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21st Century Macro-Imagineering

Lake Titicaca Hydropower Megaproject

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Abstract: Territorially shared by Peru and Bolivia, South America's largest freshwater lake is navigable Lake Titicaca, situated on an highland endorheic river basin of the Andes Mountains. Currently, Lake Titicaca is mostly regulated by ever-changing Nature. But, since its closure during 2001 AD, a small anthropogenic dam (at elevation 3804 m), emplaced at the headwaters, the Rio Desaguadero is still the altiplano lake's only flowing freshwater outlet. Intriguingly, from circa 1908 AD, Macro-Imagineers foresaw the creation of a second, completely artificial, flowing freshwater outlet for Lake Titicaca's 935 km3 of valuable liquid freshwater accumulation. Such a lake-tapping hydropower megaproject could allow diverted freshwater to perhaps reach the Pacific Ocean. Here, we cursorily reappraise several similar 20th Century dam and pipeline macroproject proposals, with the educative goal, achieved by careful reconsideration, of exposing the basic megaproject proposal physics related to a potential major future South America hydropower installation.

Key words: hydropower, Macro-Imagineering, Lake Titicaca.

Resumo: Territorialmente compartilhado pelo Peru e pela Bolívia, o maior lago de água doce da América do Sul, conhecido como Lago Titicaca, está situado em uma bacia endorrêica do altiplano da Cordilheira dos Andes. Atualmente, o Lago Titicaca ainda é regulado principalmente pela natureza local em constante mudança. Mas, após a construção de uma pequena barragem em 2001 d.C. (a uma altitude de 3804 m) situada nas cabeceiras, o rio Desaguadero permanece o único escoadouro natural do lago. Curiosamente, por volta de 1908 d.C., os macro-imaginadores previam a criação de uma segunda saída, completamente artificial, para os 935 km^3 da valiosa água doce líquida. Semelhante megaprojeto hidrelétrico poderia permitir que a água doce desviada alcançasse talvez o Oceano Pacífico. Aqui, reavaliamos várias propostas semelhantes de macroprojetos de barragens e dutos do século XX, com o objetivo educativo, guiado por uma cuidadosa avaliação, de expor a física básica da proposta para uma futura instalação hidrelétrica na América do Sul.

Palavras-chave: hidrelétrica, Macro-Imaginação, Lago Titicaca.

1. Introduction

Today's documented data and information — knowledge — is fraught with unlinked puzzle pieces caused by knowledge-base gaps as well as truly unknown errors of which humans are, as yet, absolutely unaware. Macro-Imagineering's adherents work against time-schedules founded on the limitations of well-defined monetary budgets. Because the hydro-social cycle is very complicated in any region anywhere within Earth's bioshell, no macro-imagineer is likely ever to be able to examine every elemental question to the exacting degree that prudent geoscientific rigor would usually demand; indeed, the wisdom of "Macro-Imagineering Judgement" typifies this constrained capability, as well as necessary outcome, to arrive at some timely and good work-to-be-done decision with whatever geoscientific data and information are available. Sometimes cost-escalating over-design of megaprojects located at especially difficult real-world worksites results [1]. Nature sculpted Lake Titicaca's tectonic uplift plain Basin — also known as "watershed" — as an ecological system or geographical unit located at 150 45' South latitude by 690 25' West longitude. The present-day and projected future hydro-social cycle driver of cooperation between Peru and Bolivia could be increasingly clearer climate regime change risks. Bolivia and Peru first commenced organized co-management of Lake Titicaca during 1955, sharing bathymetry data since 1976 and comprehensive hydro-meteorological information by 1985. Subsequently, Peru and Bolivia finalized the Lake

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Titicaca, Desaguadero River, Poopo Lake and Coipasa "Salar" Binational Master Plan (TDPS system) after the negotiations lasting from 1955 until 1996 AD [2]. Figure 1, below. Placement of an outline map of territory at the beginning of any proposed macroproject general description indicates a substantial intellectual adventure will follow.

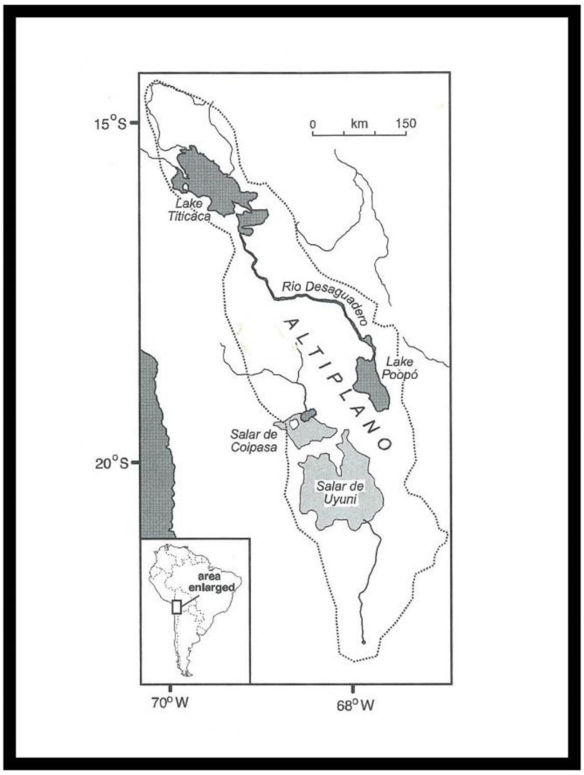

Figure 1. Map of TDPS.

Climate change risks, with all the implications for the mandates of the TDPS system governing authorities, remain difficult to forecast, but could be severe, especially when superincumbent upon existing macro-problems (increasing population density and sewage flows, variability of supply and quality of potable water, increased urbanism and agricultural consumptive demand for irrigation water, and legal conflicts concerning end-usage) [3]. Bad freshwater management practices and procedures, exemplified most tellingly by the rapid area diminishment of the present-day hydrologic condition of the Aral Sea in the Old World [4], are to be avoided in the New World! Although Peru has the greatest concentration of extant glaciers in our world's Tropic Zone, the glaciers essential to maintaining Lake Titicaca's mass are receding by sublimation, combined with a shorter precipitation season, already measured and computer climate model-predicted air warming and increased solar radiation impacts [5], the result is an observable freshwater volume reduction of Lake Titicaca and, consequently, also its total evaporative area. During the 20th Century Lake Titicaca fluctuated ~7 m [6]. The average precipitation directly onto Lake Titicaca is ~800 mm/year with the mean annual evaporation estimated to be ~1,700 mm/year [7]; the endorheic basin in which the variably-sized Lake Titicaca pools is ~56,494 km^2 — approximately 39.1% of the TDPS. By international agreement Peru retains authority over 74.1% of the Lake Titicaca Basin section of the TDPS, Bolivia holds absolute responsibility for 25.9%.

2. Geographical particulars and specifics

The Andes Cordillera arose because of the interaction of the South America tectonic plate and the Nazca tectonic plates [8]; this subduction zone is our world's oldest and lengthiest. Located on a tectonic uplifted plain, the ancient Lake Titicaca is probably a Quaternary Period remnant after its Basin filled to a maximum ~4,000 meters elevation. Nowadays, the tourist-appreciated scenic 8,500 km^2 Lake Titicaca has an estimated surface elevation of ~3,810 m; human altitude sickness symptoms ordinarily present themselves above 2,500 m altitude and yet permanent human occupation of the highlands by roaming hunter-gatherers occurred sometime before 5000 BC [9]! Set in the Tropic Zone where zonal overturning of the Walker circulation occurs, the TDPS is known to have been beset with mega-drought periods as well as pluvial excess periods such as the Last Glacial Maximum, some of which have been experienced by people living within Lake Titicaca's watershed.

Indeed, the presently existing elevation of the lake's watery free-surface has submerged ancient artifacts and settlements. The pattern of verticality of the landscape's anthropogenic components — terraces, raised farm fields, sunken gardens and manicured pastures — derives from climatic and biotic differences directly related to height above sea-level. Freshwater availability in Peru varies markedly: the Pacific Ocean coastal region is home to 65% of Peru's 32.5 million people but contains only ~1.8% of the nation's water resources whilst TDPS has but 5% of the country's population. Peru's upper-Amazon River Basin zone, however, produces 95% of the freshwater resources! So, not so surprisingly, Peru has attempted to satisfy freshwater consumptive demand of its coastal cities with a number of geographically large-scale macroprojects consisting of upper-Amazon River Basin river diversions/reversals. The rivers flowing down the steep western slope of the Andes Mountains separating Lake Titicaca Basin from the Pacific Ocean-facing coastal region have small watersheds and only those which drain still glaciated mountains have sufficient freshwater for continuous irrigation agriculture.

Commonly it is assumed that the greatest potential for new hydropower generation is from unregulated rivers flowing down the steep eastern slopes of the Andes Mountains. Peru has an urgent requirement to increase its renewable sources of electrical energy because human population increase, particularly in the Lima-Callao region, imposes an increasing public electricity demand (supposedly, the theoretical estimated hydropower potential for all Peru is ~206,107 MW; as of AD 2017, the installed hydropower capacity totaled ~5,385 MW).

Lake Titicaca constitutes a freshwater resource for approximately 2.5-3.0 million persons residing and working in Peru and Bolivia. However, yearly ~90% of the lake's pooled freshwater is lost from the Basin into the thin air through technically unmitigated evaporation whilst ~10% is allowed to leave Lake Titicaca as a managed freshwater discharge through the Rio Desaguadero Dam. Figure 2, below. "Proyect Especial del Lago Titicaca" — the PELT project of 1989-1993 AD — provided the necessary and vital TDPS hydrological data that eventually led to an international agreement-defined freshwater flow rate of 20 m3/second to be equally shared by Peru and Bolivia downstream of the Desaguadero Dam and a nearby International Bridge [10].

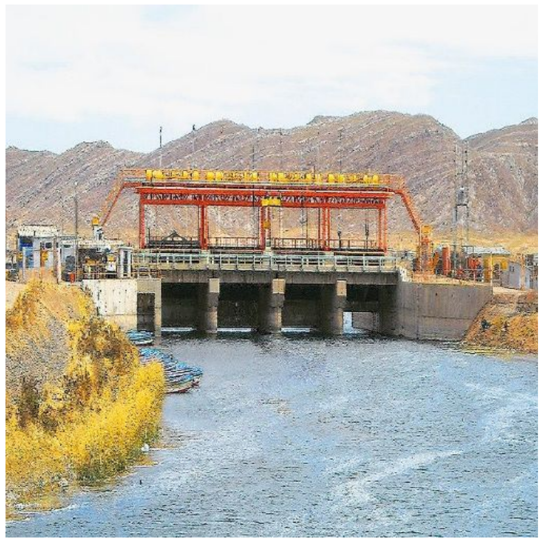

Figure 2. Flowing river freshwater-level control gates at present-day undersized Desaguadero Dam located at the shallowest, slightly polluted southern end of Lake Titicaca. We postulate the dam could be heightened and extended horizontally with freshwater-restraining flanking earthen embankments to increase massively upstream freshwater retention capacity of Lake Titicaca.

3. Stabilized Lake Titicaca hydropower serving some coastal Peruvian communities

Whilst work on the "National Map of Peru" commenced on 10 May 1921 by plane-table and alidade methods, reportedly it remains incomplete even well into the age of the satellite-centered Global

Positioning System [11]. Accurate topographic mapping is essential to the macro-planning of any megaproject that relies on freshwater's falling gravitationally a long distance from the 4,000-4,200 m-high western heights of the breath-taking Andes Mountains to the Pacific Ocean's shoreline! Charles Reginald Enock (1868-1970), a renowned British explorer of Peru, was the first to explore afoot and impressionistically chart the rough topography and valuable surface mineral resources of the TDPS as well as its immediately surrounding mountainous terrain [12]. He suggested a 120 km-long tunnel might convey Lake Titicaca's excess fluid content to the populated coastal region adjacent to the Pacific Ocean and generate hydropower simultaneously [13]. (NOTE: electricity-generating hydropower's global history started after AD 1880.) A vertical drop to AD 2018 prevailing sea-level of, say, 20 m3/second from an selected elevation of 3,810 m could, theoretically, produce 640 MW, nearly 11.88% of Peru's current actual electricity production or 0.31% of its theoretical maximum hydropower electricity production. Although we cannot be certain, we suspect C.R. Enock may have been inspired by the USA macro-imagineer Alexis Von Schmidt (1821-1906) who, from 1865 AD onwards, proposed and promoted a freshwater aqueduct to deliver at ~23 m3/second to the City and County of San Francisco originating at, and drawing from, the famed Lake Tahoe [14]; Lake Tahoe straddles the State of California-State of Nevada boundary—therefore it is also an enormous bistate managed pool of freshwater. Whatever is the verifiable historical truth, the idea was again bruited during the late-1950s by French macro-imagineer Marcel Mary [15]. Translated into summary English and generalized, Mary offers the opinion that a diversion of Lake Titicaca to the Pacific Ocean by sediment and rock piercing at great ground depth would present operators with a large hydraulic head — perhaps as much as 3,500 m — and could supply ample irrigation liquid to Peru's coastal farmers; if Lake Titicaca were artificially drained by valve-controlled pipe at its deepest lake-bottom location (~284 m near Soto Island north of Puno), freshwater could be made to slant-fall ~3,500 m, ultimately to join a river which releases flowing freshwater into the Pacific Ocean. Within a range of about 250-700 m, both Francis and impulse turbines can be utilized for electricity generation, possibly in multiple power-stations (output and dynamic behavior of serial water-turbines in a hydraulically coupled system) that could then feed electricity to long-distance transmission-lines draped across the rugged landscape of the upper slope of the western Andes Mountains.

4. Proposal physics: assumed base-of-mountain hydropower station

Rock-mass conditions that influence tunneling costs the significantly are mechanical rock properties, discontinuities in rock-masses and the presence or absence of suddenly interfering hot or cold groundwater inflows. As a linear excavation operation, tunneling has special quirks in access and logistics in the overcoming of undetected and unforeseen macro-problems; there is a unique interdependence between design and construction. Selection of the best course of any Tunnel Boring Machine (TBM)-dug freshwater-tunnel ought to be done on the basis of on-site Macro-Engineering assessment bolstered by astute geological surveys and studies. Studies will aim to predict, in the alternative suggested freshwater-tunnel routing, the influence of the rock mass conditions and the extent of definitive field-studies that necessarily must be done thoroughly and correctly before commencement of expensive water-tunnel digging and lining tasks can be undertaken. The economic benefits following such crafted studies can be estimated as a considerable percentage of the final construction cost of tunnel driving using a suitable TBM. As with other modern-day macroprojects, applied Macro-Engineering has changed from its 20th Century incarnation; 21st Century applied Macro-Engineering leaders of any megaproject today must have a list of titled cultural groups to be met, Environmental Impact Statements to be submitted for approval with various governing organizations, national and international laws to be respectfully complied with, and regional and even world public hydro-social cycle concerns to be addressed. Yet the result — a legal and financial "Go-ahead!" — if done properly, is well worth these constraints of time and direct financial hardship: hydropower technology chosen wisely, democratically, and consensually, rather than being dictated. In Europe, Switzerland enhanced its national identity via tunneling macroprojects [16] and, during the 21st Century, other ecosystem-nations of which Europe is comprised will do the same [17-18]; in other words, Peru-Bolivia could have a big emerging opportunity to cooperatively buff their respective international reputations in several disciplines of modern Technology! The only comparable tunneling megaproject being contemplated currently is sited in China's Tibet [19-20]; China's scheme involves a 42 km-long inclined headrace tunnel.

Ordinarily, Lake Titicaca hydropower potential would remain untapped and worthless (on a significant geographical and economical scale) in the near-term future for a number of logical related reasons: (I) the absence of Environmental Impacts Statements; (II) formidable geological and geomorphological impediments such as infamously powerful earthquakes and jagged incidental terrain; (III) nearly non-existent traffic infrastructure such as tunneled highways and railways; (IV) high-to-very-high initial monetary investment costs and long-period financial pay-backs; (V) the requirement for reliable long-distance weather-proofed electricity transmission lines; (VI) the reluctance of international financiers to consider low-interest loans to Peru and Bolivia; (VII) occasionally volatile and sometimes inconsistent national political opinions regarding priorities of national, regional and centralized or decentralized energy system development and (VIII) the considerable on-going development of alternative renewable energy resources. Furthermore, we must assume that future global climate regime change, expressed regionally, may instigate flexibility requirements for many existing and planned infrastructures. If, for example, the altiplano climate regime becomes drier than today's, then Lake Titicaca will be gradually reducing in area; on the other hand, if the altiplano becomes climatically wetter, Lake Titicaca will increase in volume and may then pose a severe emplaced lake-shore infrastructure damage risk. Our offered technically-based macroproject proposal might create new facts on the ground — that is, a situation is formed whereby, in either instance, Peru's coastal population will flourish and prosper with the availability of additional hydropower!

The conventional method to harness hydropower obtained from a high-elevation permanent lake is by drilling an admittedly difficult-to-complete inclined tunnel through the intermediate hard-rock mountains. But, in our case, this usual method is excessively expensive and requires inordinately long periods of dangerous excavation. So far, the world-practice of tunneling has no experience with very long-distance slant-bored tunnels, especially those incised by TBM in hard-rock mountain geological formations. As of 2018 AD, we offer an important technical innovation: to install a hermetic steel or prefabricated reinforced-concrete tube — possibly similar to that which might be used by a Hyperloop installation — emplaced by heavy-life helicopters, possibly entirely robotic in few critical operations, over the directly affected landscape of the western Andes Mountains (Figure 3).

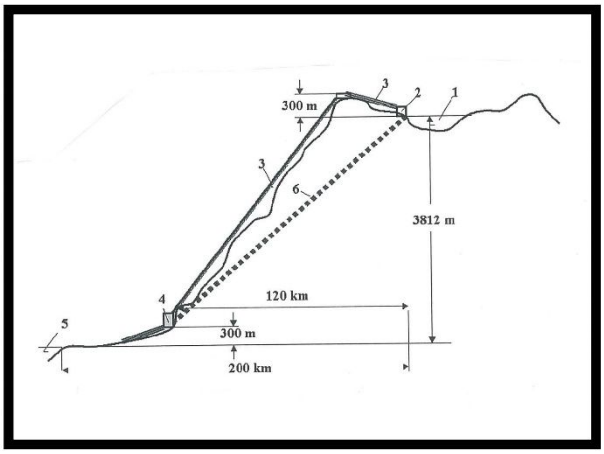

Figure 3. Sketch of proposed Lake Titicaca Electricity Generation Station. Notations: 1= Lake Titicaca; 2=freshwater pumping plant; 3= water tube (sub-aerial pipeline); 4= hydropower station; 5= Pacific Ocean; 6= possible subterranean tunnel through rocky mountain. In Peru, the shortest distance is between Puno to nearby mountain top is a distance of ~20 km, the linear distance to the nearest natural flowing river west of the penetrated mountain that drains into the Pacific Ocean is ~60 km and, thence, to the Pacific Ocean is ~200 km. In Bolivia, the shortest distance from Pucarani to Rio Zongo, after passing the ridge, is ~50 km.

4. Macro-Imagineering conclusions

The inexpensive hydropower plant, having a generation capacity of 640-1000 MW may be built during the 21st Century near Lake Titicaca without any hazardous, ugly modification to Lake Titicaca's picturesque region or its visible volume of freshwater with a freshwater expense of ~20-35 m3/second. For this result to occur, the floodgates of the Rio Desaguadero Dam must be, at minimum, permanently shut after international negotiations have been successfully concluded between Peru and Bolivia. If we choose to harness permanently a flow of freshwater moving at >30 m^3/second then Lake Titicaca's free-surface area will assuredly decrease. We can, however, generate, transmit for distribution and end-use, more or less for-ever, a maximum power output of up to 6,100 MW. Lake Titicaca will vanish, but our innovative recommendation will still produce utilizable electricity. If, sometime, we find a truly economical means for halting or greatly reducing the high-altitude lake's freshwater evaporation — as, for instance, by installation of particularized floating covers of huge numbers of plastic shade-balls [21] — then it will certainly become possible then to "Save Lake Titicaca" in perpetuity whilst also obtaining a great quantity of exportable generated electrical power! Produced electricity will be fed into the dispersed main load-centers by the national grid whilst the released freshwater can be used for downstream agriculture pursuits and to fulfil urban population needs. The most likely geopolitical obstacle: Bolivia may never agree to such freshwater diversion because Lake Titicaca is already a shared resource managed at the present time by the TPDS. However, western Bolivia also has a known need for low-cost electricity and, therefore, we think that an amicable binding international agreement is potentially possible.

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