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***Review Paper***

# Chemical Dissolution and Pollutant Inflow in River Systems: A Comprehensive Review of Water Contamination Processes

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## Abstract

*This review is a complete study on the chemical dissolution and inflow process of pollutants in river systems and special attention was given in the understanding of why water is polluted. Rivers, being the main elements of hydrological cycle, are extremely prone to pollution of both natural and anthropogenic sources. Chemical dissolution happens when minerals, metals and organic compounds dissolve into water bodies and change the chemistry of the river and may cause damage of aquatic ecosystems. Due to industrial outflow, agricultural effluents, and urban effluents, the inflow of pollutants is the main cause of degradation of water quality. These are chemicals such as heavy metals, pesticides and organic toxins which are very dangerous to the environment and human health. The review explains the different aspects that impact the behavior of pollutants in rivers including the flow processes, the interaction of the sediments and seasonal changes and the significance of the riverine processes in changing and transporting contaminants. It also emphasizes the existing monitoring techniques, pollution prevention approaches and the effects of climate change on the processes of contamination. The relationship between chemical dissolution and pollutants inflow is important to understand to come up with useful management practice and policies to enhance the quality of water and safeguard aquatic life. The review can be a basis of conducting additional studies on how the problem of water contamination in river systems can be mitigated.*

**Keywords:** Hydrological cycle, agricultural effluents, urban effluents, water contamination.

## Introduction

Rivers constitute very vital natural resources, which are vital in sustaining the ecosystem as well as giving water to a range of human activities. They also provide drinking water, irrigation, industries and transportation, support biodiversity and provide essential ecosystem services, including nutrient cycling, sediments transport, and habitat. However, rivers are getting increasingly endangered by pollution through natural and human-made sources, which results in the notable decline in the quality of the water and the well-being of the ecosystem[1].

This contamination is usually motivated by two significant processes, which are chemical dissolution and inflows of pollutants that are worsened by human activities like mining, urbanization and agriculture[2].

Mining, building, and deforestation subject the soil and rock matrices that would have been fairly stable in the past to the elements, accelerating the release of minerals and chemicals in to rivers. Sulphur dioxide and nitrogen oxide emissions caused by industries result in acid rain which further increases the rate of chemical dissolution such that the pH of water is reduced, and the toxic metals of the area are further washed away. Natural dissolution and human activities may result in the discharge of toxic compounds such as heavy metals (e.g., arsenic, cadmium and mercury) into the river systems which has far-reaching negative impacts on the quality of water[3].

Another significant cause of river pollution is inflows of pollutants. Such pollutants are usually industrial releases, agricultural effluents, urban sewage and inappropriate garbage disposal. As opposed to the natural mechanism of chemical dissolution, when materials disintegrate naturally and are already in the surrounding environment, the inflows of the pollutants are mostly anthropogenic and are caused by the direct contribution of the substances of a harmful nature to the rivers[4]. Industrial enterprises, such as the release of a broad spectrum of the toxic chemical and heavy metals into rivers, are able to cause severe damage to aquatic ecosystems.

Another major source of pollution is agriculture particularly where the intensive farming activities are common. River systems are exposed to high amounts of nutrients and chemicals as a result of the use of synthetic fertilizers and pesticides[5]. This causes pollution in rivers because cities release untreated or poorly treated sewage into rivers. Most cities discharge the wastewater into rivers where the water carries with it the pathogens, organic material and various chemical compounds used in the house hold products. This is further worsened by the growth of the impervious surface such as roads and buildings in the city which create larger amounts of storm water runoff. This runoff is usually rich in oils, heavy metals, sediments as well as plastics which affect pollution of rivers especially during heavy rainfalls[6].

The sum of the processes of chemical dissolution and the inflow of the pollution are severe in changing the physical, chemical, and biological characteristics of the rivers. One such case is the agricultural runoff pollution of nutrients that can add to the impact of the industrial discharges through acidification. Under these circumstances, the greater the acidity, the more likely that the toxic metals in river sediments will be dissolved and become more biologically available and more toxic to aquatic organisms. Moreover, pollutants of different sources may interact in complicated ways and have cumulative effects which are more harmful than the overall effects of each pollutant[7]. The changes that these processes cause on river ecosystems are far-reaching. Since excess nutrients cause eutrophication, it results in the over-growth of algae and depletion of oxygen to form dead zones where fish and other aquatic beings cannot live. The heavy metals and toxic chemicals will build up in sediments, which are harmful to the ecosystem of the river in the long-term. Such pollutants may find their way into the food chain by feeding on contaminated organisms resulting in bioaccumulation and biomagnification, and thus finding their way to higher trophic levels, such as humans[8].

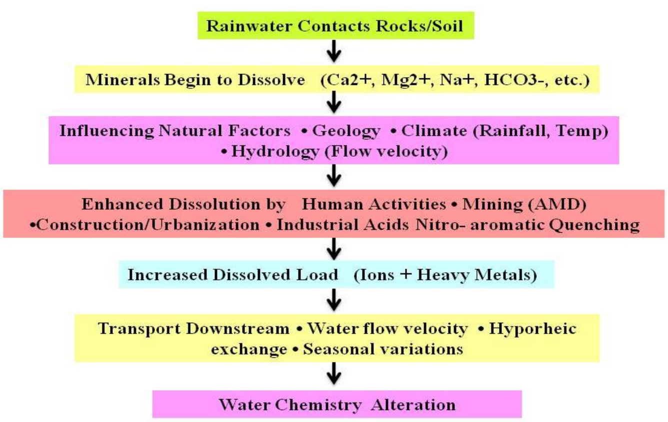


**Figure-1:** Mechanism of Chemical Dissolution in River Systems.

Bioaccumulation may also lead to toxic chemicals accumulating in fish and other aquatic creatures which present further health hazards to individuals who ingest the infected fish. These effects are rather serious, which is why the issue of river systems contamination is essential to preserve the ecological situation and health of people. Such good mitigation measures should comprise pollution prevention, pollution control and river restoration. Pollution prevention entails checking the emission levels of industries, there is also enhancement in agricultural practices and availability of sewage treatment systems to ensure that untreated sewage is not released into the rivers. Besides avoiding new contamination, there is need to restore degraded rivers so as to restore them. Such activities can entail actions like elimination of polluted sediments, recovery of riparian areas, and decontamination of pollutants using constructed wetlands[9].

## Conceptual Framework and Definitions

**Dissolution and Dissolved Load Chemical:** Chemical dissolution involves breaking down of minerals and organic substances available in the catchment area of the river through dissolution in water. This is the key phenomenon of the dissolved material flow in the river system and strongly impacts on the water chemistry of a river as a whole. As rainwater or surface runoff contacts rocks and soils, it dissolves some minerals, discharging ions like calcium, magnesium, sodium, sulfate, bicarbonates and some trace metals, including iron and copper, and manganese, into the river[10]. Temperature, rainfall and pH of water are the environmental parameters that affect the rate of chemical dissolution. At high rainfall, weathering and dissolution take place at a faster rate since the greater the water the more the minerals are broken down. Equally, in rainy and hot climates, the rate of weathering is increased, and rivers can transport more dissolved ions. On the other hand, dissolved ion concentrations can be lower in arid areas that receive lower rainfall and undergo slower rates of chemical weathering. The acidity or alkalinity of the water is yet another important factor that may either speed up or delay the dissolution of minerals. As an illustration, in the regions where the acid rain or acid mine drainage is taking place, the reduced pH of the water causes the dissolution of the metals in the rocks to increase the amount of the toxic metals such as the lead, arsenic and cadmium in the river system. These toxic elements are more soluble at lower pH and consequently cause increase in concentration of dissolved elements in the river water[11].

**Inflow of pollutants: Sources and types:** Both point and non-point sources of pollutants enter rivers, and each of them is involved in water contamination in a different manner. Point sources are discrete points of discharge of the pollutants into the rivers i.e. industrial effluents, sewage treatment plants or storm water drains. On the other hand, non-point sources are diffuse sources which do not have individual sources such as agricultural run off, urban surface run off, and even atmospheric deposition.

These two forms of pollution may have devastating effects on the water quality and the river ecosystem. River pollution can be broadly classified into three; inorganic contamination, organic pollution, and biological contamination[12]. The most common ways of introducing inorganic pollutants include industrial activities, agricultural activities and natural weathering. They are heavy metals, like lead, cadmium, mercury, and arsenic, metalloids, and mineral ions. Industrial effluents are usually a source of toxic metal and other inorganic chemicals in the rivers, whereas agricultural effluent is a source of nutrients such as nitrogen and phosphorus, which can result in nutrient enrichment. These are potentially harmful pollutants which may result in bioaccumulation in the food web, toxicity to fish and invertebrates, and ecosystem functions[13,14]. Main sources of organic pollutants are agricultural run-offs, industrial discharges and domestic waste. Heredbicides and pesticides that have been used in agriculture are usually present in the river systems and mostly in the agricultural areas. These organic compounds may be harmful to aquatic life, as they influence reproduction, growth and survival. Other such organic pollutants are pharmaceuticals and personal care products that are usually found in the urban rivers and which may take long before it can be eliminated, and in the process interfere with the ecosystems. A lot of organic pollutants are not biodegradable and get deposited in the bottom of rivers becoming a long-term environmental hazard[15].

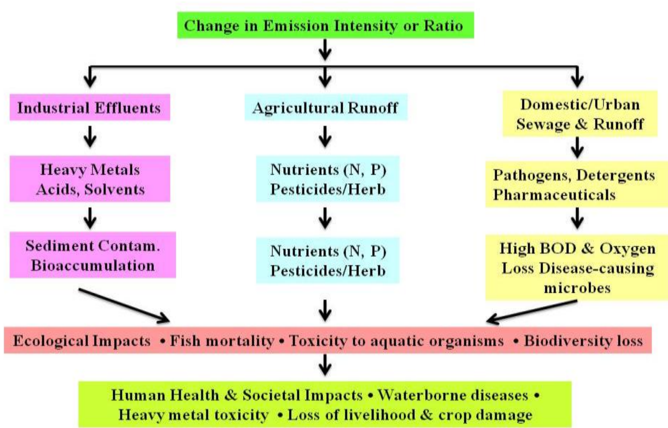


**Figure-2:** Pollutant Inflow Pathways and Impacts on River Systems.

## Mechanisms of Chemical Dissolution and Transport

**Geochemical Weathering and Rock-Water Interaction:** Chemical dissolution in the rivers is also closely related to the geochemical weathering that is the disintegration of rocks and minerals into smaller particles and ions when exposed to water, air and biological activity. When water passes over the landscape, it reacts with rock, minerals and soil particles which enables dissolution of minerals and release of ions into the river[16,17]. The chemical composition of rocks, climate, as well as the dynamics of water flow are some of the factors that affect this process. The kind of rocks in the catchment area of a river dictates the ease of minerals being dissolved in the water. E.g., carbonate rocks such as limestone are highly vulnerable to the dissolution process due to the fact that they have calcium carbonate, which is a mineral that is very easy to dissolve in slightly acidic environments. The calcium and bicarbonates in the river water are elevated by the dissolution of calcium carbonate in areas where limestone is eminent[4]. On the contrary, silicate minerals are present in igneous rocks, such as granite or basalt and dissolve more slowly and offer various ions, e.g., sodium and potassium. Climate also determines the rate of weathering. Chemical weathering is faster in areas characterized by large rainfall and high temperatures. Slightly acidic rainwater, the existence of which is caused by dissolved carbon dioxide, increases dissolution of minerals, providing the releases of ions in the river system. In areas which are cold or dry like in areas where there is limited flow of water, weathering is less rapid and the rivers may have lower dissolved ion content.

**Increased Dissolution by Human Intervention**: The chemical dissolution rate of rivers can be increased due to human activities especially mining, construction, and urbanization. The kind of mining activities exposes the rocks and minerals to the external environment, both air and water, resulting in quick weathering and the discharge of minerals to their immediate rivers[18]. Specifically, the drainage of mining regions is a major environmental problem, that is, acid mine drainage (AMD). When minerals containing sulphur like pyrite are exposed to air and water, they undergo the oxidation process that leads to the formation of sulfuric acid. The acid is then able to remove heavy metals of copper, zinc, and cadmium in the rocks around it, polluting the rivers and ecosystems[19]. The same happens with the development of dams, roads and buildings, which can shake the soil and rock surfaces in the river catchment region, and accelerate the rate of weathering and improve the chemical dissolution. As an example, minerals can be exposed to water during excavating and construction, which will cause an acceleration in the degraded process and a rise in the number of dissolved substances into the river[20].

Dissolution may also be strengthened when industrial discharges are added to rivers to bring acidic or chemically reactive substances. Most industries such as mining, chemical production and paper production discharge waste water that is very acidic or includes reactive chemicals that have the ability to raise the dissolution of minerals in riverbeds. Such compounds have the capability to dissolve the metals and other contaminants of the riverbed, further lowering the quality of water and raising the level of toxic compounds in the water[21].Another important aspect of transport of dissolved substances is the movement of water via a river system. The rate of dissolution and downstream transportation of chemicals depends on the speed and the quantity of water. As an illustration, where velocity of flow is high, water has a higher ability to dissolve minerals and transport them to the river system. On the other hand, when dry seasons have low water flow the concentration of dissolved materials may go up due to decrease in water flow and therefore more mineral dissolution is possible[17]. They can also be affected by seasonal different conditions i.e. the monsoon rains or dry seasons which can greatly affect the movement of dissolved materials. As an illustration, when the water volume in the river system is large due to heavy rains, the dissolved contaminants are diluted leading to the contaminant concentration in the river water decreasing. Conversely, when dry seasons occur, when river flow is lower, then contamination can be more concentrated because the flow is lower, and the dissolved pollutants can be concentrated in the water[13].

## Pollutant Inflow into Rivers: Anthropogenic Contributions

**Industrial Effluents and Chemical Discharges:** One of the primary sources of the pollution of the river systems is industrial activity, as factories and manufacturing plants release wastewater with a great variety of harmful substances. These are both organic and inorganic and may be containing heavy metals, solvents, acids and other harmful chemicals. These effluents may differ extensively in their composition and toxicity depending on the type of the industrial process and this makes the handling of these effluents to be very difficult[22]. Emission of industrial effluents in rivers without proper treatment is a serious environmental problem. A lot of industries like the mining industry, chemical processing industries, the textile industry, and the paper manufacturing industries, release waste water into the surrounding water bodies. These pollutants may have both short term and long-term ecological impacts. Indicatively, industrial effluents contain heavy metals like mercury, cadmium, and lead that can be accumulated in the river sediments and aquatic organisms and thus bioaccumulation and biomagnification occur via the food chain[2].Thus, industries that deal with chemical processing can discharge various solvents, pesticides, and industrial chemicals, the majority of which are recalcitrant and very dangerous to aquatic life and human beings. Part of these pollutants may cause an immediate effect leading to direct poisoning of aquatic organisms, and others may have a long-term effect, affecting the ecosystems. The unregulated release of industrial effluents into rivers through the unprocessed or inadequately processed industrial effluent can cause chronic pollution that is very hard to rectify, and which can cause degradation in the river ecosystems over a long period.

**Agricultural Runoff Nutrients and Pesticides:** Agricultural practices are also a major contributor to river pollution especially with the runoff of surplus fertilizers, pesticides as well as herbicides into water bodies. One of the causes of nutrient pollution in rivers is the large usage of synthetic fertilizers. Nitrogen and phosphorus are fertilizers that are regularly used to promote the growth of crops. Nonetheless, when these nutrients are applied in large amounts, they tend to surpass the absorptive ability of the soil thus being washed away during rains. Such runoff makes its way into the rivers where the surplus nutrients cause eutrophication, which is the process that breaks the natural balance of the ecosystem[5]. Eutrophication is caused when the nutrients that are in excess (mainly the nitrogen and phosphorus) promote the overgrowth of algae in rivers. These algae blooms are able to block the sunlight which prevents plants in water to photosynthesize. When the algae decay and decompose, the oxygen concentration in the water decreases resulting in hypoxia (low oxygen concentration) which is harmful to most aquatic life, especially fish. In severe instances eutrophication can lead to the formation of dead zones, which are sections in rivers and lakes that have very minimal oxygen supply that support the life that exists within the water. Also, algae decompositions burn huge quantities of oxygen due to which hypoxic conditions are aggravated[23]. Besides fertilizers, pesticides and herbicides that are applied to the agriculture industry can also pollute rivers. These chemicals are engineered to kill or repel pests and weeds, however, they have unwanted effects when precipitated during rainfall off the fields. Organophosphates, carbamates and chlorinated hydrocarbons are very toxic to aquatic organisms because, they are toxic to fish and invertebrates, as well as reproductive and neurological impairment. There is also a possibility of these chemicals bioaccumulating in food chain eventually affecting higher-level predators such as human beings[14].

**Domestic Sewage and Urban Wastewater:** Another type of major pollution to rivers is domestic sewage especially in cities. Sewage is a mixture of very diverse contaminants, such as organic matter, pathogens, detergents, pharmaceuticals and personal care products. The contaminants are deposited in rivers by way of untreated or poorly treated wastewater releases. The discharge of sewage in rivers is common in most parts of the world particularly in the low-income or densely populated urban centers which lack proper sewage treatment facilities. Most of the systems are old-fashioned or poorly maintained even in urban areas that have treatment plants thus failing to remove all the contaminants before the wastewater can be released into the river[14]. The sewage adds organic matter in the river systems which add to the biological oxygen demand (BOD) of water, i.e. the micro organisms in the water need more oxygen to digest the organic matter. This causes the dissolved oxygen to be depleted and this may be detrimental to aquatic life, especially fish. The sewage is also an extremely diverse source of pathogens such as bacteria, viruses, and protozoa, which are extremely harmful to human health. Use of contaminated water in drinking and recreational purposes has the potential of causing water borne diseases like cholera, typhoid and dysentery[12].

## Ecological and Human Health Impacts

**Ecosystem Degradation:** When rivers are polluted, this may be disastrous to the aquatic life. The addition of surplus nutrients into rivers causes eutrophication, which result into algae blooms, depletion of oxygen, and destruction of aquatic life. Due to the growth of algae, there is a blockage of light to submerged plants hindering photosynthesis leading to depletion of oxygen in the water. When the algae dies and decomposes the oxygen gets used up by the microorganisms which worsens the hypoxic conditions causing fish kills. This activity causes a major change in the biodiversity of rivers with species which cannot tolerate low oxygen level being unable to survive. In the long term, eutrophication may lead to a change in ecosystem of a river, which was a rich aquatic community but changes to become an algae and low-oxygen-tolerant dominated ecosystem[24]. Direct adverse effects of the toxic pollutants such as heavy metals, pesticides, and industrial chemicals can also have direct negative effects on aquatic life. Such contaminants interfere with the physiological functions of fish and invertebrates, which makes them unable to grow, reproduce, and survive. They may also lead to mortality in certain situations especially in sensitive species[24]. Also, the toxic substances may be deposited in sediments of rivers where they are kept over a long period of time, always emitting contaminants into the water column.

**Human Health and Societal consequences:** Rivers are resourceful sources of drinking, irrigation and industry, hence vital in the survival and economic growth of human beings. Nevertheless, rivers that are contaminated are very dangerous to the lives of people who rely on them. Water borne diseases are the health risks that are the most immediate and that which are transmitted by contaminated water. Sewage and agricultural runoff contains pathogens that cause a very broad variety of diseases including gastrointestinal diseases, like cholera, dysentery, and typhoid fever[23]. Rivers that are polluted also affect the economy of the local people by causing scarcity in clean water to support agriculture, industry, and tourism. Thus, water contamination can lead to low crop production in farmers who irrigate their farms with river water and industries that require clean water to conduct their manufacturing activities to incur higher costs since they will require to treat their water. In addition, the presence of polluted rivers will reduce the likelihood of recreational pursuits, fishing and boating, which means tourists will reduce their revenues[1].

## Mitigation and Management Plans

**Prevention of Pollution and Control of the sources:** The best way to ensure the protection of the river ecosystems is to prevent the pollution at its source. The industries ought to be made so that they treat wastewater before it gets into the water body so that the hazardous chemicals and metals are eliminated or neutralized. The wastewater treatment regulations and standards must be instilled to reduce the emissions of the pollutants into the rivers. Agriculture must be sustainable and must embrace areas like precision farming that minimize the use of fertilizers and pesticides and minimizing on the runoff. The cities are supposed to enhance better waste disposal systems to avoid the dumping of untreated sewerage into rivers. There should be the use of storm water management systems to collect the runoff and treat them before they reach rivers to minimize the contamination[25].

**Ecological Remediation strategies:** Along with the pollution prevention, the ecological remediation techniques can become useful in the process of the cleanup of the polluted river systems. Constructed wetlands and biofilm reactors employ the use of plants and microorganisms respectively to treat the water by filtering and decontaminating the water and organic contaminants respectively. These two techniques could be used to eliminate nutrients, heavy metals, and organic pollutants of the river water. Replanting of the riparian vegetation on riverbanks may also be instrumental in enhancing the quality of water by ensuring erosion is minimized, sediments are trapped and pollutants are filtered before they get into the river[26,27].

**Policy and Management Interventions:** River management needs to be an integrated system comprising of ecological, engineering and regulation strategies. Stricter rules should be enforced by the governments to reduce pollution caused by industries, agriculture, and cities. The use of harmful chemicals and the scheme of responsible use of water can be reduced through the public awareness campaigns, as well. The interdisciplinary stakeholder management efforts are needed to deal with the multifaceted problems of river pollution[1,28].

**Table-1:** Key Concepts in Chemical Dissolution and Pollutant Inflow in River Systems.

| Topic | Key Points | Examples / Effects |
|---|---|---|
| Chemical Dissolution | Natural process where minerals/organic matter dissolve into river water; influenced by geology, climate, and hydrology. | Release of $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, bicarbonates; acid rain increases dissolution of toxic metals. |
| Human-Enhanced Dissolution | Mining, construction, acid rain, and industrial discharges accelerate weathering and metal release. | Acid Mine Drainage (AMD) mobilizing arsenic, cadmium, iron; increased acidity lowers water quality. |
| Pollutant Inflow (Anthropogenic) | Pollutants enter from point and non-point sources (industry, agriculture, sewage, runoff). | Heavy metals, nutrients, pesticides, pathogens, plastics. |
| Industrial Effluents | Discharge wastewater containing heavy metals, acids, solvents. | Bioaccumulation of Hg, Pb, Cd; toxicity to aquatic life; long-term sediment contamination. |
| Agricultural Runoff | Excess fertilizers (N, P), pesticides, herbicides entering rivers via runoff. | Eutrophication, algae blooms, hypoxia; bioaccumulation of pesticides causing neurological and reproductive harm. |
| Domestic Sewage & Urban Wastewater | Untreated/poorly treated sewage adds pathogens, organic matter, detergents, pharmaceuticals. | Waterborne diseases; oxygen depletion due to high BOD; increased stormwater runoff carrying oils/metals. |
| Ecological Impacts | Degradation of aquatic ecosystems due to nutrient overload, toxic pollutants, low oxygen. | Fish kills, biodiversity loss, dead zones, sediment contamination. |
| Human Health Impacts | Exposure through drinking water, irrigation, and contaminated fish. | Cholera, dysentery, typhoid; chronic metal toxicity (kidney damage, neurological disorders, cancer). |

| | | |
|---|---|---|
| Mitigation Strategies | Pollution prevention, ecological restoration, policy interventions. | Wastewater treatment, sustainable farming, constructed wetlands, riparian restoration, stricter regulations. |

## Conclusion

Water quality degradation is largely caused by chemical dissolution and inflow of pollutants in the river systems. The combined factors of natural geochemical weathering and human actions cause these processes and lead to a variety of pollutants introduced into rivers such as heavy metals, nutrients, and organic chemicals. The consequences of these pollutants on the ecosystem of rivers and on human health are immense and there are major impacts on the biodiversity, water supply and economic growth.

The source control, ecological remediation, and integrated river management would be a complex solution to the problem. The quality of the river water and the sustainability of clean water availability to the future generations can be achieved by practicing sustainable agriculture, industry, and urban development, as well as spending on the development of new pollution treatment technologies.

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