

Wildenschild, D., Sheppard, A.P., 2013. *X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems.* Advances in Water Resources, Vol. 51, pp. 217-246.

Wilhelmsen, Ø., Skaugen, G., Jørstad, O., Li, H. 2012. *Evaluation of SPUNG* and Other Equations of State for Use in Carbon Capture and Storage Modelling*. Energy Procedia, 23, pp. 236-245.

Wise, D.L., Houghton, G., 1966. *The diffusion coefficients of ten slightly soluble gases in water at 10-60°C*, Chemical Engineering Science, Vol. 21, Issue 11, pp. 999-1010.

Zeng, J., Bejtka, K., Ju, W., Castellino, M., Chiodoni, A., Sacco, A., Farkhondehfal, M.A., Hernández, S., Rentsch, D., Battaglia, C., Pirri, C.F., 2018, *Advanced Cu-Sn foam for selectively converting CO_2 to CO in aqueous solution*. Applied Catalysis B: Environmental 236, pp. 475-482.

Zeng, J., Castellino, M., Sacco, A., Chiodoni, A, Hernandez R.S.P., Pirri, C., 2021. *Facile synthesis of cubic cuprous oxide for electrochemical reduction of carbon dioxide.* Journal of Material Science, Vol. 56, pp. 1255-1271, 10.1007/s10853-020-05278-y

Zeng, J., Jagdale, P., Lourenço, M.A.O., Farkhondehfal, M.A., Sassone, D., Bartoli, M., Pirri, C.F., 2021. *Biochar-supported BiOx for effective electrosynthesis of formic acid from carbon dioxide reduction*. Crystals 11(4), pp. 363.

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Rainwater harvesting for home-garden irrigation: a case study in Italy

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In residential buildings, drinking water is often used for tasks that do not necessarily require high quality water, such as home-garden irrigation. Our research focuses on the idea of harvesting rainwater to promote sustainable management of low-quality water resources on a building scale for irrigation purposes. The effectiveness of a collection system depends on the weather conditions, which determine also the water need of the plants, on the size of the cultivated area and on the collection surfaces. In this research, a rainwater harvesting system (RWH) for the irrigation of home-gardens in the city of Celano (L'Aquila – Italy) has been analysed. The obtained results show that to maximize water savings a great investment is necessary, i.e. not refundable in a reasonable period due to the low cost of drinking water. On the contrary, to maximize the economic return, it is required a smaller and cheaper tank, but the maximum water savings efficiency decrease to about 60%. In the latter case the RWH system can be cheaper than an irrigation plant supplied by the aqueduct. In the work graphs are provided for practical design use for realizing a RWH system in areas with meteorological conditions similar to those of the survey area, according both the highest water savings efficiency or the highest economic return.

Keywords: *drinking water, home-garden, sustainable management, harvesting rainwater.*

Recupero dell'acqua piovana e irrigazione dei giardini privati: un caso studio in Italia. *Al giorno d'oggi negli edifici residenziali l'acqua potabile viene ancora impiegata per mansioni che non richiedono acqua di elevata qualità, come ad esempio l'irrigazione del giardino. Questo studio è basato sull'idea della raccolta d'acqua piovana con lo scopo di promuovere la gestione sostenibile di acqua di bassa qualità a scala di edificio ad esempio per l'irrigazione del verde privato. L'efficienza del sistema di raccolta dipende dalle condizioni meteorologiche, che influenzano anche il fabbisogno idrico delle piante, dalle dimensioni dell'area coltivata e dalla superficie di raccolta. In questo lavoro di ricerca sono stati analizzati sistemi di raccolta dell'acqua piovana per l'irrigazione di giardini nella città di Celano (L'Aquila – Italy) garantendo la continuità del verde urbano presente nella città. I risultati ottenuti mostrano, in termini economici, che per massimizzare il risparmio di acqua, anche con un'efficienza del 100%, è necessario sostenere alti costi che non possono essere ripagati in un ragionevole periodo di tempo a causa del basso costo dell'acqua potabile, mentre per massimizzare il ritorno sull'investimento si devono installare serbatoi più piccoli poiché più economici, ma il valore massimo di efficienza nel risparmio d'acqua diminuisce fino al 60%: in questo caso, per alcune combinazioni di area del tetto e del giardino, la scelta del sistema di raccolta dell'acqua piovana è più conveniente rispetto all'irrigazione basata sulla sola fornitura dell'acquedotto. Nel presente lavoro sono presentati dei grafici di uso pratico per la progettazione di sistemi di raccolta dell'acqua piovana, in zone con un clima simile a quello del sito di studio, scegliendo di massimizzare il risparmio d'acqua potabile o il ritorno sull'investimento.*

Parole chiave: *acqua potabile, verde privato, gestione sostenibile, recupero acqua piovana.*

1. Introduction

In almost all the houses, drinking water, taken from the aqueduct, is used for internal and external uses. Among these, it is included garden irrigation, an activity for which it is possible to use non-potable water, saving drinking water for its real purpose (Conte, 2008; Palla *et al.*, 2011; Lucìo *et al.*, 2020).

For this reason, it is born the idea of mitigating the consumption of drinking water for the maintenance of private greeneries using rainwater collected by a Rainwater Harvesting System (RWH). In this system the water is collected from the roof of the building and stored in underground tanks, from which water can be withdrawn for the irrigation. This practice can have also the important effect of reducing the water volume in the sewage system and preventing the damages caused by the crisis of the sewage system during big storms, especially in urban environment. Nevertheless, the realization costs of a domestic RWH system (namely, price of tank and its accessories) are generally higher than the benefit due to the annual savings in the water bill and this is a problem that can limits the diffusion of this good practice (Campisano, 2017a). The present study shows the role of the different variables for a correct choice of the tank size.

In this paper it is reported a general method for the analysis and design of a RWH system with a case study in the city of Celano (L'Aquila – Italy). Specifically, the method is based on a water balance equation on a daily scale, where the water volume present in the tank is linked to the volume of the previous day: the main input/output are the daily meteoric inflow and the daily water demand of the cultivated area, respectively.

The aim is to provide the reader with a valid decision support tool for the implementation of the

RWH system, addressing both the economic and the environmental aspect. In order to pursue this aim, the proposed method starts from section 2, where are reported well-known methods for modelling the RWH system and for the estimation of the water demand of a cultivated surface; then, in section 3, it is presented an approach for the choice of the tank based on both water savings and economic viability of the system.

In section 4 the application of the method to gardens located in the town of Celano is shown. The results, that consist in a series of graphs, are both a resume for the case study area and a practical tool for the reader to design a RWH system also in different geographical zones but with similar climatic conditions.

2. Mathematical model

The analysis of the behaviour of a building-scale rainwater harvesting system, for maintenance of private greenery, requires the knowledge of many elements. Figure 1 represents a sketch to understand the functioning of a RWH system that involves different quantities: (1) geometric quantities like the harvesting surface H, the cultivated surface C and the tank capacity S, and (2) time dependent quantities like the rainfall P_t, the inflow volume q_t, the stored volume V_t, the rainwater supply Y_t, the water demand d_t, the drinking water supply M_t and the overflow O_t. In this work, a combination of H and C is defined *host system*.

In order to explore the performance of the system, a mathematical model simulates the mass balance equation for the tank at the daily scale. The input data are the meteorological data of the rainfall historical series. These meteorological series have a length of T days: this period, that for an accurate climatic description of the site should be at least 30 years long, should contain an integer number of years to permit the cost calculations, based on the annual price of water. With reference to the symbols in Figure 1, the mass balance equation for the tank can be written as

$$V_t = q_t + V_{t-1} - Y_t - O_t \qquad (1)$$

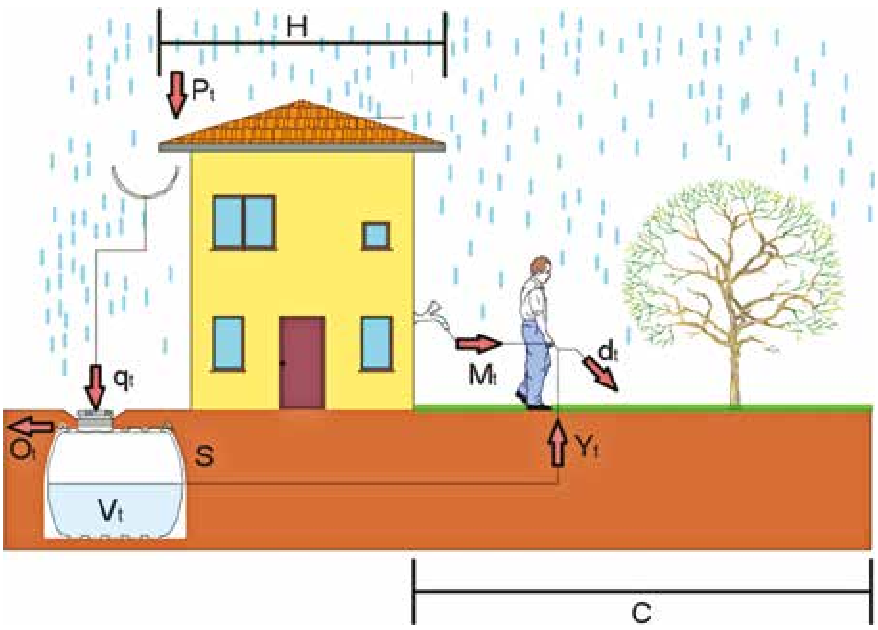

Fig. 1 – Configuration of the rainwater harvesting system.

where subscript t is related to the *t-th* day of the period T. The terms of the mass balance are evaluated using the *Yield After Spill* (YAS) rules (Palla *et al.*, 2011; Jing *et al.*, 2018):

$$Y_t = MIN\{d_t\,;V_{t-1}\} \qquad (2a)$$

$$V_t = MIN\{q_t + V_{t-1} - Y_t\,;S - Y_t\} \qquad (2b)$$

The first day of simulation the tank is considered empty, i.e $V_0 = 0$ (Palla *et al.*, 2011; UNI, 2012). According to Figure 1, in this study it is supposed that the area occupied by the tank does not reduce the cultivated area and the amount of water lost for evaporation from the tank can be neglected. The surface H is assumed to be equal to the horizontal projection of the roof, which is supposed to be made of waterproof material with a slope < 3% and a runoff coefficient ϕ = 0.8 [–] (Farreny *et al.*, 2011; UNI, 2012).

The daily flow of rainwater collected from the rooftop q_t [m^3/day] is linked to the harvesting surface H [m^2], to the rainfall height P_t [m^3/(m^2•day)] and to the runoff coefficient ϕ [–] (Palla *et al.*, 2011)

$$q_t = \phi \cdot p_t \cdot H \qquad (3)$$

The daily volume of water necessary for irrigating the C area, can be computed as the sum of the single demand of the n crops growing in the cultivated surface. The demand due to a crop is the product of the area occupied by the *i-th* crop C^i and the volume of water demand per unit area v_t^i [m^3/ (m^2•day)]. The water demand v_t^i can be estimated as

$$v_t^i = ETE_t^i - P_{n,t} \qquad (4)$$

where ETE_t^i [m^3/ (m^2 · day)] is the effective evapotranspiration of the *i-th* crop on the *t-th* day and $P_{n,t}$ is the daily net infiltration, i.e. the volume of daily rainfall that infiltrates in the ground and reaches plant roots. Daily net infiltration has been computed according to FAO indication (Doorenbos and Pruitt, 1977), while ETE_t^i has been calculated as

$$ETE_t^i = EV_t \cdot K_p \cdot K_{c,t}^i \qquad (5)$$

where $K^i_{c,t}$ [-] is the crop coefficient, K_p [-] is the pan coefficient and EV_t is the evaporation. In particular the evaporation has been calculated through the formula of Tombesi-Lauciani (Giannini and Bagnoni, 2000):

$$EV_t = a \cdot F \cdot (T_{m,t})^{0.9} \cdot 10^{-0.008 \cdot u_{m,t}} \qquad (6)$$

where a [-] is an environmental constant function of the geographic position and of the period of the year, F [-] is the Thorntwaite factor, $T_{m,t}$ [°C] and $u_{m,t}$ [%] are the mean daily temperature and the relative humidity value, respectively. Equation (6) is valid only for $T_{m,t} \geq 0$, while when the temperature is negative EV_t is clearly equal to zero. According to Allen *et al.* (1998) $K^i_{c,t}$ depends on the cultivar and its phenological phase, while K_p = 0.8 (Giannini and Bagnoni,2000). After computing the water demand for each crop, daily water demand from the whole garden can be computed, i.e.

$$d_t = \sum_{i=1}^{n} v_t^i \cdot C^i \qquad (7)$$

where C^i is the area occupied by the *i-th* crop.

3. Best tank capacities

In order to choose the tank size, different aspects should be considered. In fact, the highest reduction of drinking water consumption (environmental criterion) would lead to install a very big and expensive tank, that could not be refunded in a reasonable time period by the money saved through the reduced consumption of drinking water supplied by the aqueduct. For this reason, the economic viability of a RWH system (economic criterion) has to be also considered (Kim *et al.*, 2021). These approaches can be stated as two design criteria for the tank size, i.e. (1) maximum water savings efficiency and (2) maximum economic benefit. Through the first criterion the highest reduction of water consumption is required, while through the second criterion the highest money benefit respect the initial investment within an established period of time is pursued.

The two criteria give clearly two different tank capacities for each host system. The analysis is carried out on the results of the repetition of the mass balance equation shown in section 2 for different tank capacities S. In the following the elements used for the analysis are described.

3.1 Environmental criterion

The efficiency W_s is an index of the water savings and it is calculated as the ratio between the total rainwater volume supplied in the reference period T and the total water demand in the same period (Palla *et al.*, 2011) and it shows how much drinking water can be replaced by the harvested rainwater. Its mathematical expression is

$$W_s = \sum_{t=1}^{T} Y_t \Big/ \sum_{t=1}^{T} d_t = V_r / D \qquad (8)$$

Since the water demand (denominator) is not influenced by the tank capacity and the rainwater volume supply (numerator) grows with the tank size up to a maximum value, the idea is to choose the optimal tank looking for which tank size makes the numerator close to its maximum value: in practical case the numerator is not maximized, because further increases of the tank size, when the tank is large, result in negligible water saving increments.

3.2 Economic criterion

This criterion is based on an economic comparison between the irrigation plant based on RWH system and the same irrigation plant supplied by the aqueduct, taking into account the future growth of water price and the *discount rate* of the money, r_d. The sum of the *present value* of future annual costs is computed for both the aqueduct-based plant and the RWH-based one and then the difference between the two results, called *Net Present Value (NPV)* is computed. For the RWH-based plant it has to be also considered the initial cost (C_i). The *NPV* is computed for the whole period of the expected system life U_L [years].

The building cost C_b of the RWH system comprehends the tank price as well as pump and installation cost (namely, the excavation) and it could be expressed as a linear function of excavation volume V_e,

$$C_b = e \cdot V_e + f \qquad (9)$$

where the two coefficients e and f depend on local economic condition. Instead, the costs distributed along the system life comprehend the cost of energy consumed by the pump and the cost of drinking water C_w that has to be bought from the aqueduct in case of rainwater lack (i.e., empty tank). The pumping cost can be considered as a fraction (pp) of the initial cost C_b (see Section 4), so that it becomes dependent on the system size, thus

$$C_i = C_b \cdot (1 + pp) \qquad (10)$$

The annual cost per unit volume k_y of water from the aqueduct usually depends on the yearly volume of consumed water. This study focuses only on the annual volume of drinking water used for irrigation purpose M_y, where y indicates a generic year of the system life U_L. In the case of aqueduct-based plant, all the water demand D_y is supplied by the waterworks, so $M_y = D_y$. Thus, present values of the annual cost can be expressed, both in presence of a RWH system (subscript RWH) and in absence of it (subscript AQD) as

$$C_{w,RWH,y} = M_y \cdot k_y/(1 + r_d)^{y-1} \quad (11a)$$

$$C_{w,AQD,y} = D_y \cdot k_y/(1 + r_d)^{y-1} \quad (11b)$$

Defined the above-mentioned quantities, the computation of the economic return *NPV* (*Net Positive Value*) is given by

$$NPV = \frac{U_L}{N} \cdot \sum_{y=1}^{N} C_{w,AQD,y} + -\left(\frac{U_L}{N} \cdot \sum_{y=1}^{N} C_{w,RWH,y} + C_i\right) \quad (12)$$

where N is the length of the meteorological data series, expressed in years. The value of *NPV* is a function of the tank capacity S and the best tank size maximizes *NPV*. However, *NPV* could be positive, negative or null: if the result is positive, it means that the RWH plant is cheaper than the aqueduct-based plant and the value is the money savings in a period equal to U_L; instead, if *NPV* is negative, the RWH system is more expensive than the aqueduct-based in the U_L period. Finally, if *NPV* is zero, there is no money difference between the two plants. Nevertheless, it has to be remembered that all RWH systems always produce a water saving, although it can be not economically viable.

4. Case study

The case study considers home-gardens in the town of Celano (L'Aquila), located on the central Apennines at 800 m a.s.l, (42°05'03.5''N, 13°32'51.9''E). In Figure 2 meteorological information is given, i.e., monthly average temperature and monthly rainfall height. The mean annual rainfall is about 860 mm.

The meteorological data are referred to the twenty-nine years period 1951-1979. In particular, the temperature data are measured in Goriano Sicoli station, while rainfall height is measured in San Pelino station, both located near the study area (Regione Abruzzo, 2020). Table 1 shows the values of parameter a and F (see Section 2) for the case study.

Referring to the Figure 1, the cultivated area C has been designed according to a national regulation law (MATTM, 2020) that concerns green areas. The regulation law requires that the green areas should be constituted by native crops. For this reason, two green models, widespread in the study area, have been adopted. The first model (M1) is a vegetable garden with five different crops: carrots, potatoes, eggplants, tomatoes and lettuce. Each crop occupies an area of one fifth of C. The second model (M2) is constituted by fescue meadow and fruit trees (i.e., apple, pear and apricot), having a trunk diameter equal to 30 cm and a foliage diameter equal to 3 meters. Based on these values, the pertinence land area of a tree has been determined, that is 20 m^2 of cultivated area and so the number of trees contained in each *host system* has been calculated. In M2 the meadow occupies the whole cultivated area except the trunks area, while for trees a surface occupied by roots equal to the

Tab. 1 – Values of the constants a and F in the survey area.

Month	*a* [-]	*F* [-]
January	0.68	0.81
February	0.95	0.82
March	1.23	1.02
April	1.33	1.125
May	1.14	1.265
June	1.11	1.285
July	1	1.295
August	0.98	1.2
September	1	1.04
October	1	0.95
November	0.84	0.805
December	0.75	0.765

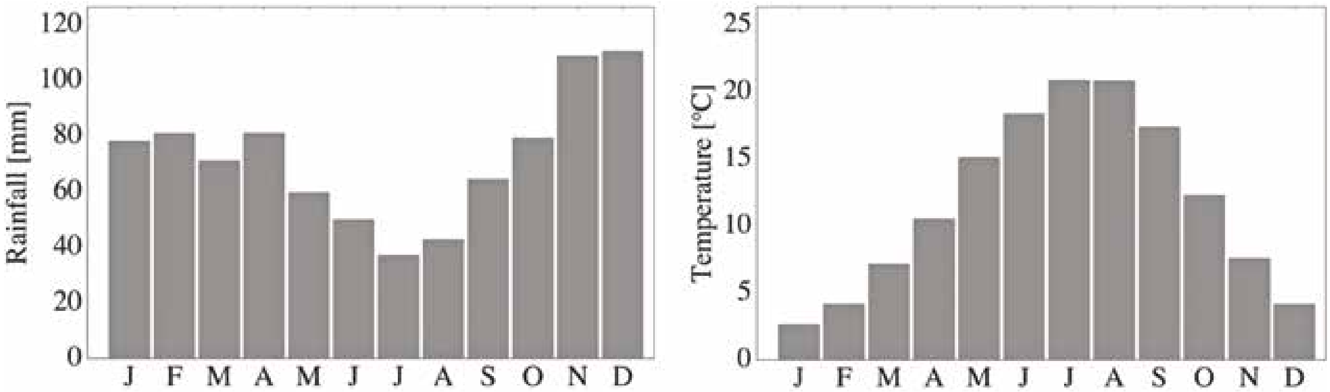

Fig. 2 – Monthly rainfall height (left) and monthly average temperature (right).

Tab. 2 – Crop coefficients for each phenological phase.

Crop	Initial	Intermediate	final
Carrots	0.7	1.05	0.95
Lettuce	0.7	1	0.95
Eggplant	0.6	1.05	0.9
Tomatoes	0.6	1.05	0.8
Potatoes	0.5	1.15	0.75
Fruit tree	0.5	1	0.8
Fescue meadow	1.05	1.1	1.1

projection of the foliage area to the ground has been considered.

The values of the crop coefficients $K^i_{c,t}$ for each crop present in the models and their phenological phase (initial, intermediate and final) are shown in Table 2. The temporal evolution of each phase (not reported) has been defined thanks to the support of some farmers of the survey area.

After analysing the temporal trend of the drinking water price in Celano, it was supposed that the cost per cubic meter of water k_y [€/m^3] will rise by 0.05 € per year in the future, starting from the actual cost (Tab. 3) defined by the water utility of the study area (CAM, 2020).

Tab. 3 – Water tariff in the study area.

Yearly consumption M_y [m^3]	k_y [€/m^3]
0-60	1.97
61-180	2.23
>180	3.12

The cost of the RWH system is based on commercial available tanks and it is composed of different parts, i.e., (1) tank price, (2) cost of excavation, (Regione Abruzzo, 2020) and (3) price of pump, filters, pipes and accessories. As a consequence, the coefficients of equation (9) can be estimated as e = 206.37 €/m^3 and f = 1462.1 €. The energy cost for water pumping has been computed starting from standard Italian norms, the rainwater volume supply and the price of energy (0.25 €/kWh): in this way the coefficient of equation (10) is pp = 0.004 for model M1 and pp = 0.01 for model M2.

The expected system life U_L is 35 years and the discounting rate r_d applied to the future annual costs is posed equal to 3.5% (European Commission, 2008; Matos *et al.*, 2015; Campisano *et al.*, 2017b; Kim *et al.*, 2021).

5. Results

The analysis considers different *host systems* characterized by their *H* and *C* values. In Figure 3 the results of the tank capacities analysis are shown for both green models, i.e., the vegetable garden, M1, and the meadow with trees, M2. Graphs are represented as function of two variables, harvesting area *H* and cultivated area *C*, while the values of the tank capacities that leads to the highest water savings efficiency are represented with level curves. In Figure 4, graphs show the values of tank capacities that lead to the highest economic return, while in Figure 5 is reported the amount of the economic return. Finally, in Figure 6, water savings efficiency has been represented as a function of the ratio between *H* and *C*, for both best tank choice criteria.

Dealing with the results related to maximizing the efficiency, Figure 3 shows that values of the best tank according to environmental criterion can be very large (higher than 10 m^3), considering both their dimensions related to the garden size and their real com-

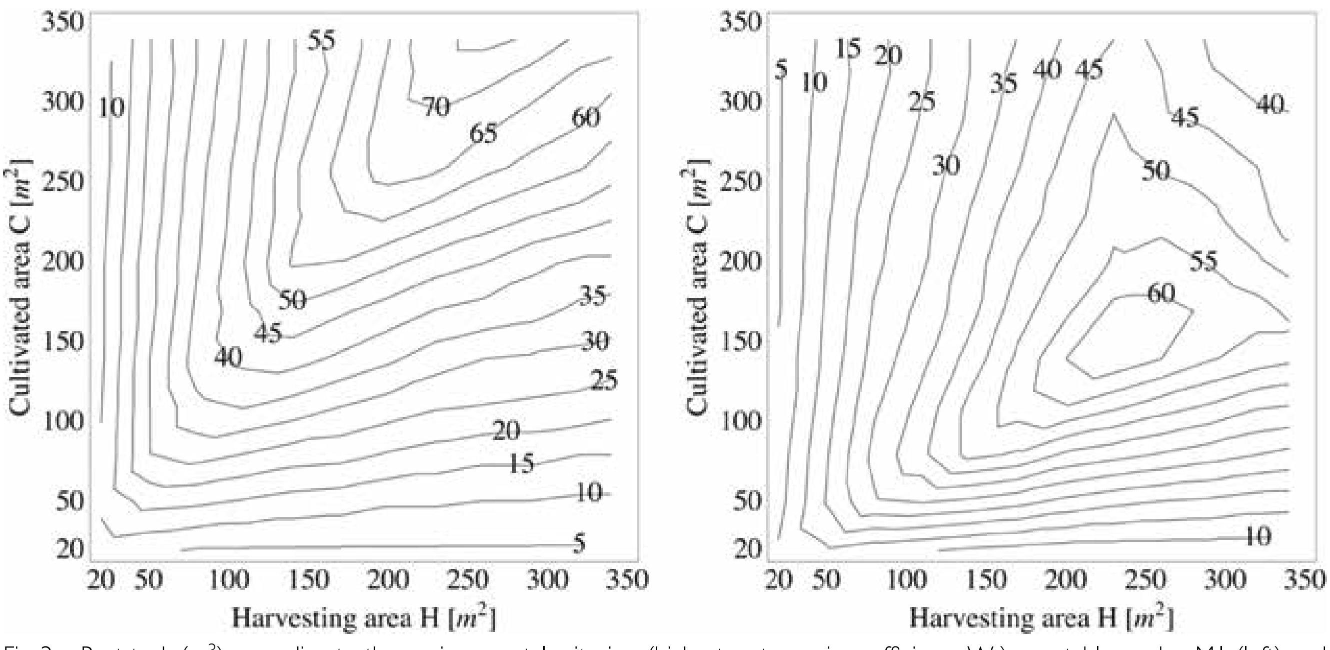

Fig. 3 – Best tank (m^3) according to the environmental criterion (highest water savings efficiency W_s): vegetable garden M1 (left) and meadow with trees M2 (right).

mercial availability. Observing the results shown in Figure 3, it can be also noticed that there is a difference between the two models due to the lower water demand of the vegetable garden than the meadow with trees. In Figure 3, two regions with different behaviour separated approximately by a line of expression $H = C$ for model 1 and $H = 2C$ for model 2 can be detected. In the region where H is bigger than C, for model M1 (or twice bigger than C for model M2) for H that remains constant, S grows with C, while when C is constant, S slightly decrease when H grows; the opposite behaviour happens in the other region. The reason of this behaviour can be understood observing Figure 6, where in former region ($H/C > 1$ for M1 or $H/C > 2$ for M2) Ws is approximately 1. As a consequence all the water demand can be satisfied by stored rainwater, while in the other region Ws is lower than 1, and so there is not enough water to satisfy the irrigation demand. Thus, in case of system with Ws of about 1, the greater is C the bigger should be the tank, instead in case of Ws significantly less than 1, an increase of demand (C) cannot be satisfied: this greater demand tends to empty the tank, and therefore a smaller tank can be sufficient.

Figure 4, instead, shows that best tanks obtained with economic criterion are generally small, being lower than 10 m^3. These tanks are usually more available on the market. It is shown that where $H > C$ the best capacity raises with the increasing of C, while for $H < C$ the best capacity raises when H increase.

In Figure 5 the related *NPV* in 35 years due to the choice of the best tank according to the economic criterion is shown. Two regions are present: a region ($NPV > 0$) where the RWH system is cheaper than the irrigation plant connected to the aqueduct and a region ($NPV < 0$) where the RWH system is more expensive. The line with the value zero represents the *host systems* (pair values H and C) for which the money savings due to the RWH has reached the initial cost of installation, so there is no economic difference (in 35 years) between the RWH system and the aqueduct-based system.

From Figure 5 (left) it is also possible to observe that for the most combination of H and C there is an economic loss, that is due to the low water demand and low recovered rainwater volume: this fact, together with low cost of drinking water, gives a small annual economic benefit. For this reason, only larger *host systems*, with great water demand, give a positive *NPV*. Nevertheless, the loss is not so high, in fact, considering typical initial cost for optimal tanks, about half of it can be recovered at the end of system life. For model M2 (Fig. 5 right) instead, there are more situations with positive economic return, because the water demand is higher than M1.

Finally, Figure 6 shows clearly that the choice of a tank with the economic criterion leads to a smaller water savings efficiency than the environmental criterion, although some *host system* can reach remarkable water saving values too.

6. Conclusions

In this paper a method for the design of a RWH system for private greenery irrigation is proposed: two models of greenery are stu-

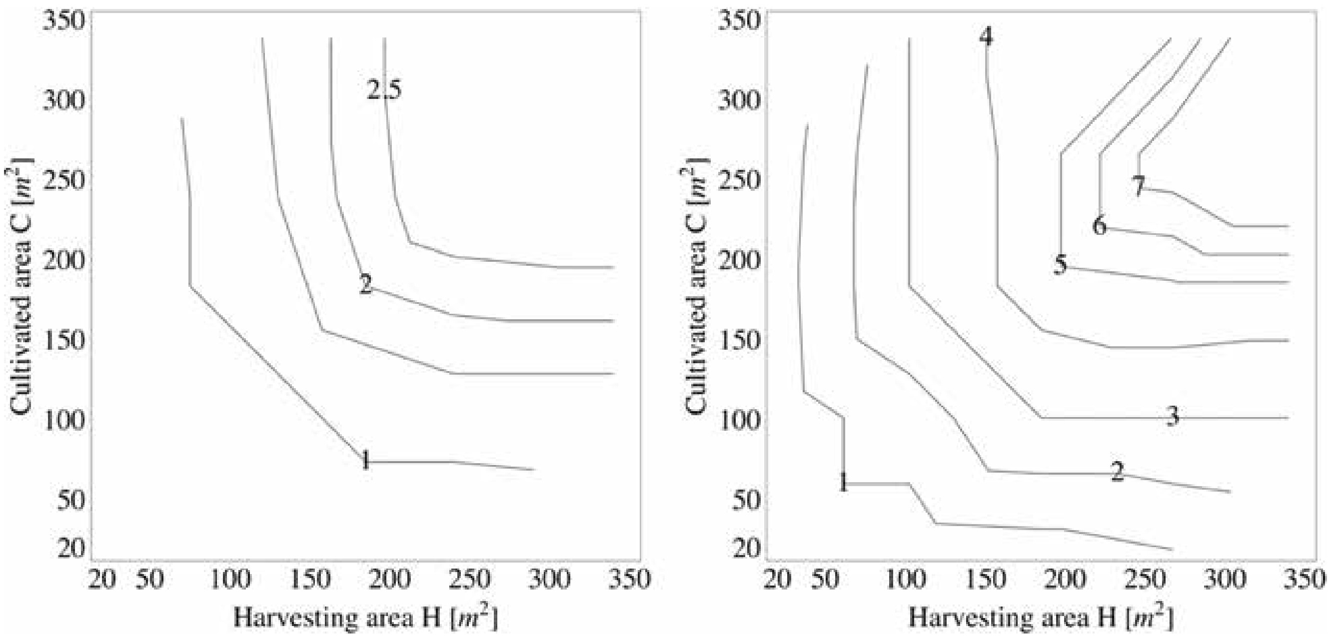

Fig. 4 – Best tank capacity (m^3) according to the economic criterion (highest Net Present Value in 35 years): vegetable garden M1 (left) and meadow with trees M2 (right).

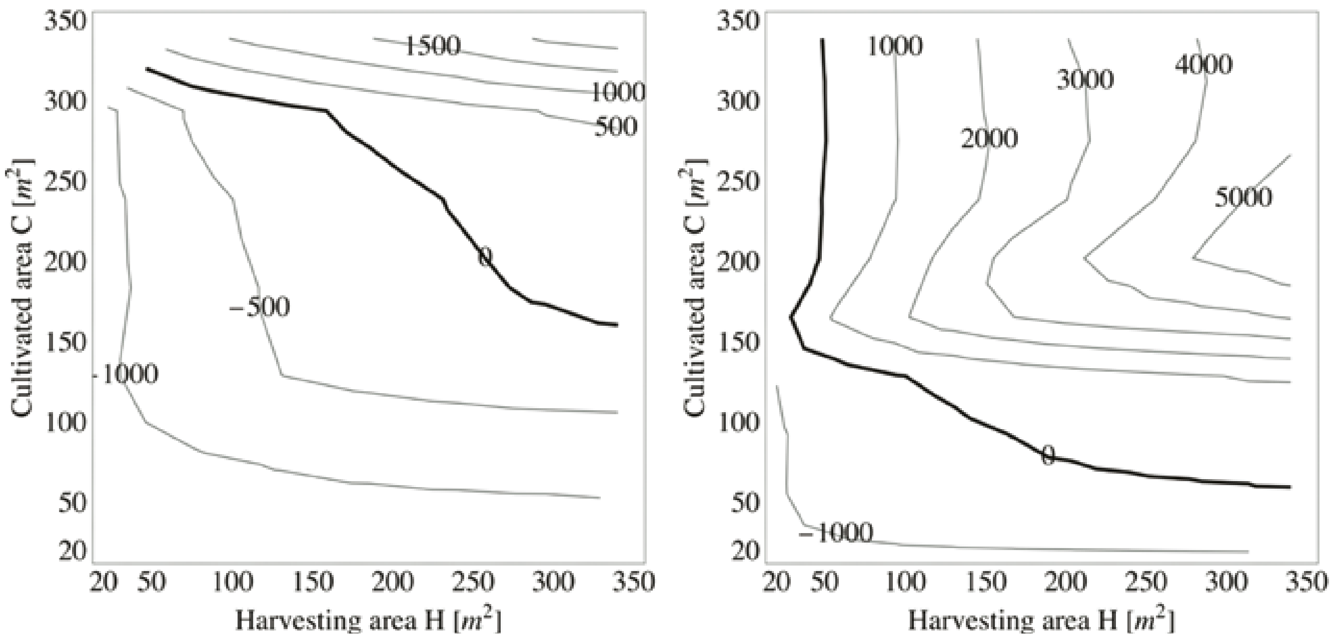

Fig. 5 – NPV (€) in 35 years of the RWH systems designed according to Figure 4: vegetable garden M1 (left) and meadow with trees M2 (right).

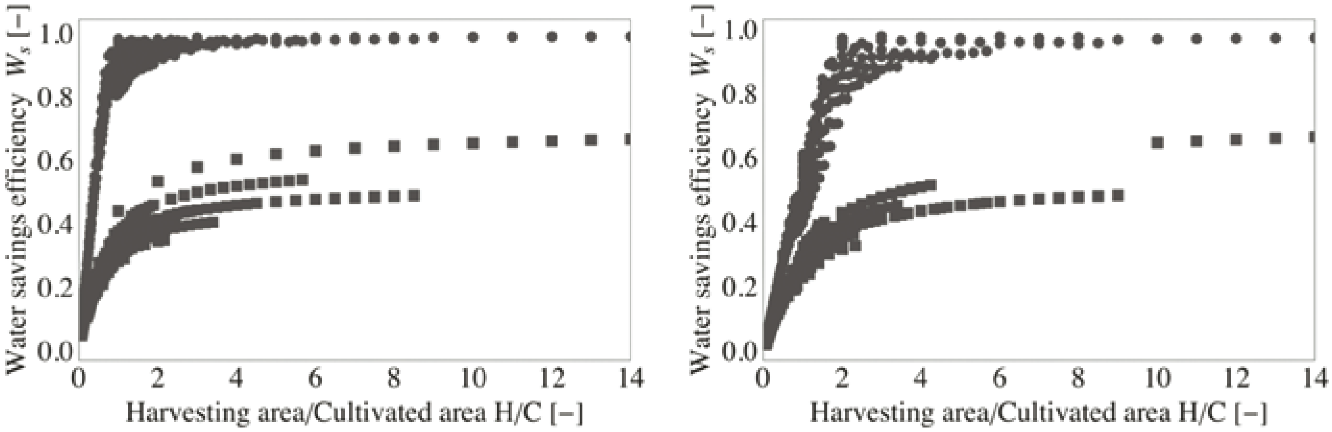

Fig. 6 – Water savings efficiency for environmental design (maximum Ws, dots) and economic design (maximum NPV, squares): vegetable garden M1 (left) and meadow with trees M2 (right).

died, a vegetable garden (M1) and a meadow with fruit trees (M2). The method is based on a daily hydraulic analysis of the water volume stored in the tank, with input the historic meteorological data and geometric data of the so-called *host system* characterized by an harvesting area *H* and a cultivated area *C*. The analysis explores the results for a series of possible capacities for the tank, both in terms of water savings efficiency and in economic terms (*Net Present Value*). The aim is to identify the best tank to install in each *host system*. Results for the case study show that there are two criteria for the choice of the tank capacity: the maximum water savings efficiency, that leads to high costs of installation, and the maximum *NPV*, that leads to lower water savings efficiency. The study has shown that RWH irrigation plant for some *host systems* can be cheaper (at the end of the system life) than aqueduct-based plant, if a good choice of the tank size is made.

The graphs shown in this work can be directly used for the design of a RWH irrigation plant also in different geographical zones but with a similar climatic conditions.

Although the green models considered are only two among the many possible, they can be considered as reference for the design of RWH system for a lot of other kinds of home-gardens, even in different geographical zones but with similar climatic conditions.

Some approximations have been done in the work, for example neglecting soil water content dynamic, but they are issues for future studies, as well as the use of a more detailed crop water requirement estimation method, especially dealing with cases characterized by more detailed meteorological data.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Irrigation and drainage paper No. 56, Crop evapotranspiration.* FAO, Rome.

Campisano, A., Butler, D., Ward, S., Burns, M., Friedler, E., DeBusk, K., Fisher-Jeffes, L.N., Ghisi, E., Rahman, A., Hiroaki, F., Mooyoung, H., 2017a. *Urban rainwater harvesting systems: Research, implementation and future perspectives*. Water research, vol. 115, pp. 195-209.

Campisano, A., D'Amico, G., Modica, C., 2017b. *Water Saving and Cost Analysis of Large-Scale Implementation of Domestic Rain Water Harvesting in Minor Mediterranean Islands*. Water, vol. 9.

Conte, G., 2008. *Clouds and flush toilets*, Environment editions. (Italian).

Doorenbos, J., Pruitt, W.O., 1977. *Irrigation and drainage paper No. 24, Crop water requirements.* FAO, Rome.

European Commission, Directorate General Regional Policy, 2008. *Guide to cost-benefit analysis of investment projects*.

Farreny, R., Morales-Pinzon, T., Guisasola , A., Tayà, C., Rieradevall, J., Gabarrell, X., 2011. *Roof selection for rainwater harvesting: quantity and quality assessments in Spain*. Water research, vol. 45, pp. 3245-3254.

Giannini, A., Bagnoni, V., 2000. Irrigation techniques data sheet for Tuscan agriculture. ARSIA. (Italian).

Jing, X., Zhang, S., Zhang, J., Wang, Y., Wang, Y., Yue, T., 2018. *Analysis and Modelling of Stormwater Volume Control Performance of Rainwater Harvesting Systems in Four Climatic Zones of China*. Water Resources Management, vol. 32, pp. 2649-2664.

Kim, J.E., Teh, E.X., Huemphrey, D., Hofman, J., 2021. *Optimal storage sizing for indoor arena rainwater harvesting: hydraulic simulation and economic assessment.* Journal of Environmental Management, vol. 280.

Lúcio, C., Silva, C.M., Sousa, V., 2020. *A scale-adaptive method for urban rainwater harvesting simulation.* Environmental Science and Pollution Research, vol. 27, pp. 4557-4570.

Matos, C., Bentes, I., Santos, C., Imteaz, M., Pereira, S., 2015. *Economic Analysis of a Rainwater Harvesting System in a Commercial Building.* Water Resource Management, vol. 29, pp. 3971-3986.

MATTM – Italian ministry of the environment, decree 10/3/2020. Main environmental criteria for public green areas management. (Italian).

Palla, A., Gnecco, I., Lanza, L.G., 2011. *Non-dimensional design parameters and performance assessment of rainwater harvesting systems.* Journal of Hydrology, vol. 401, pp. 65-76.

UNI/TS 11445, 2012. Rainwater harvesting systems for non-potable uses. (Italian).

Web sites

Regione Abruzzo, Idrografico mareografico, www.regioneabruzzo.it/content/idrografico-mareografico (last access 7/11/2020).

Regione Abruzzo, Nuovo prezzario regionale, www.regioneabruzzo.it/content/nuovo-prezzario-regionale (last access 9/12/2020).

CAM – Consorzio Acquedottistico Marsicano S.p.A., www.camspa.com/archivio2_aree-tematiche_0_100.html (last access 7/12/2020).

DX.DOI.ORG/10.19199/2021.163-164.1121-9041.089

Engineering geology challenges at the Politecnico di Torino

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The Engineering Geology area studies the physical geography and geomorphology of the "Environment system". In particular, Engineering Geology deals with the defense of the soil, territory and civil protection, with attention to landslides, hydrogeology, the study of underground water circulation, the geological-technical survey, geological exploration of the subsoil and thematic cartography, geological and hydrogeological risk; interpretation of aerial photos and satellite images, topographical analysis on digital models of the survey, study of climate changes and their influence on erosion, sedimentation and pedogenesis processes, the study of geothermal systems, the analysis of geological systems related to hydrocarbons and minerals. Research methods include field and laboratory experiments and appropriate numerical modeling software is often used. In conclusion, the aim of this paper should be a review of all engineering geology tematics analysed and studied by Applied Geology Group in Politecnico di Torino.
***Keywords**: Engineering geology, hydrogeology, Springs analysis, DSGSD, GWHP, raw materials.*

***Le sfide della geologia applicata all'ingegneria al Politecnico di Torino.** Il settore della geologia applicata, della geografia fisica e della geomorfologia studia il "Sistema Ambiente". In particolare, la geologia applicata si occupa della difesa del suolo, del territorio e della protezione civile, con particolare attenzione alle frane, all'idrogeologia, allo studio della circolazione delle acque sotterranee, al rilievo geologico-tecnico, all'esplorazione geologica del sottosuolo e alla cartografia tematica, all'analisi di rischio geologico e idrogeologico. Rientra tra le competenze del geologo applicato l'interpretazione e lettura di foto aeree e immagini satellitari, analisi topografiche su modelli digitali di rilievo, studio dei cambiamenti climatici e loro influenza sui processi di erosione, sedimentazione e pedogenesi. Tematica appartenente al settore è lo studio dei sistemi geotermici, analisi dei sistemi geologici legati a idrocarburi e minerali. I metodi di ricerca includono esperimenti sul campo e in laboratorio e spesso viene utilizzato un software di modellazione numerica appropriato.*

In conclusione, l'obiettivo di questo articolo vuole essere una revisione di tutte le tematiche di geologia applicata analizzate e studiate dal Gruppo di Geologia Applicata del Politecnico di Torino.
***Parole chiave**: Geologia applicata, idrogeologia, analisi di sorgenti, DGPV, GWHP, materie prime.*

1. Introduction

In the age of human activities, Engineering Geology plays a key role in the sustainable development of our societies: scientists, regulators, and practitioners of Engineering Geology are called to confront themselves with the purposes, methods, limitations, and findings of their works (AA. VV., 2014).

Engineering Geology is traditionally a discipline that is strongly related to practice and practical applications of broad geological knowledge. Engineering geology as an established professional practice has been in existence for some 70 years, although some may argue that the practice has been around for as long as man has been carrying out engineering works in and on the ground. As the industry grew it became increasingly clear that the meanings of words, observations, and results were too often being misunderstood, making effective work increasingly difficult.

The development of these various specialized fields reflects the complexity of modern engineering design and construction, especially those designs involving the interface between naturally occurring earth materials and the engineered structure, or the use of naturally occurring materials within the constructed facility.

Geological engineering is primarily a reflection of legal and technological conditions within the USA and in the other part of world. Technological developments in Canada, western Europe, and elsewhere generate very similar demands for individuals with appropriate technical skills. A brief historical review of the relationships between engineers and geologists over the past 200 years provides some insight into the current situation surrounding the accepted professional stature and roles for geologists and engineers (AA.VV., 2014).

Individual practitioners are increasingly likely to become involved in litigation, professional liability has become an important concern for many professions in many countries, and the engineers and the geologists are not immune from this condition. These concerns have led to increased professional registration options for both geologists and engineers, although the exact methods of achieving this vary from country to country.

Geological engineering has developed as a relatively small and unique specialization within the broader engineering profession. The skills of a geological engineer are becoming more desirable than ever as the technologies involved in construction continue to evolve.

The Applied Geology group (AGg) of Politecnico di Torino, explain the engineering geology: in particular deals with the defense of the soil, territory and civil protection, with attention to landslides, hydrogeology, the study of underground water circulation, the geological-technical survey, geological exploration of the subsoil and thematic cartography, geological and hydrogeological risk; interpretation of aerial photos and satellite images, topographical analysis on digital models of the survey, study of climate changes and their influence on erosion, sedimentation and pedogenesis processes, the study of geothermal systems, the analysis of geological systems related to hydrocarbons and minerals. Research methods include field and laboratory experiments, and appropriate numerical modeling software is often used.

2. Engineering geology in Department of Environment, Land and Infrastructure Engineering at Politecnico di Torino

Large engineering projects were constructed all over the world; however nowadays in general more developed countries tended to be more sensitive to their environmental impacts and engineering geological arguments (Oliveira, 2014). In DIATI – Department of Environment, Land and Infrastructure Engineering at Politecnico di Torino the geology is explained through a perspective applied to engineering and numerous aspects are developed.

2.1 Hydrogeology, protection and planning of groundwater resources.

Firstly, the Hydrogeology: in the sense of protection, monitoring and planning of groundwater resources (Lo Russo, Taddia 2009; Vigna *et al*., 2010), assessment of water flows and matter, management and protection of groundwater resources (Fig.1). In order to contribute to the solution of the problems concerning groundwater the conceptual model for the groundwater flow system, the schematization of the aquifers boundaries and the estimation of basic hydrogeological parameters are among the main issues which

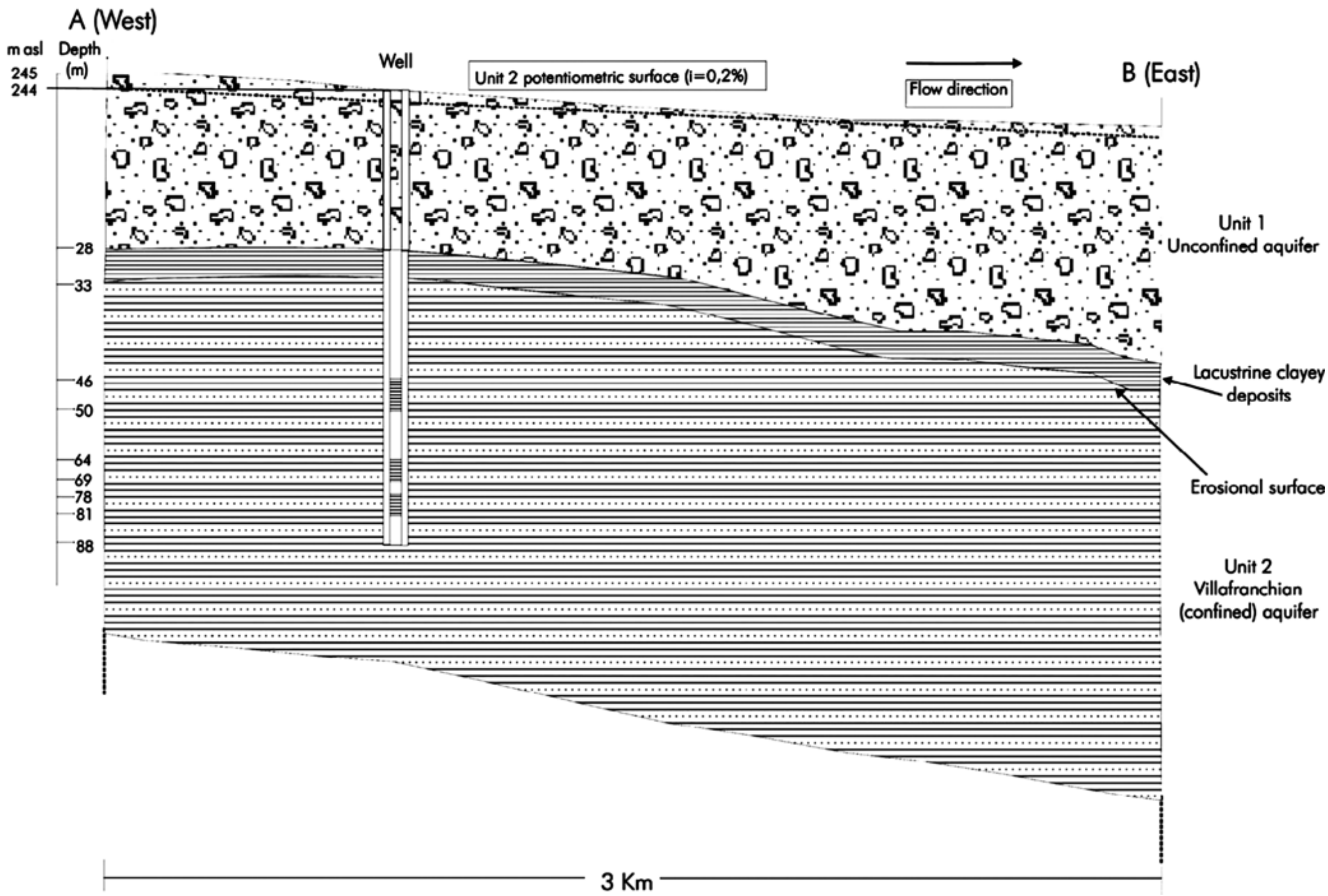

Fig. 1 – Typical representation of hydrogeological aquifer in Piedmont region (Lo Russo, Taddia 2012).

should be investigated.

Artificial tracers for to analysed the path of groundwater is a technologies that study on the hydrogeological use of fluorescent markers (fluorescein and tinopal) to testing in different hydrogeological context the reconstruction of the tracer arrival curve.

With regard to the analysis of water flow and transport of substances in the unsaturated zone the research focused on the application and comparison of methods for assessing the average annual recharge of the unconfined aquifer by means of chlorides concentration profiles and different water balance methods. The research has produced original results both in relation to geographical areas of application (Turin plain) and to the operational acquisition and processing of field data (Lo Russo *et al*., 2011). If we transfer in mountain areas the hydrogeology aspect also concerns the springs analysis: monitoring and implementation of conceptual models relating to the operation of numerous springs fed by aquifers in carbonate and massive rocks with different degree of fracturing, karst and type of land fields (Vigna 2014). In a typical Alpine context, aquifers in high-mountain carbonate rock supply springs at the foot of mountains (Vigna *et al*., 2014). Their main recharge areas are at high altitudes. These areas are present above the forest-line, where soil is very limited, and are characterized by signs of Quaternary glaciations. They are supplied by pluvial and snow precipitation (Vigna, Banzato 2015). This type of research in particular examined the geomorphology, caves, the fillings and the paleoclimatic data of high Alpine karst areas for example Bossea Caves. The karst degree in these aquifers can be different: some of these aquifers can be very karstified (high permeability), others can have a very dense fractures network (relative low permeability) (Fig.2) (Vigna, Banzato 2015; Filippini *et al*., 2018).

Fig. 2 – The karst spring, this particular spring is named "Pis Spring" in Cuneo area near Turin and this is a very famous Piedmont spring.

The research also focused on the protection of water supply sources and on potential interference with anthropogenic land uses both for wells than for springs. In particular, a novel method aimed to quantify the springs vulnerability to pollution (VESPA method) has been tested and validated basing on monitoring data of water discharge, electrical conductivity and temperature (Galleani *et al*., 2011; Banzato *et al*., 2017). Further developments were focused on the use of time-series analysis techniques to analyze and model recession hydrographs of mountain springs (Cerino Abdin *et al*., 2021).

On the other hand, several Alpine springs are located in correspondence at massive rocks, their location appears strongly influenced by the tectonic discontinuities developed in the bedrock and by the morphostructures related to Deep Seated Gravitational Slope Deformations (DSGSDs) (Fig. 3) (Gizzi *et al*., 2019).

Optimizing the present and future management strategies of mountain groundwater resources has become increasingly necessary. The accuracy and frequency of the flow rate (Q) measurements determine and restrict the processes that can be studied using spring hydrograph and recession curve analysis (Cerino Abdin *et al*., 2021).

Another aspect of research is hydrogeological flow in gypsum karst areas.

Although largely underexploited, karst aquifer systems often deliver large amounts of high-quality drinkable water and already serve about a quarter of the world's population. Gypsum crops out in almost all Italian regions, but the most significant evaporite karst areas are located in Piedmont, Emilia-Romagna, Marche, Tuscany, Calabria, and Sicily.

The gypsum aquifers in Piedmont region, on the contrary, are sandwiched between sediments with low to very low permeabilities. The waters flowing in these evaporite aquifers derive from slow recharge from the upper and lower aquitards. These gypsum aquifers are, thus, generally characterized by the presence of an extensive saturated zone, along a karstic network that is heavily

Fig. 3 – Typical fracture spring in Germanasca Valley near Turin (Gizzi *et al.*, 2019).

influenced by the fractures in the host rock. In the area of Moncalvo and Calliano the surface topography is characterized by a series of gentle hills mostly carved into the post-evaporitic sediments (marls and clays) (Fig. 4A). The evaporite beds are inclined 10-20° and are mostly buried underneath the Late Miocene-Pliocene sediments (Fig. 4B). The underground quarries in this gypsum follow the overall geometry of these evaporite bodies and intersect different aquifer levels. A series of boreholes with piezometers, together with kilometers of quarry galleries excavated in the gypsum have allowed reconstructing the hydrogeological structure of this area with great accuracy (Vigna *et al.*, 2010; 2017).

2.2 Underground Karst Laboratory of Bossea

Understanding flow dynamics in karst systems has many implications on water quality assessment and storage estimation. Karst aquifers are vulnerable to contamination and it is fundamental to assess how contaminants are transmitted from the surface to the karst springs (Nannoni *et al.*, 2020).

In this perspective, two underground laboratories have been installed in the Bossea Cave, aimed respectively at the study of karst hydrogeology and the study of the effects of climate change in the subsoil.

Bossea is a show cave attracting about 30,000 visitors each year, located in the Ligurian Alps of Southern Piedmont (Northern Italy) within a strongly deformed zone comprising metamorphosed carbonate rocks (marbles) of Jurassic to Cretaceous age and Permian meta-volcanics. The downstream part of the karst system, open to tourists, developed mostly by erosion and collapse whereas dissolution speleogenesis is secondary and important mainly in the inception stage. Bossea is an important geosite where, in a scenic underground environment, unique Quaternary paleontological findings are displayed to the public and two state-of-the-art laboratories record continuously environmental, hydrologic, and hydrochemical parameters (Antonellini *et al.*, 2019). This laboratory, located inside the cave environment, has been equipped over the years with increasingly sophisticated instruments and works in four different scientific fields: hydrogeology, meteorology, natural radioactivity, and biospele-

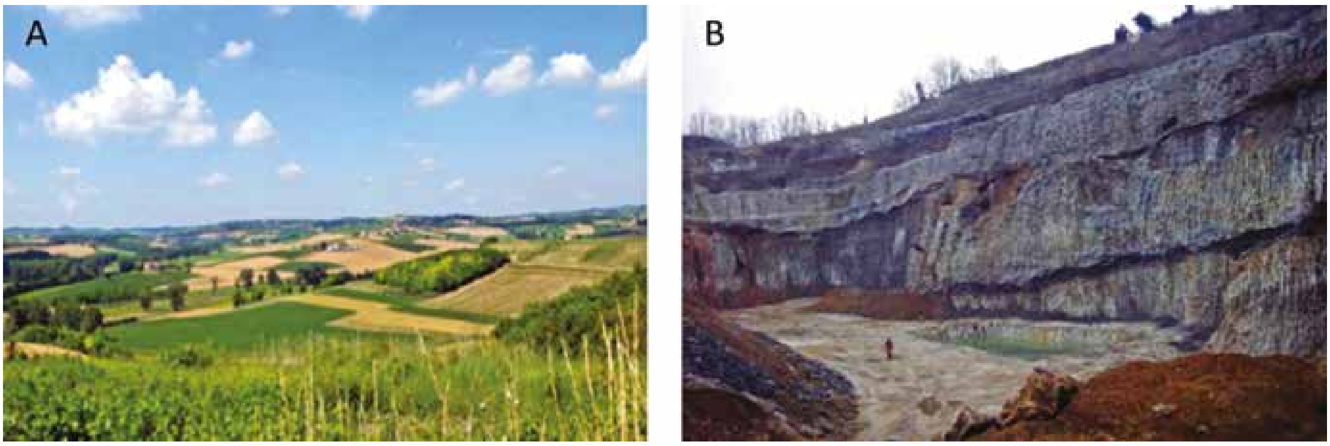

Fig. 4 – The gypsum area in Piedmont region [A]: The hilly landscape around Monferrato mostly carved in the Post-evaporitic sediments of Messinian age; [B]: The main macrocrystalline gypsum beds exposed at the surface in the open pit quarry at Moncalvo (Modified by Vigna *et al.*, 2017).

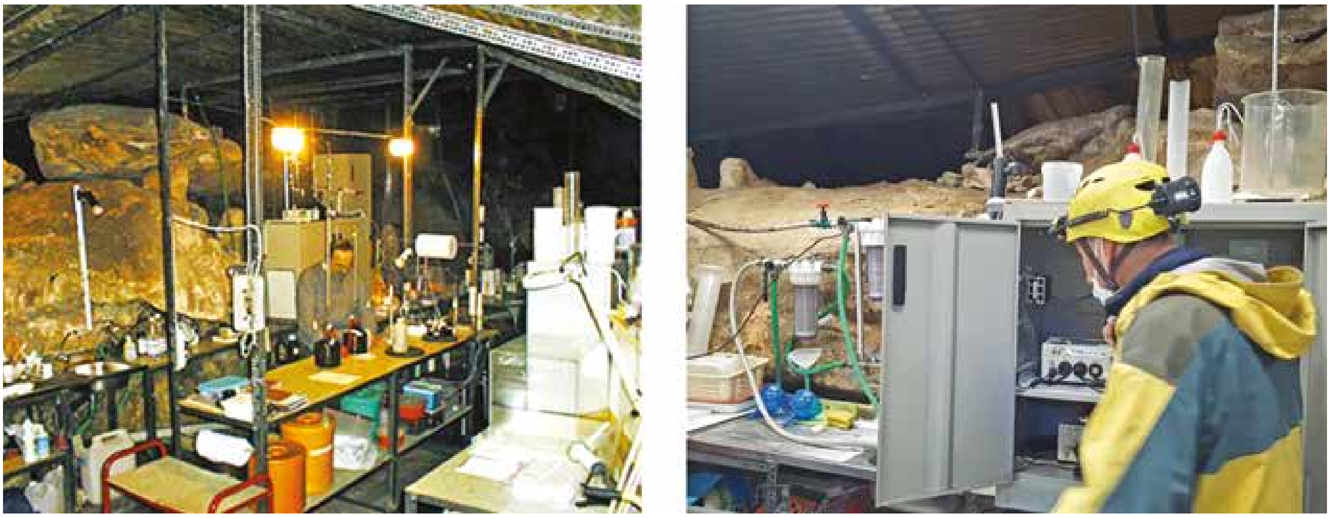

Fig. 5 – Underground Karst Laboratory of Bossea with sophisticated instruments.

ology. Several tracing experiments and the continuous monitoring of the dye tracer arrivals in different spots have enabled to build an increasingly detailed map of the different zones that recharge the Bossea karst aquifer.

The meteorological monitoring comprises air temperature and relative humidity variations, evaporation and condensation, and CO_2 levels. Rainfall and snowmelt are also measured above the cave, and the response of these infiltration events are recorded inside Bossea in different sites.

The study of the natural radioactivity of the underground environment is very interesting, because the cave is developed at the structural contact between the underlying Permian volcanic rocks and the covering Mesozoic carbonates. Radon (222Rn) deriving from the radioactive decay of 238U diffuses rapidly into the cave atmosphere and also into the percolating and flowing waters.

The research relates to the dynamics of gas exchange between rock, water and atmosphere. Different types of instruments and dataloggers are tested in the cave for the detection of Rn in the water. The biospeleological investigations have lead to the discovery of over 100 different species of cave dwelling fauna, making Bossea one of the most important biological hotspots in Italy.

The Underground Karst Laboratory of Bossea (Fig. 5) is one of the most important National Laboratory in Italy and is managed by the Alpine Club of Cuneo (CAI Cuneo) and the Central Scientific Committee of CAI in collaboration with the Diati department by Applied Geology group (AGg) of Politecnico di Torino (Vigna *et al*., 2017).

2.3 Digital photo-interpretation and interaction groundwater and slope stability

Another aspect developed by AGg is the Interaction with groundwater and slope stability: studies relating to the Langhe hilly slopes (Bottino *et al*., 2011; Vigna 2014) and to Deep Seated Gravitational Slope Deformations (DSGSDs) in Germanasca Valley (Gizzi *et al*., 2019) and Susa Valley. This particular aspect is continuous monitoring throughsprings and drainages. This aspect is very important because often the slope stability has been influenced by the groundwater flow and shallow aquifer.

As reported in Bottino *et al.* 2011, many flooding phenomena have occurred in the hilly Langhe region (NW Italy), causing damage to properties and loss of life. In this work has been demonstrated that severe water pressure conditions can drive slope instability, provided that the operational strength on the slip surface attains the residual value. Back analysis results suggest also that, for a number of slopes, the onset of instability requires a further loss of shear strength, which can be associated with decalcification phenomena that can result from the particular hydrogeochemical conditions of the region (Fig. 6).

Another aspect related to the slope instability concentrated on the development and the application of new techniques of digital photo-interpretation in hydrogeological and engineering geology surveys. In particular the Deep Seated Gravitational Slope Deformations (DSGSDs) with hydrogeology is described in Gizzi *et al.* (2019). The continuous expansion of urban areas has caused an increase interest in finding new potable water sources and led to consider mountain aquifers as an increasingly more strategic resource.

In this contest, the mountains water resources management is a topic that has become increasingly important. As mountain aqui-

Fig. 6 – Planar landslide immediately after failure. Typical landslide body displaced by a planar sliding mechanism (modified by Bottino *et al.* 2011).

fers can be particularly vulnerable from qualitative and quantitative point of view, they need a high degree of protection: it is important to understand their recharging system, from both geological and hydrogeological perspective, in order to protect and optimize its present and future management.

In the past years, several authors in collaboration with Diati AGg (Forno *et al.*, 2011; Forno *et al.*, 2012; Piras *et al.*, 2016) have conducted detailed survey, identifying the geological and geomorphological characters and resulting in the production of a new morphological and quaternary geological map of the area. A lot of peculiar morphologies connected to DSGSDs (Fig. 7) phenomena as scarps, depressions, transversal trenches, ridges elongated parallel to watersheds has been recognized and described in Forno *et al.* (2011).

In addition, some water mountain sources, many of which potentially exploitable for drinking purposes, have been identified along the longitudinal trenches mapped in the upper sector of Rodoretto Valley: by mean exclusive geological investigations it was therefore possible to demonstrate how the pattern of the hydrographic network is strongly affected by the recognized gravitational features (Forno *et al.*, 2012).

2.4 Rock-fall risk analysis and mitigation

The research activities of Diati AGg have been aimed at the development of analytical tools able to quantify the risk to road infrastructure subjected to rock-fall. In particular, it has been developed and validated an innovative operating procedure (RO.MA) that, starting with an analysis of the rock mass conditions, through a trajectory computation, and then with a risk analysis based on the event tree method, can provide a quantification of the risk condition on the road users. This procedure has been tested and applied on many field test-sites (Mignelli *et al.*, 2014).

2.5 Tunneling and groundwater

Fundamental aspect for the Applied Geology Group is the interaction between tunnelling and groundwater, this is an important element to be considered in any underground work. This is another aspect of the hydrogeological studies, in fact the research through continuous flow monitoring systems, mineralization of water temperature for the evaluation of interferences of underground works (tunnels) on aquifers cha-

Fig. 7 – Deep Seated Gravitational Slope Deformation (DSGSD) in Rodoretto Valley in Germanasca Valley near Turin.

racterized by different levels of permeability is developed in Diati department.

Groundwater can represent a major constraint for many technical decisions related to the tunnel construction and, at the same time, a fundamental valuable natural resource to be preserved quantitatively and qualitatively during and after the tunnel completion. The knowledge of the geological subsurface system, the hydrogeological mechanisms of groundwater infiltration and circulation, the degree of the aquifers connection with the river network as well as the chemical composition of the circulating groundwater are some of the more important topics that should be analysed in the early phase of the tunnel design, as it happens for the Tenda tunnel and Euralpin Lyon Turin tunnel (Western Alps).

In the Tenda tunnel was intercepted a carbonate aquifer that feeds a series of important flow of groundwater, named Tenda Spring. This source was discovered during excavation of the railway tunnel (1889-1898). In 1990 the spring was tapped in the tunnel by the Langhe and Alpi Cuneesi Aqueduct; this infrastructure is very important for the social-economic development of a vast area, which has few other water resources suitable for human consumption and which supplies, along with some other sources, a population of over 100.000 (Banzato *et al*., 2011) (Fig. 8). This source is actually monitoring by Diati Applied Geology group.

The second important project that developed by Diati AGg regarded the "La Maddalena" exploratory tunnel. "La Maddalena" exploratory tunnel, located in Chiomonte (Italy Western Alps – Susa Valley), is one of the four exploratory adits, three in France, completed in 2010, and one in Italy, whose realization is related to Turin-Lyon high-speed rail project (Fig. 9).

Fig. 8 – Hydrogeological monitoring of Tenda tunnel.

During the tunnel construction several monitoring data have been recorded in order to assess geological parameters important for the future Base tunnel realization. In fact, one of the main task in the optimization of the final design of a Tunnel has been represented by the hydrogeological monitoring. This activity has

Fig. 9 – Realization phase of "La Maddalena" exploratory adit (Lo Russo *et al.*, 2019).

Fig 10 – Hydrogeological monitoring in "La Maddalena" exploratory tunnel.

been aimed to verify the correctness of the project hypothesis and specially to evaluate the inflow forecast in term of discharge rate and distribution, temperature and chemical facies of groundwater. The hydrogeological monitoring has proved extremely valuable not only in checking the reliability of the tunnel design forecast but also in underlining the importance of the realization of exploratory tunnels prior to the excavation of a main tunnel. Thanks to the hydrogeological and temperature monitoring of the main water inflow "La Maddalena" exploratory adit can also represent in perspective a very interesting possibility to exploit the related geothermal potential (Fig. 10).

2.6 Relationship between chemism of water and human health

Another important aspect developed by the AGg at Diati, concerns the in-complexity study of the chemism of water in relation to human health (Tiwari *et al*., 2021).

In particular in Civita *et al*., 2001, is analyzed as aluminum was determined in surface and groundwater in the Alba city (NW Piedmont Region) to provide information on natural and anthropogenic sources of contamination. Thanks to the Water Lab in Diati department it was possible to find out as aluminum is not an essential element for the biological cycle, its high concentration in both water and soil could have toxic effects both on plants and animals.

The presence of aluminum in drinkable water is of particular interest, because suggest the connection between high levels of this metal and Alzheimer's disease (Civita *et al*., 2001). This is a very important study developed by Diati AGg.

2.7 Temperature of the air and of the rock in various natural cavities

Recently the research of engineering geology has led to the analysis of the temperature of the air and rock in various natural cavities in the sector of the Ligurian and Maritime Alps. In these karst cavities there are ice deposits (Fig. 11) in the phase of evident melting due to the increase in surface temperatures (Vigna and Paro 2020).

This research activity is still under investigation.

2.8 Renewable energy: geothermal heat pump

Thanks to the international political response to climate change the past five years have been a period of unprecedented growth and development for renewable energy worldwide and according to Sustai-

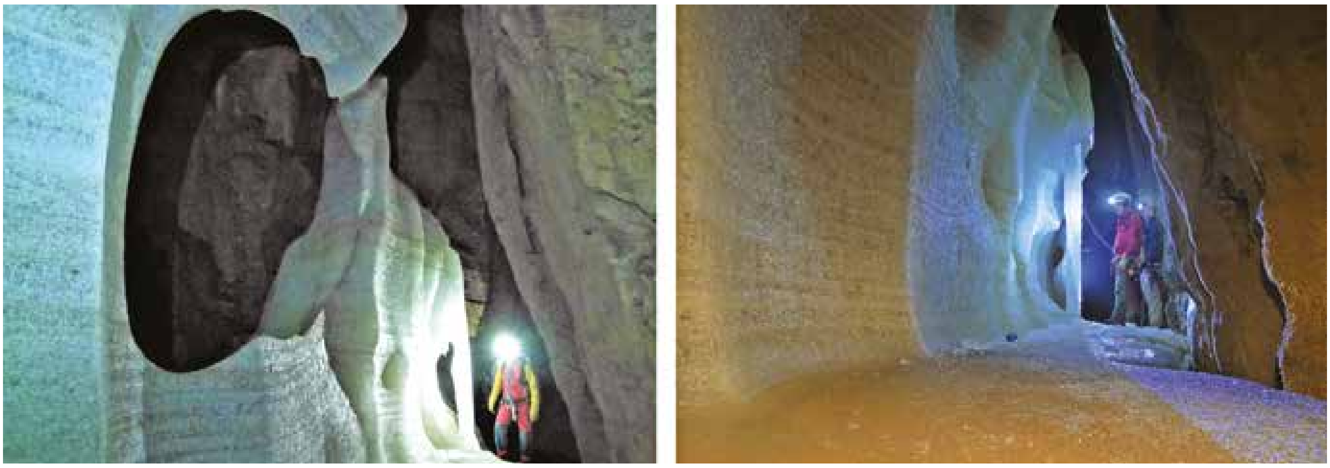

Fig. 11 – Ice-deposits in karst cavities.

nable Development Goals (SDGs) adopted by United Nations Member States in 2015 there has been a further increase in renewable energy and geothermal energy in particular.

The AGg at Diati began to deal with the renewable energy issue starting from 2009, focusing the studies on geothermal energy and its development in Italy (Lo Russo and Taddia, 2009; Taddia *et al.*, 2018).

Geothermal heat pumps represent an interesting technology expected to contribute significantly to the reduction of primary energy use for heating and cooling. Additional benefits of this technology, which also meets the European Union targets, are the possibilities of integration with discontinuous energy resources, in particular wind, combining heat and power.

The replacement of conventional heating systems such as boilers, with general heat pump systems allows the de-localization of emissions of micropollutants from urban centers to the sites in which thermal power stations are operating. Furthermore, the use of distributed production systems based on the use of renewable sources reduces also CO_2 emissions (Baccino *et al.*, 2010; Lo Russo *et al.*, 2011). Thanks to the continuous monitoring of the Politecnico di Torino geothermal plants, it was possible to develop detailed research in renewable energy fields in urban contexts.

In fact, this research, some fundamental aspects related to the development of open-loop heat pumps have been explored in a typical urban contest (Politecnico di Torino in Turin city, NW Italy). In particular, appropriate hydrogeological investigations and simulation modelling were performed for the characterization of the main hydrogeological parameters of the subsoil at the considered site. The results of the work have allowed to define several fundamental aspects in order to optimize the design choices of Groundwater Heat Pump (GWHP) systems and the importance of geological and hydrogeological surveys (Taddia G. 2018).

2.9 Energy security and transition and Raw materials in mining sustainability

According to renewable energy, recently the engineering geology developed also the energy transition strategies: the research focuses on raw materials, their identification and economic and environmental impact analyses related to their primary extraction, transformation and transport on a global scale. In the energy sector, further research focuses on numerical risk modelling and national and international energy security, with particular regard to the supply of hydrocarbons (Oil & Gas) (Gizzi *et al.*, 2021; Lo Russo *et al.*, 2020).

In the field of raw materials, research is carried out on the assessment of the potential of deposits and the environmental impacts associated with mining activities at both regional and site-specific scale (Lo Russo *et al.*, 2021).

In particular, the impacts on the environmental matrices of traditional extraction programs but also of those necessary for the extraction of raw materials necessary for the energy transition policies towards electric mobility technologies and electricity storage on a global scale are analyzed.

3. Conclusion

In conclusion, as we have seen an increase in the incidences of extreme weather events end environmental risks, there is a greater need for geoscience professionals who can assist communities in planning mitigation efforts for future flooding and landslides. There are also many current and future development projects being undertaken in landslide prone areas and in relationship at renewable energies, which requires careful consideration and planning by expert applied geoscientists. In this perspective, the group intends to continue the studies of engineering geology with great enthusiasm and professionalism.

References

AA.VV., 2014. Engineering Geology for Society and Territory. Springer International Publishing Switzerland. G. Lollino *et al.* (eds.), vol. 7, pp. 1-274 ISBN 978-3-319-09302-4 ISBN 978-3-319-09303-1 (eBook) DOI 10.1007/978-3-319-09303-1

AA.VV., 2019. Acqua: energia dal tunnel di base. Ed: De Simone Squillari Arti Grafiche. ISBN: 978-88-944868-0-3

Antonellini, M., Nannoni, A., Vigna, B., De Waele J. 2019. Structural control on kast circulation and speleogenesis in a lithological conctact zone: The Bossea cave system (Western Alps, Italy), GEOMORPHOLOGY, Elsevier, Vol. 345, pp. 21, 2019, ISSN: 0169-555X, DOI: 10.1016/j.geomorph.2019.07.019

Banzato, C., Butera, I., Revelli, R., Vigna B. 2017. Reliability of the VESPA Index in Identifying Spring Vulnerability Level, Journal of Hydrologic Engineering, R.S. Govindaraju, Vol. 22, pp. 11, ISSN: 1084-0699, DOI: 10.1061/(ASCE)HE.1943-5584.0001498

Bottino, G., Chighini, S., Lancellotta, R., Musso, G., Romero, E., Vigna B. 2011. Plane slope failures in the Langhe region of Italy. Geotechnique, vol. 10, pp. 845-859. http://dx.doi.org/10.1680/geot.7.00168

Cerino Abdin, E., Taddia, G., Gizzi, M., Lo Russo, S., 2021. Reliability of spring recession curve analysis as a function of the temporal resolution of the monitoring dataset. Environ Earth Sci, Vol. 80, pp. 249 https://doi.org/10.1007/s12665-021-09529-2

Filippini, M., Squarzoni, G., De Waele, J., Fiorucci, A., Vigna, B., Grillo, B., Riva, A., Rossetti, S., Zini, L., Casagrande, G., Stumpp, C., Gargini A. 2018. Differentiated spring behavior under changing hydrological conditions in an alpine karst acquifer, Journal of Hydrology, Elsevier, Vol. 556, pp. 13, ISSN: 0022-1694

Forno, M.G., Lingua, A., Lo Russo, S., Taddia, G., 2011. Improving digital tools for Quaternary field survey: a case study of the Rodoretto Valley (NW Italy). Environmental Earth Sciences, Vol. 64, pp. 487-1495. doi: dx.doi.org/10.1007/s12665-011-0971-6.

Forno, M.G., Lingua, A., Lo Russo, S., Taddia, G., 2012. Morphological features of Rodoretto Valley deep-seated gravitational slope deformations. Am J Environ Sci, vol. 8, pp. 648-660. doi:10.3844/ajessp.2012.648.660.

Forno, M.G., Lingua, A., Lo Russo, S., Taddia, G., Piras, M., 2013. GSTOP: a new tool for 3D geomorphological survey and mapping. Eur J Remote Sens, vol. 46, pp. 234-249. doi:10.5721/EuJRS20134613.

Galleani, L., Vigna, B., Banzato, C., Lo Russo, S., 2011. Validation of a Vulnerability Estimator for Spring Protection Areas: The VESPA index, Journal of Hydrology, vol. 396 (3-4), pp. 233-245, Elsevier, ISSN: 0022-1694, DOI: 10.1016/j.jhydrol.2010.11.012

Gizzi, M., Lo Russo, S., Forno, M.G., Cerino Abdin, E., Taddia, G., 2019. Geological and hydrogeological characterization of springs in a DSGSD context (Rodoretto Valley – NW Italian Alps). Applied Geology Approaches to Future Resource Management – Springer Nature Switzerland AG 2020 M. De Maio, A.K. Tiwari (eds.), Applied Geology, vol. 1, pp. 3-20, ISBN 978-3-030-43952-1 ISBN 978-3-030-43953-8 (eBook) https://doi.org/10.1007/978-3-030-43953-8_1

Gizzi, M., Taddia, G., Lo Russo, S., 2021. Reuse of decommissioned hydrocarbon wells in italian oilfields by means of a closed-loop geothermal system. Appl. Sci. 2021, 11, 2411, pp. 1-16 doi: https://doi.org/10.3390/app11052411

Lo Russo, S., Taddia, G., 2009. Groundwater in the Urban Environment: Management Needs and Planning Strategies, American Journal of Environmental Sciences, vol. 5 (4), pp. 494-500, Science Publications, ISSN: 1553-345X, DOI: 10.3844/ajessp.2009.494.500

Lo Russo, S., Fiorucci, A., Vigna, B., 2011. Groundwater Dynamics and Quality Assessment in an Agricultural Area: the Cuneo Plain (NW Italy), American Journal of Environmental Sciences, vol. 7 (4), pp. 354-361, ISSN: 1553-345X, DOI: 10.3844/ajessp.2011.354.361

Lo Russo, S., Taddia, G., 2012. Aquifer vulnerability assessment and wellhead protection areas to prevent groundwater contamination in agricultural areas: an integrated approach, Journal of Water Resource and Protection, vol. 4 (8), pp. 674-685, Scientific Research, ISSN: 1945-3094, DOI: 10.4236/jwarp.2012.48078

Lo Russo, S., Taddia, G., Cerino Abdin, E., 2015. Tunnelling and groundwater interaction: the role of the hydrogeological monitoring. Geoingegneria Ambientale e Mineraria GEAM, vol. 3, pp. 37-44.

Lo Russo, S., Taddia, G., Cerino Abdin, E., Parisi, M.E., 2019. "La Maddalena" exploratory edit – base tunnel of the Turin-Lyon high speed rail project: hydrogeological monitoring data analysis. Rendiconti online Società geologica italiana, vol. 47, pp. 58-63. https://doi.org/10.3301/ROL.2019.11.

Lo Russo, S., Gizzi, M., Taddia, G., 2020. Abandoned oil and gas wells exploitation by means of closed-loop systems: a review. Geoingegneria Ambientale e Mineraria GEAM, vol. 2, pp. 3-11. Doi: DX.DOI.ORG/10.19199/2020.2.1121-9041.03

Lo Russo, S., Mondani, M., Giglio E. 2021. Environmental and geostrategic effects of raw materials supply supporting the energy transition and electric mobility: a focus on the "lithium triangle" in South America. Geoingegneria Ambientale e Mineraria GEAM, vol. 162, pp. 25-33. DX.DOI.ORG/10.19199/2021.1.1121-9041.025

Mignelli, C., Peila, D., Lo Russo, S., Ratto, S.M., Broccolato, M., 2014. Analysis of rockfall risk on mountainside roads: evaluation of the effect of protection devices. Natural Hazards, vol. 73 (1), pp. 23-35, DOI: 10.1007/s11069-013-0737-4

Oliveira, R., 2014. Optimization of large civil engineering projects from an environmental point of view. G. Lollino *et al.* (eds.), Engineering Geology for Society and Territory. Springer International Publishing Switzerland, vol. 7, pp. 1-7. DOI: 10.1007/978-3-319-09303-1_1

Piras, M., Taddia, G., Forno, M.G., Gattiglio, M., Aicardi, I., Dabove, P., Lo Russo, S., Lingua, A., 2016. Detailed geological mapping in mountain areas using an unmanned aerial vehicle: application to the Rodoretto Valley, NW Italian Alps. Geomatics, Natural Hazards & Risk, vol. 8 (1), pp. 137-149, ISSN: 1947-5705, DOI: 10.1080/ 19475705.2016.1225228

Taddia, G., Cerino Abdin, E., Lo Russo, S., 2018. The role of the geothermal energy in the renewables framework: an overview. Geoingegneria Ambientale e Mineraria GEAM, vol. 1, pp. 40-48.

Taddia, G., 2018. Underground exploitation in urban areas by geothermal heat pump systems: the example of Turin Politecnico test site (NW Italy). Alpine and Mediterranean Quaternary (AMQ), vol. 31 (2), pp. 235-244. ISSN (print): 2279-7327, ISSN (online): 2279-7335. Doi: https://doi.org/10.26382/AMQ.2018.18

Tiwari, A.K., Suozzi, E., Fiorucci, A., Lo Russo S. 2021. Assessment of groundwater geochemistry and human health risk of an intensively cropped alluvial plain, NW Italy. Human and Ecological Risk Assessment, vol. 27, (3), pp. 825-845. DOI:10.1080/10807039.2020.1775484

Vigna, B., Fiorucci, A., Ghielmi M. 2010. Relations between stratigraphy, groundwater flow and hydrogeochemistry in Poirino Plateau and Roero areas of the Tertiary Piedmont Basin, Italy, Memorie Descrittive della Carta Geologica d'Italia, Istituto Superiore per la Protezione e la Ricerca Ambientale, Vol. XC, pp. 25, 2010, ISSN: 0536-0242

Vigna, B., Fiorucci A; Banzato C; Forti P; De Waele J, 2010. Hypogene gypsum karst and sinkhole formation at Moncalvo (Asti, Italy)., Zeitschrift Für Geomorphologie, Vol. 54(2), pp. 21, 2010, ISSN: 0372-8854, DOI: 10.1127/0372-8854/2010/0054S2-0015

Vigna, B., 2014. Acquisizione ed interpretazione dei dati di monitoraggio delle sorgenti. GEAM. Geoingegneria ambientale e mineraria, Pàtron Ed., pp. 16, 2014, Vol. GEAM 143, ISSN: 1121-9041 (in Italian).

Vigna, B., Menegatti, S., Bianco, F., Banzato C. 2014. Relations between snowfalls and floods of some springs fed by aquifer host in carbonate rocks (Southern Piedmont – Italy), In: Flowpath 2014, National Meeting on Hydrogeology, Università degli Studi della Tuscia (ITALIA), Flowpath 2014, National Meeting on Hydrogeology, Viterbo 18-20 giugno 2014, pp. 2, 2014, ISBN: 9788890755347

Vigna B. 2014. L'attività del Politecnico di Torino per lo studio dei fenomeni di scivolamento planare delle Langhe. Parte I: assetto geologico-strutturale ed idrogeologico, GEAM. Geoingegneria Ambientale e Mineraria, Vol. L'alluvione del 5-6 Novembre 1994 in Piemonte. Venti anni di Attività nella previsione e prevenzione in ambito geo-idrologico, ISSN: 1121-9041, ISBN: 9788863780031 (in Italian)

Vigna, B., Banzato, C., 2015. The hydrogeology of high-mountain carbonate areas: an example of some Alpine systems in southern Piedmont (Italy). Environ. Earth Sci., Vol. 74, pp. 267-280. DOI 10.1007/s12665-015-4308-8

Vigna, B., D'Angeli, I.M., Fiorucci, A., De Waele, J., 2017. Hydrogeological flow in gypsum karst areas: some examples from northern Italy and main circulation models. International Journal of Speleology, 46 (2), 205-217. Tampa, FL (USA) ISSN 0392-6672 https://doi.org/10.5038/1827-806X.46.2.2095

Vigna, Bartolomeo; Guido, Peano; Ezechiele, Villavecchia; Jo De Waele., 2017. The Karstological Subterranean Laboratory of Bossea Cave (N Italy), In: Proceedings of the 17 th International Congress of Speleology, July 22-28, Moore, K., White, S., Proceedings of the 17 th International Congress of Speleology, July 22-28, pp. 5, 2017, Vol. 1

Vigna, B., Paro, L., 2020. Ghiacciai ipogei e grotte con depositi di ghiaccio e neve, In: Ultimi ghiacci: clima e ghiacci nelle Alpi Marittime, Mercalli Luca, Cat Berro Daniele, Edizioni Società Meteorologica Subalpina (Italia), pp. 7, ISBN: 978-88-903023-9-8 (in Italian).

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