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Humanitarian engineering and vulnerable communities: hydropower applications in localised flood response and sustainable development

Spyros Schismenos [a,c], Garry John Stevens [a], Dimitrios Emmanouloudis [b,c], Nichole Georgeou [a], Surendra Shrestha [d] and Michail Chalaris [e,f]

[a]School of Social Sciences, Humanitarian and Development Research Initiative (HADRI), Western Sydney University, Sydney, Australia; [b]Department of Forestry and Natural Environment, International Hellenic University, Kavala, Greece; [c]UNESCO Chair for the Conservation and Ecotourism of Riparian and Deltaic Ecosystems, International Hellenic University, Drama, Greece; [d]School of Engineering, Western Sydney University, Sydney, Australia; [e]School of Fire Officers, Hellenic Fire Academy, Athens, Greece; [f]Military Nursing Academy (SAN), Hellenic Fire Corps, Athens, Greece

ABSTRACT

Humanitarian engineering offers substantial benefits to interventions for socio-economic development and disaster risk resilience, particularly amongst vulnerable populations facing energy insufficiency and extreme weather events in low- and lower-middle-income countries. Localised hydropower and early-warning applications are reliable and can support such communities. This study presents important criteria and in-depth investigations for small-scale hydropower generators combined with flood-warning systems. According to our findings, 300 W of generated power can provide sufficient coverage for basic energy needs under both normal and extreme conditions. Outdoor warnings such as emergency lights and sirens could increase local response capabilities and save lives during extremes. Our project highlights the use of community-led hydropower as a vehicle for disaster resilience and sustainable development.

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Off-grid renewable energy; early-warning system; low- and lower-middle-income country; extreme weather event

1. Introduction

Extreme weather events increasingly threaten human populations. Water-based disasters, such as heavy rainfalls and torrential floods are frequent and affect communities in multiple ways, including mortality, displacement, financial and income losses, and damaged infrastructure (Wahlstrom and Guha-Sapir 2015; Schismenos 2017; Schismenos et al. 2018b; Schismenos, Stevens, Emmanouloudis et al. 2019; Schismenos, Stevens, Georgeou et al. 2019). Often, populations with limited capabilities, such as those in low- and lower-middle-income countries (L/LMICs) have increased disaster risk vulnerability levels. In this study, we define vulnerable communities as small, rural/remote, low-income mono-economies that reside in riparian areas in L/LMICs. Other vulnerability characteristics that we consider are energy insufficiency, limited disaster risk resilience mechanisms and high flood risk estimates (Schismenos 2017; Schismenos et al. 2018b; Schismenos, Stevens, Emmanouloudis et al. 2019; Schismenos, Stevens, Georgeou et al. 2019).

CONTACT Spyros Schismenos S.Schismenos@westernsydney.edu.au LinkedIn: https://www.linkedin.com/in/spyros-schismenos-55a7a1108/ ResearchGate: https://www.researchgate.net/profile/Spyros_Schismenos Facebook: Spyros Schismenos Instagram: spyrosschismenos Twitter: @spyrosschismeno

According to the 2030 Agenda for Sustainable Development, energy sufficiency at the local level is one of the most crucial factors for increasing community capabilities, especially in L/LMICs (Howells et al. 2017; United Nations 2016). Community-led disaster response in L/LMICs is equally important, according to the United Nations Sendai Framework for Disaster Risk Reduction (Pearson and Pelling 2015). Disaster impacts disproportionately affect low-income populations, destroying a greater proportion of their gross domestic product (GDP) and undermining their development potential. Therefore, a combination of energy generation and early-warning at the local level could support vulnerable communities under any conditions (Schismenos et al. 2018b; Schismenos, Stevens, Emmanouloudis et al. 2019; Schismenos, Stevens, Georgeou et al. 2019). This concept accords with the principles of World Economic and Social Survey 2018: Frontier Technologies for Sustainable Development (Kamperman Sanders et al. 2018) and highlights the importance of combined humanitarian engineering applications in undeveloped, disaster-prone areas.

There is no widely accepted definition of the term 'humanitarian engineering' (Hill and Miles 2012). One reason for this is that it is not included in any of the classical engineering branches; yet it combines sub-disciplines of these branches with elements of other fields that are non-engineering (e.g. economic, cultural, ethical, socio-political, humanitarian, health and safety/disaster risk-related) (Gosink, Lucena, and Moskal 2003). Another reason is that it is a relatively new topic, especially in education and training (Hill and Miles 2012; Gosink, Lucena, and Moskal 2003). For this research, it can be broadly defined as the appropriate application of engineering concepts to fit the needs and capabilities of communities lacking sustainable development, resilience against natural and human-induced hazards, psycho-social well-being and basic infrastructure in order for them to function properly and prosper long-term (Sheroubi and Potvin 2018; Younger et al. 2018).

Humanitarian engineering solutions are often proposed as contributing to both socio-economic development and phases of disaster management, including response and recovery. They can be either emergency or permanent interventions for infrastructure restoration/establishment, water sanitation, energy supply, telecommunications, early-warning and transportation (Younger et al. 2018). They combine basic engineering principles and focus on renewable energy, environmentally friendly uses of local resources, local community engagement and expertise (Mazzurco and Jesiek 2017). They are often dynamic, portable, fast-track and ready-for-use or easy-to-build means that simplify the work of community groups and emergency professionals (Kellett and Peters 2014; Kovács and Spens 2020).

Two examples of humanitarian engineering solutions are the Telecommunications Container and the Automated Network for Air-Sea Actions (ANASA). The Telecommunications Container is a portable module that can support communications and logistics in emergency situations. It is particularly recommended for remote communities struck by natural hazards, but its applications vary considerably. It allows alternations in its interior space so that context-specific communications equipment can be installed in a modular fashion. Besides applications in emergency settings, it can provide primary or supporting communications for large scale events that are not permanent (e.g. the Olympics). The ANASA is still at concept stage and consists of a network of drones and tidal energy generators designed for air-sea-based search and rescue (e.g. detection of shipwreck survivors and asylum-seekers at sea) (Parisi et al. 2016; Schismenos et al. 2018a). The drones surveil a remote perimeter and land on the buoys that act as recharging points. The buoys are also equipped with meteorological stations, emergency lights that activate during extreme weather conditions, emergency kits and signal transmitters. There is potential for drones to drop minimal survival packs (e.g. water) to survivors while awaiting rescue teams deploy to site (Schismenos et al. 2018). Both examples have characteristics of the humanitarian engineering applications, as previously defined.

Considering those detailed above, off-grid energy generation systems could be a sustainable solution for vulnerable communities, especially if equipped with early-warning systems (EWS) (Schismenos et al. 2018b; Schismenos, Stevens, Emmanouloudis et al. 2019; Schismenos, Stevens, Georgeou et al. 2019). Used alongside traditional energy sources such as diesel generators, renewable energy systems are an increasingly important part of the energy mix for many remote communities. Solar, wind and hydropower generators are the most popular choices (Vezmar et al. 2014). This study particularly focuses on hydropower systems.

Hydropower is the most widely-used renewable energy source for electricity generation globally. In 2015, it supplied 71% of the total renewable electricity (World Energy Council 2016). It varies in scale (large, centralised, small and isolated) and can be combined with water supply services (e.g. irrigation and flood control systems). The latter provides multiple socio-economic benefits to end-users (Gielen 2012). Among the types of hydropower, localised small-scale systems, such as portable hydropower systems (PHYS) have high potential. They have minimal environmental impacts and are a cost-competitive solution for electrification in rural communities (Gielen 2012; Ioannidou and O'Hanley 2018). If combined with EWS and designed appropriately, PHYS can cover a number of basic energy needs under normal conditions (e.g. power home appliances), as well as under extreme conditions (e.g. power outdoor sirens and emergency lights), while also acting as localised flood detectors (Schismenos et al. 2018b; Schismenos, Stevens, Emmanouloudis et al. 2019; Sachdev, Akella, and Kumar 2015). For that reason, they are a feasible humanitarian engineering option for vulnerable communities.

Our current study at Western Sydney University, Australia in collaboration with UNESCO Chair on Conservation and Ecotourism of Riparian and Deltaic Ecosystems, and International Hellenic University, Greece entitled 'Hydropower for Disaster Resilience Applications (HYDRA)' investigates the feasibility of localised systems which combine sustainable hydropower generation and EWS to support remote community disaster resilience, socio-economic growth and environmental sustainability. Our preliminary analysis that is presented in this paper identifies criteria PHYS and EWS should have in order to operate effectively at the local level. The combined systems could be beneficial for populations with limited access to electricity and insufficient flood response mechanisms. Importantly, such units could be developed to ensure that they can be operated and maintained by end-users without requiring the involvement of professionals or technicians.

2. Criteria for designing combined PHYS/EWS

Despite the advantages of humanitarian engineering applications in power generation and early-warning, there are cases where localised energy supply units and EWS failed to provide sustainable benefits. Their workability over time is one of the main factors that cannot be guaranteed, especially if these systems cannot be easily managed or maintained by local end-users (Ikejemba et al. 2017; Baudoin et al. 2014). In addition, medium to large scale projects, ownership, cost, and environmental and health impacts may also affect the life expectancy of such systems (Ikejemba et al. 2017). These systems are also exposed to weather extremes and there are cases where they were destroyed or severely damaged by natural hazards. Local communities could not repair them on their own due to a lack of knowledge and/or access to replacement parts (Gurung et al. 2011). Table 1 summarises findings from the available research (Schismenos 2017; Schismenos, Stevens, Emmanouloudis et al. 2019; Schismenos, Stevens, Georgeou et al. 2019; Ikejemba et al. 2017; Baudoin et al. 2014; Gurung et al. 2011; Preston 2012; Gore et al. 2007; Soewardi and Putra 2018; Fink, Ojewole, and Tan 2014) regarding systems' requirements and key criteria for evaluating PHYS and EWS.

According to Table 1, both PHYS and EWS should fulfil specific criteria that correspond to the needs and capabilities of vulnerable communities in order to be efficient and acceptable long-term. Community engagement in both systems' operations is essential; therefore, the systems should not be complex, foreign to local 'know-how' and demanding in resources, time and oversight.

The following paragraphs present more detailed information about PHYS and EWS that further support these criteria. The purpose of this analysis is the development of a combined PHYS/EWS unit that can be used by vulnerable communities with limited capabilities.

Table 1. Evaluation criteria for PHYS and EWS.

Criteria	Description	PHYS	EWS
Disaster-resilience	Durability against floating debris, logs and products of weather extremes (e.g. hail).	√	√
Low maintenance	Requires minimal repairs over time.	√	√
Portability	Easily carried, transferred, installed, uninstalled and reinstalled by a small number of individuals.	√	√
Readily sourced materials	Made with materials easily sourced locally (e.g. recycled and natural materials).	√	√
Durability (time)	Unit lasts for relatively long periods under any atmospheric conditions.	√	√
Affordability	Can be purchased/maintained by low-income end-users.	√	√
Autonomy	Not dependent on other external systems and/or services (e.g. internet, telecommunication antennas).	√	√
Workability	Continuous operation under any atmospheric condition (operates 24/7).	√	√
Do-it-yourself/easy-to-deploy-and-operate (DIY/EDO)	Can be assembled, dismantled, rebuilt, deployed and operated by end-users with limited experience or technical knowledge.	√	√
Minor environmental impacts	No/Minor impacts caused on local ecosystems.	√	√
Minor impacts (other)	No/Minor impacts caused on the local populations and surroundings.	√	√
Safety	No/Minor impacts on human health and well-being.	√	√
Adaptability	Can be installed and operate in sites of different hydrogeomorphological conditions (e.g. water depth, width, flow). No/Minor operational impacts due to atmospheric changes.	√	√
Energy needs	Requires minimum or no power to operate.	√	√
Large range and population reach	Can reach a relatively wide radius of space and large group of people, including those with vision and hearing impairments (local level scale).	-	√
Power range	Can cover some basic energy needs under any conditions.	√	-

2.1. Further analysis on PHYS

If designed, installed and maintained properly, PHYS can offer multiple advantages compared to other renewable energy types at the local level. Even though PHYS vary in design and features, they often require the following components to be functional (Rahman et al. 2013):

- Stream with sufficient water flow
- Water turbine that converts the kinetic energy into rotational energy
- Electrical generator that converts the rotational energy into electricity
- Grid/Energy Storage Unit, or
- Cables for transferring the power to appliances.

In order to obtain maximum benefits, additional parameters should be taken into consideration. Specifically:

- The stream must have enough water volume, flow, depth and width (run-of-river system) to feed the turbine.
- The PHYS can: (i) be connected to the grid, (ii) be connected to the grid and have a battery backup, (iii) stand-alone (off-grid).
- Even though there are no agreed international standards, the size of PHYS can be either pico (usually less than 5 kW) or micro (usually between 5 and 100 kW). Table 2 presents widely-used home appliances that can be powered by PHYS and their energy requirements (DaftLogic 2020)].

Most communities, including their gathering spaces (schools, shelters, clinics) use appliances shown in Table 2. Our study suggests that some of these devices (e.g. LED lights), depending on their location, should operate under any condition as they contribute in both local socio-economy (businesses, households, public spaces) and emergency scenarios (EWS, emergency evacuation routes). Considering the findings in Table 2, we propose that the minimum required power for

Table 2. Widely-used home appliances and their energy requirements.

Home appliance	Minimum (W)	Maximum (W)	Standby (W)
100W light	100	100	0
LED light	7	10	0
32″ LED TV	20	60	1
DVD player	26	60	-
Fridge/Freezer	150	400	-
Ceiling Fan	60	70	0
Personal Computer (PC)	100	450	-
Laptop Computer	50	100	-
American-style Fridge/Freezer	40	80	-
Internet router	5	15	-
Smart Phone Charger	4	7	-

covering basic energy needs is 300 W per hour and it is delivered by PHYS. This is a realistic scenario for vulnerable populations.

This assumption is further supported when considering that 300W is the approximate average of total primary energy use in a lower-middle-income country such as Bangladesh over the last years (Kolbert 2008; Geck 2017). It should be noted that other L/LMICs of similar or lower GDP, have a lower average of total primary energy use (Geck 2017). This average rate could further decrease when referring to vulnerable communities in these countries. Therefore, our hypothesis is a realistic scenario for such populations.

2.2. Selection of PHYS turbine and generator

Hydropower turbines can be categorised into two types: (i) impulsive and (ii) reaction. The type selection should be based on the water level, flow, volume and head. Other parameters that should also be considered include the water depth, cost and power generation efficiency. More information about each type as follows (Office of Energy Efficiency and Renewable Energy 2020; Kisliakov 2011):

- **Impulsive turbine:** It uses the water velocity to run (the stream hits the 'buckets' on the runner, then the atmospheric pressure discharges it). This type is often recommended for sites with high head and low flow. The Pelton wheel and cross-flow turbine are two popular examples of impulsive hydro-turbines.
- **Reaction turbine:** It is dependent on the combination of water flow and atmospheric pressure to develop energy (the stream flows over the blades of the runner). This type is often recommended for sites with no or no head. The propeller, bulb, STRAFLO, tube, Kaplan, Francis and free flow (kinetic energy) turbines are some examples. The free flow turbine, for instance, could be an ideal option for PHYS as it generates energy mainly from the kinetic energy of the water flow rather than the water head. It can well-operate in both natural and manmade steams, tidal waters which may develop during extreme weather events, and ocean currents. Another advantage of this turbine is that it does not require large or complex civil works when installed. Instead, it can be equipped on existing structures (e.g. bridges, channels) or stand-alone on buoyant platforms.

It should be noted that there is a large variety of turbines for both types. In this study we focus on turbines that do not require high head and can operate under both low flow (often, normal conditions) and high flow (rare, extreme conditions). Besides the type and design of the hydro-turbine, an appropriate generator is important when designing PHYS. Turbines that rotate at slow speeds may require a gearbox or pulley system. In general, the most preferred choice for small-scale hydropower systems is the permanent magnet synchronous generator. This is an electrical generator that converts mechanical/rotational energy to electricity and can be used without a gearbox. It offers high efficiency with low maintenance and can also be used by other renewable energy types (wind energy) (Acharya, Papadakis, and Shaikh 2016; Smith 1994). Small hydropower generators can be categorised as direct current (DC) and alternating current (AC) generators. Specifically:

- **DC Generators:** Depending on their size, they can produce more than 3 kW. Dynamos, that are permanent magnet DC generators, are perhaps the most popular option. For slow water speed, diesel dynamos that were used in trucks or buses are preferred as they focus on the energy generation efficiency. They can generate up to 500 W and power energy storage units (batteries) similarly to car battery charging. However, the batteries should be very close to the generator in order to avoid energy loss due to distance. Besides dynamos, car and automotive alternators are also an option, however, they may lack in efficiency. Car alternators, for instance, require high rpm speed; whereas, automotive alternators require an external power supply to create a magnetic field. Most DC generators use rectifiers to convert the low-voltage DC electricity into AC electricity. The AC electricity is required for powering home appliances (120 or 240 volts) (Smith 1994).
- **AC Generators:** Depending on their size, they can produce from 500W to 10kW. They are mainly used for powering energy grids or home appliances if connected directly to houses. When connected with a power conditioner, they can maintain steady energy output, voltage and frequency regardless the speed of the hydro-turbine (Smith 1994).

2.3. Further analysis on EWS

The EWS allow us to early predict extreme weather events in sufficient lead time; from a few seconds to several weeks, depending on the type of the event, EWS type and capabilities. Their service is crucial, especially in flood-prone areas where vulnerable populations reside. According to the World Bank, the EWS hydrometeorological investments for L/LMICs have a cost-benefit ratio of 4–36 USD (Hallegatte 2012). However, in order for an EWS to be effective and end-user focused, it needs to comprise the elements of risk knowledge, monitoring and warning, information dissemination and communication, and response capability (Basher 2006). Despite the variety in types and designs, the standard action process is the same (Waidyanatha 2010):

$$\text{input scanning} \rightarrow \text{event detection} \rightarrow \text{output(s)activation}$$

Over the years, improvements in frontier (emerging) technologies have increased the reliability of input and output data. The numerical weather prediction, for instance, increases or modifies the forecast horizon based on the input data. This allows the display of multiple weather scenarios and prepares the emergency responders more effectively. The Hyogo Framework for Action that is a broader international political approach for the EWS promotion, emphasises the need for building social and disaster resilience of vulnerable populations against common weather threats, while it provides guidance on how to minimise the impacts of natural hazards (United Nations Office for Disaster Risk Reduction 2005). However, despite the general advantages, a lot more must be accomplished at the local level in order for the forecasting to reach its maximum potential.

Extreme, short-lived weather phenomena may often trigger flash floods and debris flows in small areas. While these events develop at space and time scales, the current conventional rainfall, streamflow and sediment discharge observation systems seem unable to monitor them accurately. This is because the local atmospheric, hydrological, geomorphological and environmental factors on the relative processes are poorly investigated. This leads to a plethora of uncertainties in warning and alerting management that unavoidably influence the effectiveness of the EWS (Schismenos 2017; Schismenos et al. 2018b). In general, the most common approaches for the early indication of rainfalls and floods require the comparison of the latest precipitation observations and weather forecasts in order to pre-define reference warning thresholds. However, as the forecast uncertainties for the operational efficiency of EWS are high, the challenges of detecting local severe precipitation below

Table 3. Comparison of widely-used warning methods.

Criteria	Indoor: television, line phone, pc connected to the internet	Outdoor: sirens, lights, LED signs	Portable/Other: cellphone, tablet, radio, word-of-mouth
Disaster-resilience	x	√	–
Low maintenance	–	√	–
Portability/Localisation	–	√	√
Readily source materials	–	–	–
Durability (time)	–	√	–
Affordability	–	√	–
Autonomy (e.g. no need for internet)	x	√	–
Large range and population reach (local level scale)	–	√	–
Energy autonomy	x	√	–

the resolution of most available numeric weather prediction models are still plenty (Alfieri et al. 2012).

A solution to this problem could be the use of community-centered EWS formulated based on end-users' capabilities, and local atmospheric and hydrogeomorphological conditions (Schismenos 2017; Schismenos et al. 2018b; Twigg 2004). Vulnerable communities, particularly remote populations in L/LMICs with limited access to energy and telecommunication sources cannot fully benefit from common EWS that send warning signals to cellphones or inform the public via the radio and television. Instead, autonomous and outdoor systems, such as the sirens and emergency lights that operate at the local level are more useful.

In general, the warning methods used in these cases are categorised as:

- indoor warning: home appliances that are energy- and signal-dependent.
- outdoor warning: devices that can be seen or heard in an open space of a specific radius.
- portable/other warning means portable devices and means used by individuals in ways not described above.

Table 3 summarises and compares widely-used warning methods based on evaluation criteria followed in this study.

According to Table 3, the outdoor warning means, such as local sirens, lights and signs are the most appropriate for vulnerable communities. This is because such devices are autonomous and low cost, can reach people in a relatively wide range (local scale level), be durable against weather extremes, do not require high maintenance or complex repairments and can be easily relocated if required.

Table 4 presents a combination of appliances that could be used for the emergency response of a small community during a flood event, assuming that the available power is 300 W per hour and it is delivered by PHYS. Note that in this scenario, the generated energy is directed to the appliances that contribute to community's emergency response and evacuation.

According to Table 4, during a flood scenario, a light on the PHYS could operate for 5 h. This would inform the community that the system is working during/after the flood event takes place.

Table 4. Community's emergency response and evacuation scenario: type of appliances, energy needs, number of units, hours of use, and cost.

Appliance	Power (W)	Unit Number	Hours of Use	Cost (USD)
LED light (installed on PHYS)	10	1	5	12
Audible alarm/siren and LED light (shore)	20	1	1	20
LED light (evacuation route)	10	8	1	96
LED light (shelter/safe zone)	10	3	5	36

A siren and light placed on shore could operate for an hour; time sufficient for the community's evacuation – note that short-lived disasters (e.g. torrential floods) develop in short time periods (from a few seconds to minutes). Outdoor lights could power an evacuation route and lead the rescuees to a nearby shelter (safe zone). There, 3 lights could provide illumination. The total cost of these appliances is 164 USD, which is within the limited budget of low-income communities.

3. Results and discussions

This paper highlights the needs of vulnerable populations facing energy insufficiency and ineffective flood response mechanisms. In case of flash floods or other short-lived weather extremes, these communities may not be alerted in sufficient lead time. This could result in causalities or even fatalities among the sensitive groups such as the elderly, children and people with mobility issues. In order to minimise such issues, particularly in L/LMICs, our study suggests the use of combined PHYS with EWS that operate at the local level. This humanitarian engineering solution is a promising concept that lies within the scope of the Agenda 2030 for Sustainable Development, Sendai Framework for Disaster Risk Reduction and World Economic and Social Survey 2018: Frontier Technologies for Sustainable Development.

Furthermore, we present evidence-informed criteria that should be considered prior to developing dual PHYS/EWS systems. A DIY/EDO, low-cost structure that is equipped with a reaction turbine and can operate under any condition could be appropriate for a number of riparian communities. A PHYS that is linked with flood detectors and outdoor, low-cost EWS could improve disaster response capabilities of nearby communities. However, its vulnerability to extreme weather events and their products (hail, floating debris) should be taken into consideration during the development of the system as it may affect its operations.

Lastly, this study suggests that a small but stable power supply (300 W) under any condition that is generated by PHYS can increase community capability. While it may not satisfy all the energy needs of every community, it can provide important economic, environmental and psycho-social benefits to remote communities who frequently experience energy inequality.

4. Conclusions

Remote communities in L/LMICs are at high risk of extreme weather events. Among their limited capabilities, insufficient energy generation and resilience against flood phenomena should be further explored. This study presents criteria for combined PHYS/EWS applications and investigates each system type in-depth in order to develop a prototype with such features. While the primary application of this prototype is likely to be in L/LMICs, it can also be used in riparian communities of high-income countries that experience flash floods (i.e. as a supplementary system for emergency energy generation and localised early-warning for evacuation). Our goal is to design a system that can satisfy key, basic needs of its end-users as a comprehensive humanitarian engineering intervention; contributing not only to disaster resilience but wider socio-economic development and environmental sustainability outcomes. There is substantial scope for researchers to work with such communities to develop innovative, agile, multi-use systems that can address these needs.

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ORCID

Spyros Schismenos http://orcid.org/0000-0002-0494-2180
Garry John Stevens http://orcid.org/0000-0002-3556-4098
Dimitrios Emmanouloudis http://orcid.org/0000-0001-8502-7154
Nichole Georgeou http://orcid.org/0000-0001-7434-025X
Surendra Shrestha http://orcid.org/0000-0002-9309-5584
Michail Chalaris http://orcid.org/0000-0002-4104-1859

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