Journal of Indian Geomorphology
Volume 7, 2019 ● ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Presidential Address delivered at the 30th National Conference of the Indian Institute of Geomorphologists (IGI) held at Jamia Millia Islamia, New Delhi, during 3–5 October 2018

Changing Perspectives in Geomorphology

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I feel honoured to address the august learned gathering of the galaxy of geomorphologists and geoscientists at the inaugural session of the 30th National Conference on Geomorphology and Society of the Indian Institute of Geomorphologists organised by the Department of Geography, Jamia Milia Islamia, New Delhi, Needless to say that the IGI is the largest organisation of geomorphologists in India, which recently organised the 9th ICG of the International Association of Geomorphologists (IAG) in Vigyan Bhawan, New Delhi from 6–11 November 2017 and thus made a history.

The geomorphological studies and researches have passed through the phases of increasing criticisms of Davision model of cyclic development of landforms; concentrated efforts for the replacement of cyclic model by non-cyclic model (dynamic equilibrium model), qualitative geomorphology by quantitative geomorphology; inductive method of landform analysis by deductive and analytical methods; cyclic time by graded time; decay equilibrium model by dynamic equilibrium and dynamic metastable equilibrium model; historical approach by functional approach and from mega-scale study of landforms to micro-scale landform study.

Thus regular paradigm shifts in geomorphology resulted in the emergence of new frontiers in geomorphological studies such as emergence of process geomorphology, climatic geomorphology, applied geomorphology, environmental geomorphology, anthropogenic geomorphology, urban geomorphology, social geomorphology etc.

Man as a geomorphic agent

With the scientific and technological development and advancement since industrial revolution in 1760 in general and after Second World War in particular man has emerged as a significant geomorphic agent who is capable of accelerating and decelerating geomorphic processes at short temporal scales and modifying existing physical landscapes right from tropical regions to periglacial regions in polar areas and at higher altitudes. Consequently, the following geomorphic equation of K.J. Gregory (1977) has been modified by the author by adding another factor i.e. Human:

$$F = f\,(PM)\,\Delta t \quad \text{.......................Equation 1}$$

(K.J. Gregory, 1977)

Where F = landform
F = is the function of
P = Processes (geomorphic)

M = Materials (geomaterials — rocks)
Δt = Time

F = f (PMH) t...............................Equation 2
Where, f, P and M are same as in equation (1)
t = time
H = human factor as a geomorphic process

Emerging Fields in Geomorphology

The following are emerging fields of geomorphological studies and research:

1. Anthropogenic geomorphology.
2. Urban geomorphology.
3. Urban geomorphic hazards.
4. Environmental geomorphology and geomorphology of natural hazards.
5. Social geomorphology.
6. Global warming and climate change-induced geomorphic processes and landforms

Anthropogeomorphology

Anthropogeomorphology deals with anthropogenic activities as potent geomorphic processes which can (and are) accelerate or decelerate the rate of operations of natural geomorphic/environmental processes many fold which may result in severe geo-environmental problems of various sorts which may become detrimental to human society. Almost all of the geomorphic processes — fluvial, glacial, periglacial, coastal, aeolian etc. have been greatly affected and modified by human activities, either intentional or unintentional in different geomorphic environments like — tropical, savanna, Mediterranean, polar and arctic. Consequently some geomorphic systems are *inherently fragile* affected by natural hazards like earthquakes, landslides, floods etc. and some hillslopes, riparian tracts and river regimes have *become fragile* greatly affected by man. Anthropogeomorphology or anthropogenic geomorphology includes the consideration of the following aspects:

- Human impact on hydrological processes, mainly groundwater hydrology,
- Human impact on hydrological cycle of natural drainage basins,
- Human impact on watershed geomorphology,
- Human impact on weathering, mass wasting and mass movement processes,
- Human impact on coastal processes and coastal configuration,
- Human impact on river processes by direct and indirect modifications such as point modification (such as construction of dams and reservoirs, rail and road bridges across the rivers at specific location) and reach modifications (such as construction of embankments, shortening of river courses, channel diversion, widening and deepening of channels),
- Human impact on glacial and periglacial processes through modifications and removal of surface vegetation, excavation for obtaining minerals, regular driving of vehicles, construction of buildings and triggering forest fires in permafrost regions
- Human impact on subsurface process by modification of aquifers and groundwater storage etc.
- Human impact on pedological processes,
- Human impact on soil erosion and sedimentation.

Urban geomorphology

Urban geomorphology, is the recent branch of applied geomorphology which studies the interactions between two distinct but different landscapes and environment — natural physical landscapes and geomorphic processes and urban landscapes, urban environment and urban processes. It also studies the resultant geo-environmental problems related to urban environment.

Urban geomorphology, a significant branch of applied geomorphology, studies the geological, and topographic characteristics of urban areas, the physical geomorphological processes operating therein and hydrological conditions, stages and rate of urbanisation. It also studies the interactions between physical landscapes, geomorphological processes and anthropogenic processes (i.e. urbanisation, exploitation of natural sources etc.). The changes coming out of such interactions (such as land subsidence, hillslope failure, flooding and waterlogging, changes in atmospheric chemistry, environmental degradation and pollution, water storage etc.) paves the way for environmental planning and management leading to suitable and sustainable urban planning (Singh, 2017).

The researches in urban geomorphology studies different urban centres in varying physical settings and environment such as — mountainous urban centres, alluvial riverine urban centres, urban areas of arid and semi-arid regions, urban centres in seismically active zones etc. Urban geomorphology of fragile urban centres must focus on the following aspects:

(A) Physical aspects

- Topographical characteristics of urban areas:
  - a) Types of terrain
    - (i) hillslopes
    - (ii) Dormant or extinct volcanic hillslopes
    - (iii) Flood plains
    - (iv) Plateau surface
    - (v) Riparian tracts of alluvial rivers
    - (vi) Coastal zone
    - (vii) Permafrost areas
    - (viii) Valleys
    - (ix) arid landscapes
    - (x) lake shores
  - b) Slope
  - c) Absolute and relative reliefs
  - d) Drainage systems
  - e) Climatic character
  - f) Natural Hazards
    - (i) Tropical storms including tropical cyclones, typhoons, taifu, bagio, hurricanes etc.
    - (ii) Tornadoes and dust storms
    - (iii) Seismic events
    - (iv) Volcanic eruption
    - (v) Floods and waterlogging
    - (vi) Storm surges and tsunami waves
    - (vii) Hydrological conditions and groundwater
  - g) Geomorphological processes — mode and rate of operation:
    - (i) Fluvial process
    - (ii) Coastal process
    - (iii) Glacial process
    - (iv) Periglacial process
    - (v) Weathering and mass wasting and mass movement
- Geological characteristics of urban areas:
  - a) Engineering geology related to urban setting including:
    - (i) Lithological characteristics including rocks type
    - (ii) Analysis and interpretation of soils and groundwater which may help in urban planning
    - (iii) Preparing and finalising design of engineering structure in urban area.
  - b) Environmental geology including:
    - (i) Study and evaluation of resource
    - (ii) Disposal of urban organic waste
    - (iii) Study of geological hazards which includes:
  - c) Urban geology, this includes urban environment and engineering geology.

(B) Urban Environment

The study of urban environment under urban geomorphology of an 'anthropogene city space' (urban centre) involves the following aspects:

- Growth of human population and population density

- Stages and phases of urbanisation
- Urban infrastructure
- Water quality, sanitation and health
- Water supply and disposal of organic and inorganic urban waste
- Storm drains

(C) Interactions between physical environment and human activities: Geo-environmental problems:

- The interaction between physical environment and human activities in a city or town located in a certain set of environmental conditions result in certain geo-environmental problems such as:
  - a) Earthquake hazards are common in cities located on hillslopes, at the foot-hills of volcanic mountains or in cities located in severe seismic zone (e.g. Delhi).
  - b) Severe landslide hazards occur in the cities located along unstable hillslopes such as Nainital and Chamoli of Uttarakhand.
  - c) Severe floods in the alluvial riverine cities located along the riparian tracts of rivers such as Delhi along the Yamuna river, Allahabad along the Ganga river etc.
  - d) Coastal floods caused by severe cyclonic storms, storm surges and strong tsunami waves, such as Kolkata, Visakhapatnam, Chennai, Mumbai etc. are affected by such factors.
- Environmental degradation and pollution:
  - a) River water pollution such as Agra city along the Yamuna river, Allahabad along the Ganga river etc.
  - b) Groundwater pollution
  - c) Eutrophication and shrinking of wetlands (lakes and ponds) of an urban centre
  - d) Air pollution
  - e) Solid waste pollution
  - f) Health hazards
- Natural hazards and disasters:
  - a) Seismic hazards
  - b) Tropical storms and tornadoes
  - c) Landslides hazards
  - d) Flooding and waterlogging
  - e) Tsunami disaster
  - f) Biological hazards, such as spread of diseases and epidemics — e.g. dengue and chikungunya in Delhi.
- Man-made hazards in urban areas:
  - a) Subsidence of ground surface due to excessive exploitation of groundwater resulting in the formation of large cavities below the ground surface.
  - b) Submergence and wetting of floors and walls of buildings due to waterlogging caused by floods, heavy rainfall or spilling from water supply pipes.
  - c) Submergence of foundations of buildings leading to their collapse.
  - d) Severe fire in high rise buildings.
  - e) Traffic congestion due to uncontrolled rise in number of buildings and shrinking of road space.

(D) Geo-environmental planning / urban Planning

It may be mentioned that urban planning basically involves (a) pre-urbanisation, and (b) post-urbanisation surveys of the physico-cultural parameters of sites. However, this seldom happens because almost all the major cities world over have grown from a small site of human occupancy. In spite of this impediment, urban planning should be initiated in order to ameliorate the environmental problems, both physical and social, faced by a specific city. It is also significant to point out that uniform planning for all urban centres located in varying environmental setup would not work, hence separate set of planning for different cities having specific geo-environmental problems should be prepared. For example, the cities located in the floodplains of alluvial rivers in monsoon regions like India, face acute problems of frequent severe floods and waterlogging for several days leading to collapse of buildings, choking of storm and sewer drains, spread of epidemics, disruption of supply of drinking water, electricity and telecommunication systems. In view of this the suitable engineering structures should be built along the bank of the rivers in order to stop the flood water from entering the city. There should be sufficient and efficient pumping sets in working conditions to drain out stagnant rainwater from low lying areas of the city. The storm drains and sewer systems should be cleaned before the onset of monsoon for quick disposal of rainwater.

In order to mitigate the problem of urban flooding in riverine cities the following management initiatives should be taken up:

- Integrated approach to flood management by combining watershed and land use management with urban development plan.
- Engineering measures for flood control.
- Flood forecast and flood preparedness measures.
- Clearing of road and drain encroachments.
- Scientific study of flood pattern and recurrence intervals of severe floods.
- Sustainable river-front development plan.
- Preparation of detailed contour map of city space.
- Application of watershed management plan.
- To arouse public awareness and timely evacuation of population vulnerable to floods.

Example from alluvial riverine city of monsoon region

Allahabad city is a typical example of alluvial riverine city which is located along two mighty rivers of India — the Ganga and the Yamuna and is frequently affected by floods and waterlogging for several days in continuation. The gauge level during floods ranged between 80 m and 88.84 m since 1971. The highest gauge height of 88.84 m was recorded in 1978. The floods of 1978 proved to be most notorious because flood water overtopped the embankments along the Ganga and entered the city. The rain continued while all the sluice gates were closed because the level of water in the river was much higher than the city space except for a few localities. Consequently, the flood water of Ganga, together with rainwater submerged the low lying localities and inflicted heavy loss to human health and property.

The recurrence interval of very severe floods crossing the flood level of 88 m and having maximum discharge of more than 50,000 $m^3 sec^{-1}$ for Ganga and 47,000 $m^3 sec^{-1}$ for Yamuna is 11 and 10 years respectively. The devastating flood of 1978 broke all the previous records when the flood water of the Ganga and the Yamuna stood higher by 3.6 m and 4.09 m respectively from the danger level of 84.75 m and the water spilled over the Ganga and the Yamuna embankments and inundated all the localities in the vicinity of the rivers. Since then the flood prone area, especially adjoining the Ganga is increasing regularly after each succeeding flood event. This may be attributed to the raising of the Ganga bed consequent upon silting of the river and encroachment of flood plains by unauthorised construction of houses and poorly maintained drainage systems of the city. Thus, horizontal unplanned growth of the city with ever increasing population in the low-lying geomorphologically unsuitable areas in the outskirts of the city is responsible for recurrent floods of increasing magnitude. An integrated urban planning can solve the problem.

Urban geomorphic hazards

A geomorphic hazard can be defined as any change, natural or man-induced, that may affect the geomorphic stability of landforms to the adversity of living things. The identification of geomorphic hazard is in reality based on the prediction of landform change (Chorley *et. al*, 1984). The hazards, whether natural or man-induced, in an urban area and its environs may be termed as *urban geomorphic hazard*. **S**udden change in landform stability becomes lethal to human society mainly in urban agglomerations due to accelerated rate of erosion in riparian tracts along alluvial rivers or with volcanic eruption or hillslope failure due to high magnitude earthquakes. In fact, site specific geomorphic hazards are more disastrous to urban centres located on alluvial fans and cones, in delta area or along the banks of alluvial rivers. These urban centres are more vulnerable to floods and fluvial erosion. Similarly, cities located at the foothills of dormant volcanic mountains are more prone to landslide, lava flow and lahar hazards; while coastal cities in the tropical and subtropical regions are adversely affected by strong cyclonic storms and storm surges. The plains in the tropical and subtropical regions are frequently visited by tornado during summers — e.g. Great Plains of the United States of America. The significant site-specific geomorphic hazards are as follow

Fluvial geomorphic hazards

These mainly occur in floodplains dominated by seasonal rainfall like monsoons, savanna region or Mediterranean region. Examples of fluvial geomorphic hazards are:

- River floods become a menace almost every year in the riverine cities like Allahabad (along the Ganga and the Yamuna), Lucknow (along the Gomati) and Delhi (along the Yamuna) during the monsoon months. Many more examples can be cited. Flood hazards in urban space may create the following related problems:
  - a) Bank erosion resulting to loss of city space.
  - b) Flooding of low lying areas resulting into waterlogging.
  - c) Damage to household properties and civic amenities like supply of water, electricity, telecommunication system, roads and bridges.
  - d) Collapse of buildings
  - e) Spread of epidemics and other socio-economic problems
- Sedimentation and consequent rise of river bed which increases flood dimension i.e. increase in flood area.

Volcanic geomorphic hazards

These become disastrous when the city is located at the foothills of volcanic mountain and there is sudden eruption from the dormant volcano destroying the entire city.

Seismic geomorphic hazards

Cities located in the high risk seismic zones are adversely affected by high magnitude earthquakes wherein besides human casualties heavy damage is inflicted on infrastructure of urban areas. The strong shocks generated by severe earthquakes cause slope failure leading to mass movement of large volume of debris which destroy the towns located at the foothills of a mountain.

Severe fire may result from strong vibrations caused by severe earthquakes. The strong shaking of the buildings may cause severe fires in the houses because of overturning of gas cylinders.

Tropical storms as geomorphic hazards

The coastal cities in tropical and subtropical regions are very often adversely affected by severe cyclonic storms and related storm surges with high velocity gusty winds. Many examples may be cited — New Orleans city was almost flattened by Katrina hurricane in 2005 and Visakhapatnam city was greatly damaged by cyclone Hud Hud in October 2014.

Environmental geomorphology

Environmental geomorphology, a branch of applied geomorphology, has recently gained significance because it is closely related with interactions between physical landscapes and processes and anthropogenic activities (processes). In fact, studies related to environmental geomorphology and anthropogeomorphology are overlapping. Environmental geomorphology may be broadly defined as follows:

'Environmental geomorphology deals with the impact of natural landforms and processes (e.g. volcanism, floods and droughts, landslides, seismicity, denudation—weathering and erosion—processes, climate changes etc.) on human activities and human landscapes (rural and urban settlements, agricultural and industrial sectors, infrastructures, transport networks, bridges etc.) on one hand, and manipulative impact of human activities on natural/ environmental processes, geoenvironmental problems arising out of these interactions, and remedial measures thereof leading to environmental management and natural hazards and disaster reduction, on the other hand' (Singh 1998, 2017).

In fact, D.R. Coates first used the term 'environmental geomorphology' and defined this discipline as follows:

'Environmental geomorphology is practical use of geomorphology for the solution of problems where man uses to transform or to use and change surfacial process' (Coates, 1973).

D.R. Coates (1973) elaborated the basic issues and themes to be included in the discipline of environmental geomorphology:

- Study of geomorphic processes and terrain (characteristics) that affect man, including hazard phenomena such as floods and landslides (and many more).
- Analysis of problems where man plans to disturb (such as channel diversion, coastal protective devices etc.) or has already degraded the land-water ecosystem.
- Man's utilisation of geomorphic agents or products as resources, such as water or sand and gravel.
- How the science of geomorphology can be used in environmental planning and management.

Beside the above mentioned areas of studies in environmental geomorphology as presented by Coates (1973), the following themes should also be included in the ambit of environmental geomorphology:

- Man's development works in fragile geomorphic ecosystems such as permafrost areas where building activities are in progress and resulting in disturbed periglacial ecosystem.
- Deforestation and resultant disturbed glacial process — melting and retreat of glaciers, consequent increase in water volumes and glacio-fluvial erosion.
- Global warming due to increasing greenhouse effect, consequent upon industrialisation and urbanisation and resultant climate change leading to modifications of geomorphological processes.

Vulnerability identification and analysis of geomorphic hazards:

- Geomorphic hazard vulnerability
  a) Volcanic hazard vulnerability
  b) Seismic hazard vulnerability
  c) Tropical cyclone hazard vulnerability
  d) Tornado hazard vulnerability
  e) Flood hazard vulnerability
  f) Landslide hazard vulnerability
- Infrastructural vulnerability of geomorphic hazards
  a) Vulnerable water supply system
  b) Vulnerable transport system
  c) Vulnerable communication system
  d) Community vulnerability — physical and social vulnerability

Risk assessment and evaluation of geomorphic hazards

- Effect of geomorphic hazards on geomorphological resources
  a) Effect on earth materials — rocks and minerals
  b) Effect on soils
  c) Effect on landforms
  d) Effect on water
  e) Effect on glaciers
  f) Effect on tidal waves

Mario Panizza (1996) has briefly underlined the subject matter of environmental geomorphology as follows:

'Environmental geomorphology is defined as that area of earth sciences which examines the relationship between man and environment, the latter being considered from the geomorphological point of view' (Panizza, 1996).

Components of environmental geomorphology

- Geomorphological Components
  a) Geomorphological resources related with geomorphic processes and landforms.
  b) Geomorphological hazards related with floods, landslides, storm surges, seismic events, tsunami, tropical disturbances etc.
- Human Components
  a) Human activities — grazing, farming, deforestation, excavation, exploitation of natural resources and constructions works.
  b) Assessment of community vulnerability due to mining, population pressure, building construction, economic activities, development plans etc.

Social geomorphology: interactions between geomorphological and human components

The nature and pattern of interactions between geomorphological processes & forms and man & responses, whether positive or negative, form the core of social geomorphology. A few examples may illustrate such interactions and responses (results) occurring therefrom.

(A)Man as active geomorphic agent

Man significantly affects and modifies hydrological processes through deforestation, extraction of groundwater, forest fire, construction activities, agricultural practices etc. Man also changes the ecological regime by numerous economic activities. Such examples are seen all over the world:

- The Aral Sea, once one of the four largest lakes of the world occupying an area of 68,000 km^2 has now become a desert which has been named as Aralkum Desert due to diversion of water of main feeding river Syr Darya for irrigation by erstwhile Soviet Union in 1960s.
- Lake Chad of Africa has shrunk in area from 23,000 km^2 in 1960s to mere 1400 km^2 in 2005 due to natural (droughts of 1970s) and anthropogenic (damming of major feeding rivers) factors.
- Coastal processes and coastal landforms are largely modified and transformed by the construction of protective structures to halt coastal erosion such as construction of groynes, seawalls, breakwaters etc. and dredging.
- Rivers are modified and transformed through direct and indirect human interventions such as point modification (dams and reservoirs, lift canals etc.) and reach modifications (construction of embankment, channel diversion, channel straightening, meander cutting etc.).
- Periglacial processes are being largely affected by encroachment of man in permafrost areas where deforestation, building activities, farming etc. have disturbed permafrost ecosystem.
- Subsurface processes/ groundwater

are largely affected by reduction in groundwater reserve due to over-exploitation of groundwater and reduction in recharge of aquifers consequent upon deforestation.

- Accelerated soil erosion in the form of gully erosion and ravine formation is induced by man through deforestation, faulty farming practice, overgrazing etc.
- Global warming caused by man through increase in greenhouse effect consequent upon rapid increase in the emission of greenhouse gases and ozone depletion due to increasing urbanisation, industrialisation, deforestation etc. The resultant climate change affects man himself and also the geomorphological processes operating over the earth's surface.
- Global warming by anthropogenic activities affect (increase) the frequency and severity of a number of geomorphological hazards such as tropical cyclones, floods, droughts, melting of ice sheets and glaciers etc.

Many more examples of modification and transformation of geomorphological processes and landforms by man may be listed. Here man is active and geomorphological processes are passive components.

(B) Geomorphic components and man as a passive agent

It may be mentioned at the very outset that it is very difficult to clearly separate man's impacts on geomorphological processes & forms, and impacts of geomorphological processes & geomorphological hazards on man because these are very much interconnected. Geomorphological processes and landforms become active agents when they influence human society as follows:

- Natural long-term climate changes leading to glacial and interglacial phases, increased aridity or humid conditions which affect various activities of man.
- Geomorphological hazards like earthquakes, volcanic eruptions, landslides, floods, cyclonic storms etc. result in immense loss of human property and lives. Natural and anthropogenic processes, when combined, become most disastrous to human society. For example, the severe cloudburst and outburst of Chorabari lake in the Mandakini catchment in Uttarakhand in 2013 claimed thousands of lives and swept away majority of unauthorised human settlements in and along the Mandakini valley. Here man's activities aggravated the killer floods.
- Hillslopes are not suitable for human settlements and farming especially in seismic zones. High magnitude or even moderate intensity earthquakes destroy settlements and kill people as it happened in Muzaffarabad of POK in 2005.
- The natural hydrological regime of rivers provides water for irrigation, drinking, hydel power etc. But if the natural flow of rivers is disturbed by man, then the same river becomes a curse to human society. For example, construction of embankments along the Kosi river in Bihar, causes siltation and consequent rise in river beds. This results in breaching of embankments during severe floods, often turning into a disaster. Such situation occurred in 2008 when Kosi embankments were breached at several points and flood water spread over large areas marooning several villages.
- Unstable hillslopes are prone to frequent landslides. When settlements are developed at the foothills and along the slope or in the valley floors facing the hills, a sudden landslide inflicts colossal loss to human lives and property. For example, a massive landslide in August 1998 wiped out the entire Malpa village in the valley of Kali river, in Pithoragarh

district of Uttarakhand.

- Tsunami is caused by undersea earthquakes, are natural processes which affect coasts. There are certain natural buffers like mangroves, sea beaches, coastal dunes, backwaters, which lessen the ferocity of tsunami and thus coasts are protected. When these buffers are destroyed by man, the tsunami becomes a killer disaster.

Many more such examples may be added.

(C) Geomorphological hazards: Vulnerability and risks

Besides the characteristics and genesis of various geomorphological hazards, their vulnerability and risk analysis is significant field of environmental geomorphology. Hazards vulnerability has already been discussed. The study of geomorphological hazards involves risk identification, risk assessment, determination of risk magnitude, risk responses and takers, risk acceptability, risk avoidance, risk mitigation etc.

Global warming climate change and Arctic permafrost meltdown

The new thrust area of geomorphological research is the climate change-induced geomorphological processes and resultant landforms consequent upon global warming caused by anthropogenic activities and meltdown of Arctic permafrost, melting of ice sheets over the Arctic region, Greenland, Antarctica and mountain glaciers.

The meltdown of Arctic permafrost which has trapped about 1400 to 1500 billion metric tonnes of carbon from plant and animal fossils and 2000 billion metric tonnes of methane is releasing substantial amount of carbon and methane in the atmosphere which may further aggravate the rate of global warming.

Though there are contrasting opinions about the drastic impact on global atmospheric temperature through the release of carbon and methane buried under permafrost consequent upon permafrost meltdown but it is clear that thawing of permafrost caused by human factors would certainly lead to acceleration of the rate of global warming which may cause fast rate of melting of Arctic permafrost.

Thus permafrost meltdown would initiate new geomorphological processes and landforms. This process has already started in Siberian and Alaskan permafrost areas. The permafrost meltdown has generated new features which must be investigated. The scientists are already studying such changes as follows:

- Changes occurring below the surface due to thawing of permafrost
- Creations of methane bubbles, methane holes, methane eruption vents and methane craters. Examples include formation of 30 m wide methane crater on Yamal Peninsula of Russia and development of recent methane fissures in Batogaika which is increasing at the rate of 18 m per year
- Warping, folding, and caving-in of the ground surface and formation of new thermokarst lakes
- Collapse of ice-rich permafrost coastal bluffs
- Formation of new sink holes
- Regeneration of ancient microbes and spread of new diseases
- Disappearance of thousands of lakes in eastern Siberia, in the last three decades

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