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LEONARDO DA VINCI AND FLUVIAL GEOMORPHOLOGY

DAVID ALEXANDER
University College London, London WC1E 6BT, England

ABSTRACT. *Leonardo da Vinci's work as a natural scientist involved many studies of fluvial geomorphology which can now be re-examined in the light of current knowledge. His observations on river flow, floods, accelerated erosion, and sedimentation include some of the earliest examples of observational and experimental, rather than purely theoretical, science.*

Leonardo was one of the first to develop a terminology for the components of the fluvial system. He gained a basic understanding of the continuity principle of open channel flow and made many notes on patterns of flow and turbulence in the wake of obstacles and beneath overfalls. He also described and classified the braided, meandering, and straight courses of rivers and sought explanations for adjustments in river channel morphology, including the development of scour hollows.

Following Pliny and other Classical authors, Leonardo believed that the hydrological cycle is based on circulation of water inside the Earth, through which rainwater is raised up inside mountains by capillary action aided by the heat of the sun. However, his observations of evaporation caused him to abandon this theory for a brief period during 1504-1506.

Leonardo gave equal weight both to theoretical and applied studies and was often able to observe and utilize the connection between them. He used his knowledge of the behavior of fluvial systems to design structures for erosion control and proposed an ambitious scheme for regulating sedimentation to reclaim marshlands in the upper Arno basin.

Leonardo was a Uniformitarianist, not a Diluvialist, and supported the theory of slow uplift proposed by Albert of Saxony and others. He was thus unable to attribute elevated bands of marine fossils to the action of a universal Deluge, but using hypotheses of marine transgression and regression, he was able to construct a rudimentary denudation chronology for parts of Tuscany. His studies of natural landscapes were not seminal but mark the beginning of the transition from purely theoretical to observational and deductive methods of analysis in the earth sciences.

> *". . . and as the blood works in all the animals so water does in the world, which is a living body." (MacCurdy, 1956, v. 1, p. 295, C.A. 367, v.b).*
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> *"The water wears away the mountains and fills up the valleys, and if it had the power it would reduce the earth to a perfect sphere" (MacCurdy, v. 1, p. 300, C.A. 185, v.c).*[1]

[1] References to MacCurdy's translations, the *Notebooks of Leonardo da Vinci* (2 v.), contain the following abbreviations used by MacCurdy:
C.A., Codex Atlanticus; *B.M.*, Codex Arundel, British Museum; *A-I*, *K-M*, manuscripts in the Library of the Institut de France; *Leic.*, Codex Hammer, *v.*, *verso; r.*, *recto.*

INTRODUCTION

The influence of Leonardo da Vinci (1452-1519) on the environmental science of the Renaissance was small in proportion to his discoveries. It is thus paradoxical that in the last 87 years these discoveries have provoked re-examination by many hundreds of scholars. The present author uses as his excuse for adding to the increasing flood of *vinciana* the fact that there have been relatively few analyses specifically of Leonardo's geomorphological discoveries, and those that have been are almost exclusively in Italian.

Much of the natural philosophy of western civilization had its inception during the Renaissance, and looking back over Leonardo's occasionally fallacious but frequently acute observations the precursors of many modern geomorphological theories can be seen. Despite the existence of several critiques of Leonardo's writings on physical geography (for example Lorenzo, 1920; Gortani, 1952;[2] Castelfranco, 1954) the time is ripe for a reassessment in the light of the advancements that have recently occurred in the study of fluvial geomorphology. Leonardo's overall scientific achievement has been critically examined by, among others, Zubov (1968), and his observations on hydraulics have been summarized by Rouse and Ince (1957). An admirable history of other Italian physical geographers of the *cinquecento* was written by Roberto Almagià in 1909.

THE IMPORTANCE OF LEONARDO'S STUDIES OF FLUVIAL GEOMORPHOLOGY

Chorley, Dunn, and Beckinsale (1964, p. 6) wrote of Leonardo that "it would be hard not to say that he grasped firmly the ideas of both local erosion and of world-wide landscape evolution," yet they also observed that his influence on the development of geomorphology was small. Indeed, many of his scientific writings were in the form of isolated and disorganized private notes which received no systematic evaluation until the late nineteenth century. However, the same heterogeneity also concealed Leonardo's unique ability to unite large- and small-scale observations with philosophical theory and to conduct practical experiments in the cause of scientific explanation.

Although his observations on geomorphology had no immediate precedent Leonardo drew freely on the inspiration afforded by Archimedes, Euclid, Vitruvius, Pliny, and Albert of Saxony, and we are fortunate that he brought together many of his ideas on rivers in the *Trattato del Moto e Misura dell'Acqua* (Carusi and Favoro, 1923), a compendium of hydrology, hydraulics, geomorphology, and engineering. Many of his observations on erosion and its effects had a degree of precision and originality which was not regained for centuries, and it is thus not surprising that open-channel flow was one of the phenomena he understood best.

[2] Gortani (1952, p. 199) observed in surprise that: "E' veramente singolare che nelle opere in voga su la storia della geologia . . . non si faciando risalire oltre il secolo XVIII le nozioni su gli effetti meccanici delle acque correnti—denudazione e sedimentazione—che i precursori italiani avevan già poste su salde basi nel Quattrocento."

The Renaissance was marked by a gradual change from the purely philosophical approach to science of the Peripatetics and Scholastics toward the modern observational approach (Rouse and Ince, 1957). The period beginning with Leonardo and ending with Galileo Galilei (1564-1642) embodied many advances in the establishment of mechanics as an observational and rational science. Just as mechanics provided the key to the correct interpretation of flow and erosional phenomena in natural channels, so experimentation and careful observation provided the key to mechanics. As Leonardo wrote:

> "It is true that nature begins by reasoning and ends by experience; but, nevertheless, we must take the opposite route: as I have said, we must begin with experiment and try through it to discover the reason" (quoted by Rouse and Ince, 1957, p. 41).

Leonardo understood some of the most important principles of mechanics, such as continuity and relative motion, and on the basis of observational and experimental data he established theories that could then be used to explain the observed phenomena. It is as a very early example of this approach that his work on rivers bears re-examination today.

By contrast, many of Leonardo's most interesting observations on floods, accelerated erosion, and large-scale sedimentation were stimulated by a desire to search for remedies or to know the cause of the suffering that such disasters engendered. To many people familiar with his inventive genius, this pragmatic approach must seem more familiar than his experimental science. His observations on earth history and landscape evolution, however, appear to stem directly from the contemporary debate on the Deluge. Although he was not the only sceptic alive during the Renaissance, the clarity of his reasoning was unprecedented. It is thus instructive to see how his opinion became more anti-diluvial as his store of observations increased and to observe how slowly this ground was regained after his death.

PRECEDENTS

Leonardo was fortunately able to draw on the writings of Marcus Vitruvius Pollio who had summarized many of the observations made by Greek and Roman scholars on the subject of water distribution (Vitruvius Pollio, translated by Granger, 1934). It is clear that, when Vitruvius wrote, the art of water supply and regulation was well understood, but the effects of head, slope, and resistance on the rate of flow and the concepts of sediment transport and siltation were but dimly perceived (Rouse and Ince, 1957, chap. 2). Hence it could be argued that the environmental science of the Classical period affected Leonardo's work on the design of canals and hydraulic machinery more than it affected his studies of geomorphology.[3] Similarly, those advances toward the fundamental principles of mechanics which took place during the Middle Ages were concerned

[3] However, one of the most fallacious of Leonardo's assumptions, that on the circulation of water (the hydrological cycle), seemed to emanate from ideas collected by Vitruvius, who based his own, even less realistic, ideas on the geographical work of Agrippa (Granger, 1934, p. 149).

with the kinematics of motion and were ultimately most difficult to relate to, for example, erosional processes.

The representations of landforms in early works of art are almost the only surviving clue to contemporary attitudes to geomorphology in Italy. It is clear that since Roman times great environmental disasters had served only as reference points in time. Hence the earthquake and volcanic eruptions along the Bay of Naples in A.D. 62 failed to warn the inhabitants of Pompeii and Herculaneum of the impending disaster of A.D. 79, and to the artists who portrayed them they must have seemed imponderable. During the Middle Ages the perception of geomorphology had become exceedingly symbolic. Landscape was merely a background to human events or an instrument of divine policy, and plausibly accurate representations of landforms were seldom made. Nevertheless, around the biblical scenarios of Duccio di Buoninsegna (Siena, about 1253-about 1315) and Guido da Siena (active 1310) there are tracts of landscape strongly reminiscent of the erosional landforms found locally in the exposed marine clays of Val d'Orcia and Val d'Era. Such landforms appear in stylized form under the feet of the magi and their retinue in Benozzo Gozzoli's magnificent frescoes in the Cappella Medici-Riccardi, Florence.

In the *trecento* natural landforms largely served to emphasize religious (see, for instance, 'L'assunzione in cielo della vergine' of Taddeo di Bartolo, 1362-1422, in the Palazzo Pubblico, Siena, a late example) or territorial (compare 'Guido Riccio da Folignano' by Simone Martini and 'Il buon governo' (outside the gate) by Ambrogio Lorenzetti, in Siena) considerations in Tuscan art. But in *quattrocento* painting there is a distinct awakening of interest in realism (compare Richter, 1955, p. 86). The 'Agony in the Garden' of Giovanni Bellini (1430-1516) contains plausible representations of a riverine floodplain and the gullied scar of a deep-seated landslide. Filippino Lippi (c. 1457-1524) painted landscapes of precise, naturalistic sedimentary and metamorphic rock formations with a mantle of regolith.[4]

Significantly, Dante's philosophical journey across the three celestial landscapes contains very few plausible descriptions of landscape. (At a time when it seemed to be *de rigeur* for an Italian scholar to quote Dante, Amici, 1898, could only resort to: ". . . detto malebolge/tutto di pietra di color ferrigno/come la cerchia che d'intorno il volge/pozzo assai largo e profondo/dritto mezzo del campo maligno" (*l'Inferno,* Canto XVIII).) Even the river in Canto II of the *Inferno* ". . . sulla fiumana onde 'l mar non ha vanto" is only symbolic (Sayers, 1949). It has been argued that natural philosophy did not emerge in the modern world until Petrarch, some decades later. (See Clark, 1953, who contrasts Petrarch's awareness of landscape with the preceding age of the 'landscape of symbols'.) In a sense Leonardo, like the sons of Jacopo Bellini and Fra Lippi, became heir to Petrarch's formal, critical and eclectic relationship with landscape. (The realism of the *torrente* behind the right shoulder of *Monna*

[4] It should be noted that this was not environmental perception in the sense of Appleton (1975, p. 22), but rather it resulted from the reorientation, or secularization, of natural philosophy.

Lisa is, perhaps, significant. It is also known that Leon Battista Alberti wrote very perceptively and accurately of erosion and land sculpture in *De re aedificatoria* (Florence, 1485). Gortani, 1952, has compared Alberti's studies of erosion with those of Leonardo.) Although this left him remarkably little of substance to incorporate into his discoveries, the stimulus of novelty must have been apparent.[5]

THE FLUVIAL SYSTEM AND HYDROLOGICAL CYCLE

Leonardo's observations on the fluvial system were in general wide-ranging, pertinent and precise. Consider the following:

> "The streams of rivers move different kinds of matter which are of varying degrees of gravity, and they are moved farther from their position in proportion as they are lighter, and will remain nearer to the bottom as they are heavier, and will be carried a greater distance when driven by water of greater power.
>
> "But when this power ceases to be capable of subduing the resistance of the gravel this gravel becomes firm and checks the direct movement of the water which led it to this place. Then the water, as it strikes upon the gravel which has been increased in this manner, leaps back cross-wise and strikes upon other spots to which it was unaccustomed, and takes away other deposits of soil down to their foundations. And so the places where first the said river used to pass are deserted and become silted up anew by a fresh deposit from the turbid waters, and these in due course become choked up in these same places" (MacCurdy, 1956, v. 1, p. 293 C.A. 77, v.b).

He was able to draw inferences from each of the phenomena described here — entrainment, transportation, deposition, and channel braiding — and many more likewise. He ensured the precision of his observations by commencing the treatise on water with a set of terminological definitions which included the following:

fiume (river) occupies the site of the lowest part of valleys and flows continuously
torrente (ephemeral stream) flows only when it rains, joins the rivers at the lowest parts of the valleys
fonti (sources) the birthplaces of rivers
argine (bank) withstands, by its abrupt height, the widening of rivers
ripa (levee or high bank) is higher than the *argine*
riva (shore) is lower than the *argine*
paludi (marshes) stagnant waters
stagni (ponds or pools) places of refuge for the waters of floods or storms, having firm and thick beds able to prevent the loss of these waters
polulamenti (bubblings up) the beginnings of surface waters, which come from vertical movement
surgimenti (wellings up) the beginnings of surface waters by transverse movement from some grotto
pozzi (wells) the sudden deeps of rivers
procelli (storms) tempests of water (MacCurdy, v. 2, p. 78-79, I, 72 [24] r. and v.).

[5] For an analysis of the relationship between Leonardo's painting and his studies of geology and geomorphology, see Castelfranco (1954, p. 473-474).

The high degree of organization in Leonardo's studies of the fluvial system is shown by a memorandum which occurs in a manuscript of 1508-1509, several years before he organized his treatise on water. He exhorts himself to begin by writing about the movement of water, the shapes and causes of such movement, and then to describe the beds and bed materials, but without forgetting the propositions on the behavior of water *per se*. He reminds himself to avoid confusion by preserving a logical order in his statements (MacCurdy, v. 2, p. 57, F, 87, v.).

Whereas the strength of Leonardo's work on the fluvial system is in its logical progression from simple observations to well-founded deductions, not all of his beliefs about water were based on what he observed. This is particularly true of his view of the hydrological cycle, which varied between the perspicacious and the fallacious. He considered the Earth to be a sort of animated machine imbued with the characteristics of the human body, with the circulation of waters replacing that of blood. In consequence the perceptiveness of the following:

> "It is in its [water's] nature to search always for the low-lying places when without restraint. Readily it rises up in steam and mist, and changed into clouds falls back again in rain as the minute parts of the cloud attach themselves together and form drops. And at different altitudes it assumes different forms, namely water or snow or hail" (MacCurdy, 1956, v. 2, p. 19, A, 26 r.).

. . . is marred by a total misconception, with which it is very much at variance:

> "The waters range with perpetual movement from the lowest depths of the seas to the topmost summits of the mountains, not following the law of heavy things; and in this instance its action resembles that of the blood of animals which is always moving from the sea of the heart and flowing towards the summit of their head; and so when a vein there has burst open, as one sees if a vein bursts in the nose, the whole of the blood from below rises up to the height where the vein has burst.
>
> "When the water gushes forth from the burst vein in the earth it follows the law of other things which are heavier than air and so always seeks the low places."

Clearly, it is the theory rather than the observation that is misconceived.

This fallacious hydrological 'cycle' was evidently based on observations of karstic streamflow (MacCurdy, v. 2, p. 64, C. 49, v.), springs and seepage steps (MacCurdy, v. 2, p. 54, F., 72, v. and r.), and probably capillary rise. Where streamflow varied with the aspect or position of valleys Leonardo divined an internal circulation of water within mountains with the capillary rise of groundwater being attenuated by the largest or farthest-flowing stream (MacCurdy, v. 2, p. 65, G., 70, r.). The heat of the sun was the driving mechanism for water to rise up within mountains, which it did both by upward seepage and by flow in concealed channels. The analogy with the bloodstream of mammals was elaborated when Leonardo claimed that, as when the sun warms a man's head the amount of blood there increases, so the amount of solar warmth in the ground is directly proportional to the supply of water to upland springs (MacCurdy, v. 2, p. 22, A, 56, r.). The sea fitted in well with the analogy and took the place of the heart, animated by the flow and ebb of tides, the "breathing of this machine of the earth" (MacCurdy, v. 2, p. 106, Leic., 17, r.).

According to Zubov (1968, p. 195) the fallacy of Leonardo's hydrological cycle closely followed Pliny's observations on the internal circulation of the earth's waters. For two years, 1504-1506, Leonardo is thought to have abandoned his analogy between the circulation of waters and that of the bloodstream, but his enquiries eventually led him back to it and into further elaborations of it[6]. Through his observations on water flow through the Straits of Gador (Gibraltar) and on the basis of logical deduction and experimental modelling it is clear that Leonardo had a much better idea of sea currents than of water circulation on land. This is particularly surprising as at the time geographical discoveries were constantly altering the conception of the world and its oceans (Zubov, 1968, p. 234).

The workings of Leonardo's analogy between the circulation of waters and the bloodstream appear at first sight to be at variance with two of his most important precepts:

> "Water of itself does not move unless it descends" (MacCurdy, 1956, v. 2, p. 107, Leic. 21, r.).
> "The water which falls by the line nearest to the vertical is that which descends most rapidly" (MacCurdy, v. 2, p. 19, A, 24, r.).

They may also seem to contradict the myriad of his observations on hydraulics at the small scale, for instance:

> "A drop is that which does not detach itself from the rest of the water unless the power of its weight is more than its adhesion to the water with which it is joined" (MacCurdy, v. 2, p. 50, F, 66, v.).

Furthermore, it is probable that he had some conception of downward vertical infiltration:

> "Many there are that lose without ever acquiring" [of simple movement in rivers] (MacCurdy, v. 2, p. 91, K, 60, [II] v.).

It may be that he deduced something of the principle of thermodynamics (he clearly understood a little of the principle of entropy through his observation of falling water and its energy expenditure):

> "Water, which is the vital humour of the terrestrial machine, moves by its own natural heat" (MacCurdy, v. 2, p. 75, H, 95 [47 v.] r.).

However, it is clear that he regarded heat as the vital force in raising water to feed the sources of rivers. The 'terrestrial machine' absorbed this heat from the sun, converting it into a source of energy to be dissipated by raising the waters up through the mountains. The seepage of these waters into the streams - the flow from the "broken veins of the high summits of the mountains" (MacCurdy, v. 2, p. 102-103, B.M., 235, r.) freed them from control by heat.

[6] Compare footnote 3.

Since Leonardo understood so much of the true nature of the hydrological cycle, it is a great misfortune that he misinterpreted it. It is clear from his notebooks that he observed seepage into headcuts and through stream banks, karstic streams in action, and phenomena such as evaporation and infiltration. He understood that the hydrological cycle is an unbroken circle of events, endlessly repeated, and he identified some of the relations between energy and entropy. It should not surprise us that the Earth should have appeared corporeal. The analogy was a pervasive one, and animism was to be a feature of deductive geomorphology until after the death of W. M. Davis centuries later.

HYDRAULIC BASIS OF LEONARDO'S GEOMORPHOLOGICAL OBSERVATIONS

> "In these eight sheets there are seven hundred and thirty conclusions as to water (MacCurdy, v. 2, p. 17, Leic., 26, v.).
>
> "Define first what is meant by height and depth; also how the elements are situated one inside another. Then, what is meant by solid weight and by liquid weight, but first what weight and lightness are in themselves. Then describe why water moves, and why its motion ceases; then why it becomes slower or more rapid; besides this, how it always falls, being in contact with the air but lower than the air" (Richter, 1939, v. 2, *The Order of the First Book of Water,* p. 180, E, 12, a.).

Leonardo's geomorphological studies are best examined in the light of his beliefs on hydraulics and mechanics. It is unfortunate that he lived at a time when mechanics was yet to undergo its fundamental development. Thus he understood friction only in the sense that force is necessary to induce a body to motion and to overcome its static resistance; he did not understand the mechanics of fluid resistance. He attributed gravity only to moving objects ("the water of itself does not move unless it descends") and thus objects at rest, for example, areas of stagnant water, the *stagni* and *paludi,* had no direct or innate relationship with gravity. He understood that heat is an important constituent of work, but his observations on the liberation of heat energy were intimately related to the fallacious part of his hydrological cycle.

Leonardo's studies of flight indicate that he had an appreciation of relative motion; although he reasoned that flying birds are supported on air compressed by the downward motion of their wings, he realized that the same effect could be achieved by an upward draught of air[7]. His studies of projectiles show that he attributed fluid resistance to a compressive effect (which is indeed true in the case of supersonic drag), but he imagined that the projectile was further propelled by the eddies that formed in its wake. He came nearer to the truth in his studies of hydrostatics where, by experimentation, he correctly described the relationship between the weight of water, the volume it occupies and the level it attains, although he explained it by an erroneous reference to the principle of levers.

[7] Brizio (1954, p. 283) has compared Leonardo's observations on air as a fluid (in the *Trattato su Voto*) with his studies of the movement of water.

His understanding of open-channel flow was, however, so original and so acute that, according to Rouse and Ince (1957, p. 49), the principle of continuity itself might justifiably bear his name. He stated that:

> "A straight river with equal width, depth and slope acquires a degree of velocity for each degree of motion. This is evident from the proportion of motion according to which an object, the more it moves of its own natural course, the more it gathers speed, as in any other matter. The straight river as above, although it acquires a grade of velocity for each grade of motion, nevertheless, the more obstacles it encounters on its course, the more it slows down in speed" (Rouse and Ince, 1957, p. 49).

From observations such as these Leonardo was able to propound a rudimentary continuity principle:

> "A river in each part of its length in an equal time gives passage to an equal quantity of water, whatever the width, the depth, the slope, the roughness and the tortuosity" (Rouse and Ince, 1957, p. 49).

He was also able to describe correctly the flow-retarding effect of bank resistance and the deformation of the vertical velocity gradient by bed resistance. As he had only a partial idea of the meaning of friction, his interpretation of the vertical velocity gradient was surprisingly advanced. He attributed the retardation effect near the stream bed to "percussions made by the eddies" (MacCurdy, 1956, v. 2, p. 72, H, 77 [29] v.) and the drag effect of bed roughness (MacCurdy, v. 2, p. 69, H, 55 [7] r.).

His understanding of stream channel equilibrium stemmed from direct observation of adjustments in river channel morphology, of which he deduced:

> "This movement aforesaid occurs in the course of rivers, which always attack and destroy whatever opposes the direct line of their course.
>
> "But if these rivers were straight, with equal breadth, depth and slant, you would find that with each degree of movement they would acquire degrees of speed.
>
> "Consequently if there is a change or difference in their slant there is a difference in their course; and where there is less inequality in breadth they become deeper; and given an equal slant, where they are wider they become slower" (MacCurdy, v. 2, p. 76, I, 68 [20] r.).

From the point of view of his geomorphological studies it is fortunate that Leonardo had a particularly good idea of the relationship between flow and erosion. For example:

> "And if the first bed of the river was formed with uniform width, slant and straightness, what was the cause of the varying of such conditions as regards the bed? For it is here shown that the water which moves about them must of necessity be of uniform current. The matter which makes the water of the rivers turbid is that which after being carried some distance settles upon their beds, and raises them, and changes the slant of the bed; and in this way it causes the variation in the courses of the waters. And from this we conclude that the water is the cause of the variation of its bed and that the bed then of necessity changes the courses of the waters in greater or lesser speed; which variety of courses is then the most powerful cause of varying all the bed of its river; and so it is concluded: — The bed of the rivers is varied by the matter that the course of the water deposits there; and the variety in the course of the waters is further varied by the irregularity in the bed of the river" (MacCurdy, v. 2, p. 128, Leic., 33, r.).

However, some of Leonardo's best-known discoveries were in the field of rigid boundary hydraulics. He produced the first known descriptions and diagrams of the velocity distribution in a vortex, the profiles of free jets emanating from diverse heights, the surface profile of the free overfall, the hydraulic jump, the formation of eddies at abrupt expansions and in wakes, and the propogation, reflection, and interference of waves (see Rouse and Ince, 1957, chap. 5).

The motivation of these extraordinarily perceptive studies was, according to Clark (1953, 1959), at least partly drawn from contemporary belief in the Deluge and the imminence of a fresh apocalypse. Interest in the destructive and forceful aspects of water encouraged by the then apocalyptic climate of thought brought Leonardo to both useful and sterile discoveries. His fascination with the free fall of water and its turbulent and erosive effects ultimately led him nowhere, as he failed to appreciate limiting acceleration; but he understood that surface undulations are not to be confused with the speed of water, and he was quick to advocate the measurement of stream velocity using floating markers timed over set distances downchannel. He appreciated the importance of turbulence in creating scour hollows (MacCurdy, 1956, v. 2, p. 61, G, 41, v.) and bank erosion, and he observed that secondary flows in rivers are sometimes convective or circulatory. The following comment on the relationship between secondary flows and erosion is especially perceptive:

> "These eddies serve the purpose by their revolutions and delays of equalizing the excessive speed of rivers; and as therefore the eddies at the side are not sufficient, by reason of the narrowness of the rivers, it becomes necessary that new kinds of eddies should be created which shall turn the water over from the surface to the bottom and churn up all the soil which the eddy of the surface has in course of time deposited. And the other eddies do the same against the banks of the rivers" (MacCurdy, v. 2, p. 96, B.M., 30, v.).

It is clear that Leonardo had some understanding not only of the scour and deposition of cohesive sediments but also of some aspects of particle morphogenesis. He correctly observed that shingle becomes rounded during its passage along the beds of rivers (MacCurdy, 1, p. 298, F, 80, v.), and he observed the differential sediment-transport capacity of small and large eddies (MacCurdy, v. 2, p. 36, F, 7, r.).

Leonardo attempted to codify the behavior of water into a set of postulates, for example:

(Postulate IV): "Water does not move [of its own accord] except to descend" (compare MacCurdy, 1956, v. 2, p. 107, Leic., 21, v.).

But he was sometimes fundamentally wrong:

(Postulate VII): "The movement of every river in equal time gives to every part of its length an equal weight of water" (MacCurdy, 1956).

However, in one of his postulates he adduced a relationship between stream velocity and sedimentation ("the water that loiters most discharges most rapidly the matter that it carries") which enabled him to relate the degree of deposition on a floodplain to the sinuosity of meandering (MacCurdy, v. 2, p. 33, E, 66, v.), and this was fundamental to his investigation of river channel morphology in its own right.

RIVER CHANNEL MORPHOLOGY

> "Book of the different movements of waters which pass through channels of different forms" (MacCurdy, v. 2, p. 99, B.M. 122, r.).

There are a number of memoranda in Leonardo's notes which suggest that he observed the transitions between the straight, meandering, and braided courses of rivers, both downstream and with flow stage. For instance, he wrote of the River Po:

> "For when it is low its water runs many times in cross-currents, and called by the low places and directing its way towards these it takes its course and strikes the bank in its foundations, and hollows these out causing wide destruction. But when it flows in full stream the lesser quantity which formerly with its cross-current had beaten upon the banks and hollowed them, abandons its course, being dragged in company with the greater volume of water and advancing along the line of its base it forbears to damage its banks" (MacCurdy, v. 2, p. 19, A, 23, v.).

In one remarkable passage of the Codex Atlanticus (MacCurdy, v. 2, p. 13-14, C.A., 185 r.b), he described meander cut-offs and attributed them to the diversion of high-stage flows, the migration of point bars (which he attributed to the formation of large-scale eddies in the flow of the stream), and the effects of floodplain deposition. It is to his credit that he looked at the problem of river channel patterns from the scientific viewpoint, yet also pragmatically in the hope of discovering behavioral laws that might help to predict where and when a river will burst its banks during flood.

Leonardo was able to use his knowledge of the hydraulics of open-channel flow, in particular of helical flow (MacCurdy, v. 2, p. 15-16, C.A., 296, v.b), to deduce that meandering is the result of flow instability:

> "The cause of this effect is that the water that flows in the rivers always goes leaping from bank to bank. If nothing projects in this bank many lines of water gather there and unite together and leap in a mass on the opposite bank, and twist themselves in with the other lines which they meet with on their way; and having reached the embankment they gnaw and destroy it. And there are yet new lines produced there which leap back and damage the other bank; and so from place to place they begin to form eddies of varying depths, and hence it comes about that straight rivers become winding and crooked" (MacCurdy, v. 2, p. 31, C, 26, r.).

He saw that meanders can be constricted by valley formations (MacCurdy, v. 1, p. 310-311, B.M., 168, v.), and, astonishingly, he also observed that streamflow can undergo regular oscillations downstream in both the horizontal and vertical dimensions. In relating the modulation of streamlines and the interference of turbulence to the development of the channel bed (MacCurdy, v. 2, p. 86-87, 1, 105 [57] v. and 106 [58] r.), he came very close to describing the mechanism of the pool-riffle sequence (Yang, 1971).

Leonardo also observed the migration of sand dunes on a shingle bed, the gradual formation of floodplains, and the high variability of deltas. The last of these was of particular interest to him from the point of view of military engineering and the construction of coastal highways.

Characteristically, Leonardo had an all-embracing scientific axiom to account for erosional landforms. The waters of the Earth are perpetually trying to escape from the hydrological cycle in order to lie flat on the surface of the Earth. Under their own impetus they cascade down the mountains but are then heaved up to the tops again by the power of the sun. Land sculpture is thus created as a response to unevenness in the destructive power of flowing waters and reflects the pattern of 'veins' in the terrestrial organism (MacCurdy, 1956, v. 2, p. 67, H, 37, r.).

EROSION AND SEDIMENTATION

> "That part of the bed or of the bank which projects with the sharpest angles into the straight course of the waters suffers most damage in the flow of the water" (MacCurdy, v. 2, p. 67, II, 35, v.).

Leonardo was able to connect the above statement with observation of turbulence, flow stage, and the weight of water bearing on the channel bed. His work on overfalls was particularly well-suited to the study of scour hollows, which he frequently described in painstaking detail when writing about the turbulence of a jet of water striking a pool. Similarly, he observed downstream turbulence:

> "So moving water strives to maintain the course pursuant to the power which occasions it, and if it finds an obstacle in its path it completes the span of the course it has commenced, by a circular and revolving movement" (MacCurdy, v. 2, p. 25, A, 60, r.).

A "kind of pit" is formed on the lee side of the obstruction and replicated with decreasing magnitude in the downstream direction as the turbulent wave strives to dissipate its energy. Leonardo understood that breaking the velocity or turbulence of water is necessary to achieve deposition, for example as tree roots do to the rivulets that trickle along an eroded channel bank, and he succeeded in relating velocity to the size range of sediments deposited:

> "Where the water has least movement the surface of the bottom will be the finest mud or sand" (MacCurdy, v. 2, p. 66, H, 30, r.).

On the subject of bank erosion he observed that width constrictions are particularly liable to bank collapse, because of the increase in velocity and turbulence, and that turbulent water does more harm to the banks than clear water. Profitting from his understanding of open-channel continuity relationships, he also related channel entrenchment to narrowing of the banks.

The inadequacy of Leonardo's understanding of the problem of free fall was reflected in his analysis of the kinetic energy of rainfall impact. One reason for the continuing division of the Earth into mountains and plain (despite river erosion on the mountains and sedimentation on the plains) was, he wrote, that droplets of rain were allowed greater time to accelerate before striking the lower areas of land, and they thus acquired greater weight, gravity and velocity than those that struck the highlands (MacCurdy, v. 1, p. 294, C.A., 160, v.a).

APPLIFD GEOMORPHOLOGY

The following vivid passage reflects Leonardo's concern over floods and alluviation:

> "Among irremediable and destructive terrors the inundations caused by rivers in flood should certainly be set before every other dreadful and terrifying movement, nor is it, as some have thought, surpassed by destruction by fire. I find it to be the contrary, for fire consumes that which feeds it and is itself consumed with its food. The movement of water which is created by the slopes of the valleys does not end and die until it reaches the lowest level of the valley; but fire is caused by what feeds it, and the movement of water by its wish to descend. The food of the fire is disunited, and the mischief caused by it is disunited and separated, and the fire dies when it lacks food. The slope of the valley is continuous and the mischief done by the destructive course of the river will be continuous until, attended by its valleys, it ends in the sea, the universal base and only resting place of the wandering waters of the rivers.
>
> "But in what terms am I to describe the abominable and aweful evils against which no human resource avails? Which lay waste the high mountains with their swelling and exulting waves, cast down the strongest banks, tear up the deep-rooted trees, and with ravening waves laden with mud from crossing the ploughed fields carry with them the unendurable labours of the wretched weary tillers of the soil, leaving the valleys bare and mean by reason of the poverty which is left there.
>
> Among the irremediable and destructive terrors the inundations caused by impetuous rivers ought to be set before every other aweful and terrifying source of injury. But in what tongue and in what words am I to express or describe the aweful ruin, the inconceivable and pitiless havoc, wrought by the deluges of ravening rivers, against which no human resource can avail?" (MacCurdy, v. 2, p. 10-11, C.A. 108, v.b.).

This comparison between the destructive powers of water and fire, both regarded as fundamental elements of the Earth, is elaborated in other passages of the Codex Atlanticus. One wonders what Leonardo's reaction would have been had he remained alive long enough to witness the exceptional flood of 1557, which caused widespread damage in the Arno basin and flooding in the city of Florence.

The measures that Leonardo advocated to protect against flooding and soil erosion were ahead of their time. He suggested reinforcing the outer banks of meanders and, where flows were known to have been excessively violent and turbid, constructing conduits in order to reduce their transporting power and facilitate deposition. He advocated the construction of sediment check dams in order to reduce stream gradient and predicted that they would cause deposition to take place upstream. He prepared comprehensive plans for the regulation of flows in the River Arno by canalizing certain sections and, in order to preserve navigability, controlling seasonal fluctuations in discharge using water from reservoirs situated in Valdichiana. But there were many phenomena for which he was not able to offer a solution. He observed the connection between catastrophic floods and landslides, which often occurred where few prior indications had been available for prediction, and he described the passage of a floodwave across the dry bed of a stream. On soil erosion, he wrote:

> "The rivers make greater deposits of soil when near to populated districts than they do where there are no inhabitants. Because in such places the mountains and hills are being worked upon, and the rains wash away the soil that has been turned up more easily than the hard ground which is covered with weeds" (MacCurdy, v. 1, p. 295, C.A., 160, r.a.).

He also observed the connection between the high sediment load derived from accelerated erosion (the precipitous landforms of which he described), the development of floodplains and deltas, and the formation of sedimentary rocks.

It was perhaps novel of Leonardo to advocate reclaiming marshes by inundating them with sediment. He suggested that, not only should marshes be slowly drained by cutting an exit channel, but a channel leading into the marsh from above should be cut in order to supply sediment that would be stripped off the less productive uplands and deposited below amidst the stagnant water of the area to be reclaimed. In the context of his time, this course of action was probably more sensible than attempting to conserve upland soils against erosion. The reclamation of marshlands had in any case become a *cause celèbrè* in Tuscany. The region of Valdichiana, which lies between the Arno and Tevere (Tiber) basins, had become progressively waterlogged since the Classical period and consequently by 1500, disease, improverishment, and unrest were common among the inhabitants (see Machiavelli (ed. Berardi, 1969, p. 501-505); also Enciclopedia Italiana, 1933-1942). Although the ambitious project to redirect the drainage of the Chiana from the Tevere to the Arno was largely carried out by others (Fossombroni, 1789), the precepts involved were those that Leonardo had formulated in his plans for the reclamation of the Pontine marshes, and he made several useful topographical sketches of Valdichiana in connection with his scheme for the canalization of the Arno, which involved creating a reservoir in the Valdichiana, adjacent to Arezzo, to provide a constant supply of water for the Arno canals. The scheme ran into political opposition from the Pisans, whose trade was threatened, and was abandoned in 1504.

Leonardo's advice was often sternly pragmatic:

> "In order to enable each large river to maintain itself within its banks, it is necessary for an official to be appointed with authority to command the people who live near to it, and so to effect repairs whenever it has burst its banks" (MacCurdy, 1956, v. 2, p. 137, C.A. 297, r.b).

He gave advice on dredging and on stabilizing the banks of canals by planting willow trees, and he advocated the use of accurate calculations relating to downstream slope and to the positioning of sluices for the regulation of floodwater. He suggested that barriers could be constructed to trap sediment where bank erosion had damaged buildings, yet he wisely advocated a cautious approach:

"That a river which has to be diverted from one place to another ought to be coaxed and not coerced with violence; and in order to do this it is necessary to build a sort of dam projecting into the river and then to throw another one below it projecting farther; and by proceeding in this way with a third, a fourth, and a fifth, the river will discharge itself in the channel allotted to it, or by this means it may be turned away from the place where it has caused damage . . ." (MacCurdy, v. 2, p. 143, Leic., 13 r.).

It has been shown above that Leonardo could apply himself with equal sagacity to environmental questions at both large and small scale and could conduct both pure and applied research. Although he was essentially a solitary student — his notes were invariably made only for his own use — he participated in the scholarly debates of the time and was an entrenched heretic. Untrammelled by the need to explain landscapes and geology according to divine intervention, he produced a great deal of argument relating to the evolution of the Earth and to that of Tuscany in particular.

THE EVOLUTION OF LANDSCAPES

"Of the stupidity and ignorance of those who imagine that these creatures were carried to such places distant from the sea by the Deluge" (MacCurdy, v. 1, p. 321-322, Leic., 10, r.).

It is clear that Leonardo understood much of how fossils are formed and observed beds of them high above sealevel. But in his desire to explain this he set himself a hard task:

"In this work of yours you have first to prove how the shells at a height of a thousand *braccia* [c 600 m] were not carried there by the Deluge, because they are seen at one and the same level, and the mountains also are seen which considerably exceed this level, and to enquire whether the Deluge was caused by rain or by the sea rising in a swirling flood; and then you have to show that neither by rain which makes the rivers rise in flood nor by the swelling up of the sea could the shells being heavy things be driven by the sea up the mountains or be thrown there by the rivers contrary to the course of their waters." (MacCurdy, v. 1, p. 313, Leic., 3, r.).

He wrote at length of the trapping of fish, crustacea, shells, and leaves within sediments deposited by wave action or by rivers. He suggested that the sediments had a relatively low weight, enabling the form of the trapped organism to be preserved. In time they became a sticky paste which permeated into all hollow parts of the organism and set to become rock (MacCurdy, v. 1, p. 297, F, 79, v.).

Leonardo observed regularly stratified beds of shells in the mountains around Parma and Piacenza as a result of his surveys for hydraulic engineering projects and his studies of rivers (MacCurdy, v. 1, p. 320, Leic., 9, v.). In formulating an explanation of the altitude of marine fossils he was able to draw on the work of Herodotus, Eratosthenes, Strabo, Ovid, and, above all, Albert of Saxony, to whom reference is made in his notes. Albert and his teacher, Jean Buridan, had already propounded a theory in which the uplift of mountains compensated for slow alterations in the 'balance' of the Earth, caused by erosion and reactions to the differential supply of solar heat (Zubov, 1968, p. 237). Perfect balance would be achieved when the center of gravity *(centrum gravitatis)* coincided with the geometric center (*centrum magnitudis*), an idea taken up by Leonardo when he envisioned the Earth becoming a perfect sphere after the excess of erosion. Leonardo modified the earlier theory to state that uplift occurred when the center of the various masses at the Earth's surface converged upon the "common" or elemental center, the mean center of all terrestrial phenomena (Brizio, 1954, p. 286). Like his two predescessors, Leonardo must have cut a solitary figure in propounding a theory of slow uplift.

Even 250 years after Leonardo developed these theories the Deluge and the confinement of earth history to a mere 7000 years was strongly upheld by influential thinkers. Leonardo's heresy was a result of his profound materialism and, specifically, of his deep meditations on the meaning of time (Zubov, 1968, chap. 6). He was unable to adduce from the evidence of his eyes a theory that would support the Deluge. Fortuitously, the theory of slow uplift did not support the Deluge: universal rain would have led to the planar equilibrium of the Earth's surface, rather than the high mountain beaches evinced from the fossil record. In the Codex Hammer, of uncertain date, the tenets of the Biblical story of earth origins are considered in the light of the spatial and altimetric distribution of fossils and salt deposits, the mechanics of sediment transport (with reference to the proverbial 40 days), the arrangement of fossils in beds and their possible genitive processes, and, encouragingly, the observable workings of the hydrological cycle. The Biblical story was found to be at variance with all these phenomena.

Initially, Leonardo theorized that if the Deluge had risen to several *braccia* above the highest mountain the excess water must have "evaporated into the sun" (MacCurdy, 1928, p. 217). But as this theory ran counter to all his more homely observations of terrestrial processes, especially those on the fall of water under the influence of gravity, he abandoned it and there is no clear evidence that he ever revoked his subsequent heresy[8]. The following passage illustrates the clarity of his reasoning and its basis of mechanics, hydraulics and sedimentology:

> "I hold that the Deluge would not be able to carry up into the mountains objects native to the sea unless the sea had become so swollen as to form a flood so great that it even mounted above the height of these same places, and this process could not have occurred because it would have created a vacuum; and if you should say that the air would rush in there we have already concluded that what is heavy cannot be supported on what is light wherefore we conclude of necessity that this Deluge was caused by rain water; and if this was the case all this water flowed into the sea and the sea does not flow up the mountains; and if it ran into the sea it pushed the shells along the shore into the sea and did not draw them to itself. And if you should say that because the sea was raised by rain water it carried these shells to such a height, we have already stated that things heavier than water cannot float upon its surface but remain at the bottom and

[8] According to another of Leonardo's early arguments: "From the two lines of shells [observed in a bed of fossils] one must needs suppose that the earth in distain plunged beneath the sea and so formed the first layer and that the flood afterwards formed the second" (MacCurdy, 1956, v. 1, p. 310, B.M., 156, v.).

are not moved from there unless by pressure from the waves. And if you were to say that it was the waves which carried them to these high places we have proved that the waves when of great depth move in an opposite direction at their base to the movement above, this being shown by the turbidity of the sea arising from the soil that has been washed away near its shores" (MacCurdy, v. 1, p. 318, Leic., 9, v.).

His theory of isostasy was enriched by a sound knowledge of the formation of sedimentary rocks, probably based on local observations of the Calabrian marine stratigraphy (Ruggieri and Sprovieri, 1977) and of flysch deposits (Baldacci and others, 1967):

"The stratified rocks are created in the vast depths of the seas because the mud which the storms detach from the sea coasts is carried out to the deep sea by the recoil of the waves; and after these storms it is deposited on the bottom of the sea, and as no storm can penetrate the sea on account of the great distance that is below the surface it lies there motionless and becomes petrified; and sometimes it remains in the form of white clay which serves for making pots; and thus with blocks set at different angles it is made up of layers of as many different thicknesses as are the differences in the storms whether greater or less" (MacCurdy, 1956, v. 1, p. 334, Leic., 35, r.).

He was able to show that stratified rocks, as well as fossils, could not be formed by the fluvial processes of the Deluge. However, his strict adherence to the principle of uniformitarianism gave him a simplified view of the balance between erosion and isostatic adjustment that could not accommodate discontinuous behavior or volcanism, which he largely ignored. This belief has been described as 'neptunian' because of its emphasis on uniform fluvial erosion (Sacco, 1938), and when Leonardo observed contortions of strata the only plausible explanation was unfortunately a gravitational rather than an endogenous one, invoking "gigantic collapses of the earth into itself." He did, however, observe that fossils occurring in the vicinity of Verona differ in type among four levels of deposition (Sacco, 1938, p. 466).

Zubov (1968, p. 223) praised Leonardo's "ability to make objects of the distant past seem 'close to the eye,' to illustrate them with the light of thought". It is indeed remarkable that Leonardo managed to push back the recesses of time at a moment in history overshadowed by the narrow philosophies of diluvialism and imminent apocalypse. His uniformitarian beliefs were established at the beginning of a period in which, as Engels observed, the "absolute immutability of nature" became a prominent axiom. According to such a philosophy the Earth could not be seen to have evolved; however, within the sweep of the terrestrial pendulum, the periods of uplift and land sculpture, Leonardo was able to construct a denudation chronology for several Alpine[9] and Mediterranean landscapes[10], including the Val d'Arno. In this he was

[9] Leonardo also clearly identified the scene of river capture in certain glaciated areas.

[10] Spurred both by diluvialism and by his work on sea currents to consider the Mediterranean basin *per se* and its connection with the supposed Flood, Leonardo ranged over the origins of the Nile floodplain, the Straits of Gador (Gibraltar), and parts of central North Africa. It is salutary to reflect that he did not confuse flooding of the Mediterranean basin with the Deluge.

motivated by the desire to use paleontological evidence to refute the Deluge.

The geological history of the Val d'Arno is now known to be complex, involving several phases of marine transgression and regression and of orogeny. Apart from several areas of metamorphic rocks, the origins of its deposits have been greatly debated. Those authors who believe that the majority of the deposits are allocthonous and due to Alpine orogeny (the *faldisti,* Rapetti, 1971) have been opposed by those who consider the heterogeneous deposits of the 'Tuscan' series to be autochthonous (Merla, 1951). The genesis of the lake basins of the central northern Appennines has been variously ascribed to tectonic movements before, during, and after the main Tertiary orogenic phase (Principi, 1926; Giannini and Pedreschi, 1949). Five subdivisions have been proposed for the fluvio-lacustrine structure of the Arno basin, including the Lake of Florence, which was filled by water left during a phase of regression of the sea and subsequently inundated by alluvium during the Quaternary.

A description in the Codex Hammer (MacCurdy, 1956, v. 1, p. 316-318, Leic., 9, r.) shows that Leonardo identified a lake basin bounded by Monte Albano and Serravalle and containing the sites of Florence, Prato, and Pistoia. He believed a further lake basin to have extended upstream to the site of Arezzo and to have been joined to the flooded basin of the Chiana, ending near Perugia, which to this day contains the swampy Lago di Trasimeno. Leonardo observed palaeochannels in the Quaternary alluvium northwest of Arezzo and noted that the sediments were fluvial rather than marine. On observing the beds of marine fossils high on the promontory of San Miniato he suggested that they were laid down under fairly stable conditions of high sealevel rather than during the Deluge or through some other tortuous and catastrophic fluvial action. He therefore cogently argued that the sea had fallen in level after depositing the fossils, and by observing shells in different places at different levels, he unwittingly recognized that movements of the sea must have occurred in stages or episodes.

LEONARDO'S IMPACT ON FLUVIAL GEOMORPHOLOGY

> "Fuggi quello studio del quale la resultante opera more insieme coll'operante d'essa".[11]

It may appear that many of Leonardo's discoveries in the field of fluvial geomorphology were less original than they at first seem. He has been labelled a mere follower of the fourteenth century scholar Albert of Saxony, and his most original and fortuitous discoveries might be termed coincidences. But it has been shown above that he based his deductions on careful experiment and observation (for instance, he was evidently capable of distinguishing between fluvial and marine sediments) and that he rarely accepted literary sources without attempting to verify them personally.

[11] "Avoid those studies of which the result dies with the worker" (Leonardo).

Leonardo's studies of hydrodynamics and hydrostatics were partially replicated by Girolamo Fracastoro (1478-1553), partially rediscovered by Benedetto Castelli (about 1577-1644) and partially improved upon by Evangelista Torricelli (1608-1647). His work as a hydraulic engineer was overshadowed by the works of Geminiano Montanari (1633-1687) and later by those of Vittorio Fossombroni (1754-1844) and Pietro Paleocapa (1788-1869). Using Copernican theories on gravity the problem of free-fall was better solved and therefore the basis of mechanics and hydrodynamics was better established by Galileo. Consequently, Giovanni Domenico Guglielmini (1669-1710) in his seminal work *de Fluminum Natura* was able to replicate many of the observational studies of Leonardo whilst achieving greater success in the description of continuity, velocity, and the hydrological cycle.

Castelli (1660) was particularly close to Leonardo in approach. His work on irrigation, water supply, land reclamation *(bonificazione)*, and public hygiene was as all-embracing as Leonardo's. His work on the engineering hydraulics of the Bologna canal is comparable with Leonardo's canalization projects, and it is instructive to compare his studies of channel confluences and stream braiding with those of Leonardo. However, his exposition of the $Q = vA$ relationship in open channels (Castelli, 1660, p. 82-83) is clearer than Leonardo's, and he had a more sophisticated understanding of velocity gradients. Like Leonardo he recognized that fluvial studies are a "materia difficile, importantissima e poco maneggiata da altri".

Guglielmini's approach was strictly practical. As with Leonardo's work, observation overshadows but does not exclude experimentation. In *Aquarum Flumen Mensura* (1719, p. 105-236) one can observe the rise of empiricism; there is even a table of velocities relative to various channel slopes. However, Guglielmini's knowledge was sometimes weaker in theory than Leonardo's; for example, he attributed meanders to uncertain gravitational effects acting on the slow-flowing streams of valley bottoms which were "nearer to the centre of the earth's gravity". Charles Vallancey, writing in Dublin in 1763, claimed to have based his treatise on inland navigation on the work of Guglielmini, Castelli, and others, but his simplistic and unperceptive treatment of the principles of river flow compares poorly with Leonardo's work more than 200 years previously.

Although it is clear from his notes that Leonardo engaged in scholarly debate (MacCurdy, 1956, v. 1, p. 310 B.M. r.), there would appear to be a marked absence of references to his work in subsequent studies of fluvial activity (for example, as summarized in Fossombroni, 1823). His manuscripts, which were in any case often hard to decipher, remained scattered and sometimes badly neglected for more than 300 yrs after his death.

Whilst we may conclude that his subsequent influence was small, Leonardo's broad and perceptive insights into geomorphology and his use of a surprisingly modern experimental method are not to be forgotten. Given that he made valuable studies of so many natural phenomena, further consideration of his work leads to a greater perspective on how present-day knowledge of geomorphology came about. At a time when the complexity of landforms is at last being studied in detail Leonardo's ability to generalize, to construct theory, and to renew his philosophical knowledge without losing sight of observational details is exemplary.

The work of many of his contemporaries and successors, who studied fluvial activity from a purely theoretical or an exclusively pragmatic viewpoint, has been forgotten. But Leonardo gave equal weight to both theoretical and applied studies, and the sense of balance he thus achieved has made his contribution to geomorphology more lasting. The heresy of his observations on fossils, raised beaches, isostasy, and erosional history condemned them to a period of obscurity that has undoubtably retarded progress in the earth sciences, and one can only hope that inspired heretics will not suffer an equally unjust fate in the future.

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