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Review Article

STUDY ON TURQUOISE AND BRIGHT SKY-BLUE APPEARING FRESHWATER BODIES

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ABSTRACT
Water is very essential and a major component of all living creatures. Pure water is colourless, tasteless and odourless, but is generally found in impure state. Water found in oceans, rivers, lakes and ponds appear of different colour. Suspended and dissolved particles influence the colour of water. Freshwater bodies sometime appear turquoise (blue-green) and bright sky-blue and catches the attention of people. Turquoise and bright sky-blue appearing freshwater bodies are found in different parts of the world in different set of environmental conditions. For example, glacial-fed lakes also appear turquoise, crater lakes also bears turquoise colour and calcium carbonate rich water bodies also appear turquoise. Recently, rivers polluted by anthropogenic activities are also seen to bear turquoise color appearance. The turquoise appearance of water bodies is mainly due to the scattering of light in the blue-green range of the spectrum by suspended particles present in the water. There is diversity in the causal factor(s) responsible for such coloration in different set of conditions, but turquoise freshwater bodies originating under similar conditions in different parts of the world have some common characteristics. Moreover, the information about turquoise appearing freshwater bodies in different parts of the world are present but are scattered into pieces. There is a great need felt for compilation of different turquoise appearing freshwater bodies in the world. In this paper, different turquoise appearing freshwater bodies throughout the world have been identified. The causal factor(s) responsible for such coloration is also discussed. Since, the turquoise appearing freshwater bodies originating in similar conditions in different parts of the world bears some common characteristics, so based on it, a categorisation of turquoise appearing freshwater bodies for the first time is proposed in this paper for a better understanding. The categorisation has been supported by examples.

Keywords: *Turquoise River, Turquoise Lakes, Blue-Green Water, Polluted Turquoise River, Mining Pollution*

INTRODUCTION
"Water is life's matter and matrix, mother and medium. There is no life without water." Albert Szent-Györgyi (Szent-Györgyi, 1971). Water is very essential and ubiquitous substance that is a major component of all living creatures (Sharp, 2001). It is the driver of nature and is the basis of all life and is the soul of earth (Szent-Györgyi, 1971). Recent development in water research also suggests that water has memory (Benveniste *et al.*, 1994). Pure water is colourless, tasteless and odourless, but it is generally found in impure state (Stroll, 1989). Though pure water is colourless, but water present in oceans, rivers, lakes and ponds appears of different colour. The colour of water is influenced by suspended or dissolved particles. Water with dissolved organic matter, such as humus, peat or decaying plant matter, can appear yellow or brown in colour. Abundance of algal growth in water makes it appear green. Soil run-off in water produces a variety of yellow, red, brown and gray colours ("CW Team").
Turquoise (also termed as *blue-green)* and bright sky-blue colour water bodies are found in different parts of the world. It might be a turquoise or bright sky-blue river, a lake or even a pond. And they also have different geographical origin, for example, a turquoise lake fed by a glacier (for example, Lake Louise and Moraine Lake, Canada and Phoksundo Lake, Nepal) (Kumar, 2013; "Environment Assessment Report", 2013) or a turquoise alpine river (for example Soca River, Slovenia) ("WWF Alpine Programme") or turquoise lake or river found in the volcanic complex (Kawah Ijen, Indonesia) (Löhr *et al.*, 2005). Hydrothermal Springs also sometimes appear turquoise. Lakes and rivers found in the area rich

in calcium carbonate may also bear turquoise appearance, for example Havasu Creek, Grand Canyon appears turquoise as a result of calcium carbonate suspended in water (Melis *et al.*, 1996). On studying the works done on turquoise and/or sky-blue water bodies, it can be observed that in the phenomena of turquoise appearance of water bodies, two factors play very important role. The first one is the presence of suspended particles in a given size range which causes scattering of light in the blue-green range of the spectrum and second is the bed sediment colour of water bodies (for example, in Rio Celeste, Costa Rica) (Castello´n *et al.*, 2013). For example, if the river-bed sediment is of white colour as a result of precipitation of suspended particles present in water then it intensifies the turquoise appearance. In different turquoise appearing water bodies, suspended particles responsible for this may be composed of different elements and compounds. The main objective of this paper is to identify different turquoise and bright sky-blue appearing freshwater bodies worldwide, factor(s) responsible for such remarkable appearance and to propose a classification of turquoise freshwater bodies based on the factors. On basis of the origin of causal agents(s), turquoise or sky-blue freshwater bodies can be grouped under two sub-headings *Natural* and *Anthropogenic* as mentioned below.

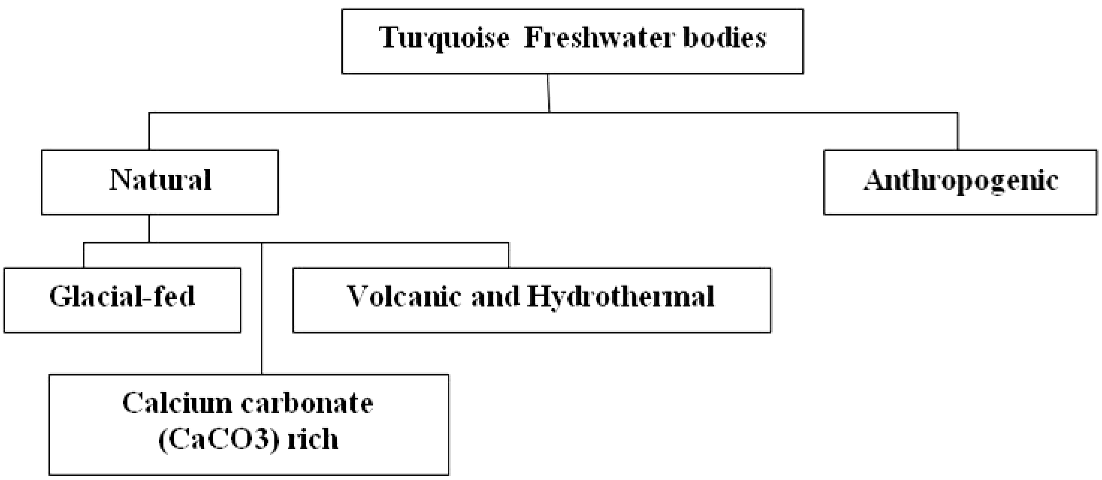

Figure 1: Chart Showing Classification of Turquoise Freshwater Bodies

Turquoise freshwater bodies can be grouped under *natural* and *anthropogenic* on the basis of the origin of the causal agent(s) responsible for their remarkable appearance. The turquoise freshwater bodies in which the causal agent are naturally produced can be grouped under *Natural Turquoise Freshwater bodies* and if the causal agent is produced as a result of anthropogenic activity then those can be grouped under *Anthropogenic Turquoise Freshwater bodies*.

Natural Turquoise Freshwater Bodies

Natural turquoise freshwater bodies can be defined as "freshwater bodies (including rivers, lakes and ponds) which appear turquoise as a result of natural processes without any human interventions". The causal agent of turquoise color in these freshwater bodies is naturally produced. Since under natural condition also, the turquoise color appearing freshwater bodies are formed in different set of environmental conditions with different causal agents, so the natural turquoise freshwater bodies can further be classified into three categories i.e., *glacial-fed*, *volcanic and hydrothermal* and *limestone ($CaCO_3$) rich*.

1. Glacial-Fed Turquoise Freshwater Bodies

Glacial-fed lakes and alpine rivers bear intense turquoise/sky-blue color. The color is caused by the presence of glacial flour or rock flour in suspended form in water (Dorrier *et al.*, 2011). Rock flour or glacial flour is the fine-grained, silt-sized particles of rock which are generated by the grinding of bedrock by glacial weathering and erosion (Chutcharavan and Aciego, 2014).

There are so many examples of glacier-fed lakes and rivers around the world which bears turquoise color. Few lakes and rivers have been discussed below.

Phoksundo Lake, Nepal

Phoksundo Lake is a freshwater oligotrophic lake located in the Shey Phoksundo National Park, Dolpa district, Nepal at an elevation of 3,611.5 m. The lake has a surface area of 494 ha with a water volume of 409,000,000 m^3 (Bhuju *et al.,* 2007).

It is Nepal's deepest and second largest lake and accounts unique trans-Himalayan ecosystem (Kunwar and Parajuli, 2007). In 2007, the lake has also been designated a Ramsar site (Bhandari, 2009). The lake is very famous for its magnificent turquoise color (Environment Assessment Report, 2013). However, the reason behind the turquoise color is not explained. The turquoise color might be due to the presence of suspended *glacial flour* or *rock flour*.

Lake Pukaki

Lake Pukaki is one of the three lakes situated in the Aoraki Mount Cook National Park. It is a glacial-fed lake (Irwin, 1978). The lake is very famous for its stunning turquoise appearance (Thompson-Carr, 2012). The turquoise appearance of lake is due to the finely-ground glacial flour (Gallegos *et al.*, 2008).

Figure 2: Different *Glacial-Fed* Turquoise Freshwater Bodies a- Phoksundo Lake, Nepal (source: www.wikipedia.org) b- Lake Samiti, India (source: www.questhimalaya.com) c- Moraine Lake, Canada (source: www.wikipedia.org) d- Soča River, Slovenia (source: www.feel-planet.com)

Lake Louise and Moraine Lake, Banff National Park, Canada

Lake Louise is a glacial-fed lake located in the Banff National Park, Canada at an elevation of 1,731 m above the sea level. The lake is 2.4 km long and 0.5 km wide with a maximum depth of 90 m. The lake was named in 1884 after the fourth daughter of Queen Victoria, Princess Louise Caroline Alberta. The lake is situated below the Victoria glacier which is named after Queen Victoria. The lake is very famous for its stunning turquoise water. The glacial flour or rock flour suspended in the lake water is responsible for its color (Kumar, 2013).

Moraine Lake is also located in the Banff National Park and bears wonderful blue-green color due to presence of suspended rock flour particles in the water (Kumar, 2013).

Samiti Lake and Gurudongmar Lake, Sikkim, India

Samiti Lake and Gurudongmar Lake is located in the Sikkim state in India. Samiti Lake is a glacial-fed lake in the Onglathang valley and is visible while climbing towards Gochala Pass. Samiti Lake is very famous for transparent turquoise look and mesmerises the travellers with its beauty (Gupta, 2014).

Gurudongmar Lake is located at an altitude of 17,100 ft (5,210 m) and is one of the highest lakes in the world. It is situated only 5 km south of China border and lies in North Sikkim district. The lake provides one of the source streams of Teesta River.

The lake remains in complete frozen condition in winters from November to Mid-May (Gupta, 2014). The lake appears brilliant turquoise during summer.

There are many other examples of glacial-fed lakes and rivers which appear turquoise. For example, Soča River in Slovenia is one of the most beautiful alpine rivers. The river is very famous for its wonderful turquoise to emerald color appearance and many tourists from all over the world visit every year to behold this beautiful river ("WWF Alpine Programme").

2. Volcanic and Hydrothermal Turquoise Freshwater Bodies

Crater lakes in the volcanic area have remarkable turquoise to emerald-green color. Crater lakes found in the active volcano areas bear turquoise color because of high acidity with presence of extremely high sulphate, aluminium, chloride and other compounds (L**ö**hr *et al.,* 2005).

In some crater lakes (like Yudamari Lake, Japan), the blue component of the blue-green lake water is attributed to fine colloidal particles of sulphur which causes Rayleigh scattering resulting in blue color and the green component of the lake is attributed to the absorption of sunlight by dissolved ferrous ions (Ohsawa *et al.,* 2010).

Dormant volcano crater lakes however also bear the same appearance (turquoise or bright sky-blue) but the causal agent of the remarkable turquoise color is different than of the active volcano crater lakes. For example, Blue Lake, Mt. Gambier located in South Australia turns vibrant blue in summer due to scattering of light in the blue-green range by tiny calcium carbonate crystals suspended in water ("Fact Sheet", 2014).

Rivers flowing through the volcanic complex areas also appear sometimes turquoise (or sky-blue) and the causal agent is again different. For example, Rio Celeste (Sky-blue River) is located in the Tenorio National Park situated in the Tenorio Volcanic Complex, Costa Rica appears turquoise or bright sky-blue because of scattering of light by colloidal aluminosilicate particles suspended in water. The aluminosilicate particles also precipitate in the form of white sediments which enhances the river water to appear remarkably bright sky-blue (Castello´n *et al.,* 2013).

Some of the lakes and river found in the volcanic areas having turquoise appearance have been discussed as example along with their causal agents.

Kawah Ijen, East Java, Indonesia

Indonesia accounts for 13% of world's active volcanoes and contains 129 active volcanoes. There are of total 21 active volcanoes and seven crater lakes found on Java (Simkin and Siebert, 1994). The most easterly situated volcanic complex of Java is the Ijen complex. The Ijen complex consists of a group of stratovolcanoes found within the 15 km wide Ijen caldera.

Kawah Ijen is an active stratovolcano located at an altitude of 2,346 m above mean sea level on the rim of caldera and contains a lake which is one of the world's largest natural reservoirs of extreme acidic volcanic water (30-40 x 10^6 m^3) with a surface area of about 1000 x 600 m and maximum depth of 180 m. The lake bears a turquoise colour.

The turquoise colour might be because of very high acidity with presence of extremely high concentration of sulphate, chloride, aluminium, and other compounds in the water (L**ö**hr *et al.,* 2005). Kawah Kelimutu, Indonesia also has turquoise appearance.

Figure 3: Different Volcanic Area Turquoise Freshwater Bodies a- Kawah Ijen, Indonesia (source: www.infopendaki.com) b- Kawah Kelimutu, Indonesia (source: www.amazing-of-indonesia.blogspot.in) c- Rio Celeste, Costa Rica (source: Castello´ n *et al.*, 2013)

Yudamari, Japan
Yudamari is an active crater lake is located at Mr. Nakadake of Aso volcano, Japan. The lake appeared turquoise or blue-green before eruption. Rayleigh scattering of sunlight caused by very fine colloidal sulphur particles result in the particular blue component of the lake water color and the green component is attributed to the absorption of sunlight by dissolved ferrous ions (Ohsawa *et al.*, 2010).

Rio Celeste (Sky-blue River), Costa Rica
Rio Celeste (Sky-blue River) is located in the Tenorio National Park situated in the Tenorio Volcanic Complex, Costa Rica. Because of its sky-blue color appearance, the river is one of the most important tourist sites in the country and gets about 20,000 visitors annually. Rio Celeste originates from the confluence of two colourless streams, *Rio Buenavista* and *Quebrada Agria*. The sky-blue water of Rio Celeste occurs on the mixing of these two colourless streams at a point known as Tenidero (dye point). A presence of white sediment can be observed at the bottom of the Rio Celeste River. The river maintains its sky-blue colour over a distance of about 14 km, including a waterfall and a blue lagoon. A detailed study was carried out to find the cause of the sky-blue color appearance of river (Castello´ n *et al.*, 2013).

The sky-blue color of the river Rio Celeste is due to the phenomenon which involves large proportion of water as the water sample from the river reveals a transparent appearance. Upon deep investigation, it was found that due to the presence of colloidal aluminosilicate particles of diameter 566 nm present in the suspended form in the river water causing Mie scattering of sunlight and resulting in the intense sky-blue appearance of Rio Celeste.

The transparent water of stream 1 (Rio Buenavista) contains the solid particles of diameter 184 nm and stream 2 (Quebrada Agria) contains solid particles of diameter <10 nm in suspension. But, upon mixing of these two colourless streams, the particle size increases in the stream 3 (Rio Celeste). This happens as when the stream 1 with nearly neutral pH mixes with stream 2 which is acidic, the stream 3 presents an intermediate pH=5.0. The decreased pH at the dye point favours the protonation of aluminosilicate particles from stream 1, resulting in the yield of hydroxyl group at the particle surfaces. As the resulting protonated particles bears a nearly neutral surface, a suppression in the electrostatic repulsion between particles in caused which leads to their agglomeration and sedimentation. Finally, these submicron sized aluminosilicate particles causes Mie scattering of sunlight, thus causing the intense sky-blue color of Rio Celeste (Castello´n *et al.*, 2013).

Blue Lake, Mt. Gambier, South Australia

Blue Lake is situated in the limestone coast of South Australia. It is a large monomictic crater lake located in an extinct volcanic maar of the Mount Gambier. It is one of the two surviving lakes of the four crater lakes on the Mount Gambier maar. The lake has maximum length of 3,566 ft and maximum width of 2,156 ft with a maximum depth of 236 ft with a surface area of 70 ha and shoreline of about 3.5 kilometres. Scientific evidences suggest that the Blue Lake was formed more than 28,000 years ago. The Blue Lake is very famous for changing its colour from grey in winter to vibrant blue in summer ("Fact Sheet", 2014).

The clean water in the Blue Lake turns vibrant blue in summer because of two reasons. First, because of the higher position of the sun in summer, more light hits the surface of the lake which increases the blue light that is scattered back from the lake by suspended small particles. Pure water scatter light in blue range, water with suspended small particles (such as Calcium carbonate crystals, etc) scatter light in the blue-green range and water with dissolved tannins (organic matter) scatter in the yellow-brown range. Second, during spring as the surface of the lake warms, dissolved carbon dioxide is released into the air in gaseous form, the pH increases and the water becomes over-saturated in calcite, as a result it begins to precipitate out. Tiny crystals of calcite forms and falls to the bottom of the lake and as they fall, they also capture organic material thus cleaning it from water. By summer the lake is stratified with the warmest layer in top 15m and the coolest at bottom, below 50m, it is then that the lake looks vibrant blue. A new layer of calcite about 3mm thick and organic material 1mm thick settles at the bottom of the lake each year. The highest calcium concentration in the lake has been reported in winter when low clarity is there and the lowest concentration during summer when the lake appears blue. With the approaching autumn, the deeper mixing is triggered by the gradual cooling of surface water as there is no longer a defined warm layer on the top, this brings water with a high carbon dioxide concentration to the surface where it is released in gaseous form and a second round of calcite precipitation and cleaning occurs. A reduce in the rate of calcite precipitation occurs by the further deepening and cooling of surface layer. This leads to a lower clarity as the algae gets dispensed and the colour changes from vibrant blue to grey. The cycle starts again when the whole lake is well mixed and the temperature is uniform throughout by winter (Telfer, 2000; Fact Sheet, 2014; Turoczy, 2002).

3. Calcium Carbonate (CaCO3) Rich Turquoise Freshwater Bodies

Water bodies rich in the calcium carbonate also appear turquoise or sky-blue in color. The source of the calcium carbonate in water can be because the area is rich in calcium carbonate or can also be from the springs (travertine). The water appears turquoise because of the scattering of light caused by the suspended calcium carbonate particles.

There are many examples of calcium carbonate rich turquoise freshwater bodies, some are discussed below.

Bear Lake, Utah

Bear Lake is one of the oldest lakes in North America and has been a point of interest for researchers since the lake has survived during the extended warm and dry climates, unlike the other lakes. The exact age of the lake is unknown, but the longest sediment bottom extracted from the bottom of lake indicates that the lake is at least 250,000 years old. Therefore, Bear Lake can help researchers understanding the past climates and environment of the area.

The lake bestrides the Utah-Idaho border, and more than half of it lies in Utah. The lake lies at the surface elevation of 5,923 feet and is 20 miles long and more than 7 miles wide. The lake has a shoreline length of around 48 miles and has a maximum depth of 208 feet. It is situated in the southern half of the Bear Lake Valley, which is nearly 50 mile long and 5 to 10 mile wide. The Bear Lake has been a site of attraction for local people and also national and international tourists because of its intense turquoise-blue colour. As per the Utah Geological Survey report on Bear Lake, the lake contains abundant suspended microscopic particles of calcium carbonate (lime) that reflect the water's natural blue color back to the surface, thus, giving the lake its intense turquoise-blue color. It is because of this color, the lake is also known as the "Caribbean of Rockies" (Davis and Milligan, 2011).

Figure 4: Different Calcium Carbonate Rich Turquoise Freshwater Bodies a- Havasu Creek, Grand Canyon (source: www.wikipedia.org) b- Bear Lake, Utah (source: Davis and Milligan, 2011) c- Plitvice Lakes, Republic of Croatia (source: www.worldfortravel.com)

Havasu Creek, Grand Canyon

Havasu Creek is the second largest tributary of the Colorado River located in Grand Canyon National Park with a number of water-falls (Havasu Falls, Beaver Falls, Mooney Falls and Navajo Falls). It attracts many visitors each year due to its spectacular blue-green appearance. Because of the travertine feature of the stream channel, there is deposition of calcium carbonate sediment at the bed. The presence of high concentration of calcium carbonate in suspended form in water leads to the scattering of light and gives water turquoise colour appearance (Melis *et al.*, 1996).

Plitvice Lakes, Plitvice Lakes National Park, the Republic of Croatia

Plitvice Lakes National Park is one of the largest national parks in the Republic of Croatia and is one of the oldest national parks in southeast Europe. It was founded in the year 1949 and was listed under the UNESCO World Heritage List in 1979. Plitvice lakes are specific geological and hydrological karst phenomena. A chain of lakes connected by waterfalls which is created by the biodynamic process of tufa development is its basic feature. There are of total sixteen larger and smaller lakes interconnected with foaming cascades and waterfalls placed within the forested karst landscape. The lake is considered of high importance due to continuous deposition of tufa. Tufa (a freshwater calcium carbonate) precipitation takes place very intensively at the bottom of the lake (Horvatinčić *et al.*, 2006). The Plitvice Lakes attract many tourists from different parts of the globe because of its majestic turquoise appearance. The turquoise appearance of the lakes can be related to the presence of calcium carbonate in water.

Anthropogenic Turquoise Freshwater Bodies

Anthropogenic turquoise freshwater bodies can be defined as "turquoise freshwater bodies in which the causal agent(s) or factor(s) responsible for the remarkable turquoise colour is not naturally produced and is result of human activities, for example mining, industries, etc. All turquoise appearing freshwater bodies which are as a result of anthropogenic activities can be listed and discussed under this group.

For example, two rivers have been discussed below which appear turquoise as a result of anthropogenic activities.

Wilge River, South Africa

Wilge River is a tributary of Vaal River in the central South Africa. It originates near Leandra. It flows into the Bronkhorspruit River downstream of Bronkhorspruit town and drains the eastern part of the region ("Department of Water Affairs and Forestry", South Africa, 2004). As a result of extensive coal mining and acid mine drainage (AMD), a turquoise or milky-blue colour was observed in the river in the month of June. The occurrence of milky-blue colour could be due to gypsum precipitation, which is a common by-product of lime neutralisation, and may originate from the Brugspruit Mine Water Treatment plant (Dabrowski *et al.,* 2013). It is also believed that the colour might be due to the precipitation of aluminium compounds as a result of neutralisation reactions in pH-neutral waters (McCarthy and Pretorius, 2009). However, the actual mechanism behind the coloration in the river remains unknown.

Figure 5: Two Turquoise Appearing Rivers as a Result of Anthropogenic Activities a- Wilge River, South Africa (source: McCarthy and Pretorius, 2009) b- Lukha River (Wah Lukha), India (source: Author)

Lukha River (Wah Lukha), Meghalaya, India

Lukha River, also known as *Wah Lukha* which means "The Serene River" in Jaintia language is located in the southern part of the East Jaintia Hills, Meghalaya. The river is very famous in the area as it turns sky-blue during the months of winter as a result of water pollution. This has been happening since last 7-8 years. As it turns blue, fishes are also found dead, floating on the surface of the water. The effluents from coal and limestone mining areas and also from the cement industries are blamed for the change in the color of the river. As per the result of physicochemical analysis, the river water is characterized by very high sulphate content and low pH. However, no clear-cut relation has been established between the change in colour and physicochemical properties of the river water and the mechanism as well as the agent responsible for such coloration still remains unknown (Lamare and Singh, 2016).

Conclusion

It can be concluded from the paper that turquoise (blue-green) and bright sky-blue freshwater bodies present in the different regions of the world have diverse causal factor(s) responsible for such coloration. The turquoise freshwater bodies originating under similar conditions in different parts of world have some common characteristics and are categorised accordingly for the first time in this paper. In general, we can conclude that in glacial-fed lakes, the causal agent for turquoise appearance is mainly *rock flour* or *glacial* *flour* whereas in active volcano crater lakes, the turquoise appearance is mainly attributed to high acidity and presence of extremely high concentration of sulphates, iron, chloride, aluminium and other compounds and, in dormant volcano crater lakes, these factors doesn't seem to cause turquoise appearance. In calcium carbonate rich freshwater water bodies, the turquoise appearance is mainly attributed to suspended calcium carbonate present in water. But in anthropogenic turquoise freshwater bodies, the causal factor(s) varies and cannot be established due to limitations of data. Hence, there is a need to study anthropogenic turquoise freshwater bodies in more details.

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Review Article

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