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RELATION OF LANDSLIDES AND GLACIAL DEPOSITS TO RESERVOIR SITES

IN THE

SAN JUAN MOUNTAINS, COLORADO

BY

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RELATION OF LANDSLIDES AND GLACIAL DEPOSITS TO RESERVOIR SITES IN THE SAN JUAN MOUNTAINS, COLORADO.

By Wallace W. Atwood.

INTRODUCTION.

With the increase in farming on the lowlands bordering the San Juan Mountains, Colo., and on the broader valley floors within the range, there has come a demand for a large supply of water to be used for irrigation. This demand has been particularly urgent on the east side of the range, among the farmers and ranchmen of the San Luis Valley. Numerous reservoirs have been planned in which the waters from the melting snows and the surplus floods from heavy rains may be stored, to be later released as needed during the growing season.

Most of the reservoir projects are associated with the great glaciated canyons of the range or with lake basins in which the waters have been artificially raised. In some of them the selection of the reservoir site has apparently been determined by the occurrence of a narrow gorge or constricted portion in the canyon, downstream from a broad, open, parklike portion. In many of these mountain valleys, however, the narrow portions have been formed by the deposition of large masses of loose material, either of landslide or of glacial origin, and such materials have not proved to be watertight. Most of the lakes in the mountains are also held back by glacial or landslide deposits. In many of the projects a perfectly good watertight dam has been constructed, but serious leakages have occurred, the waters finding a way underneath or around one end, or even both ends, of the dam. For these reasons, some projects appear to have been abandoned, and others are continued with heavy expenses for repairs. On one reservoir large additional construction has been undertaken to prevent disastrous leakage through a glacial moraine and the threatened loss of the entire amount of capital invested. Nevertheless, other reservoirs are being planned in places where just such loose materials border the sites of the proposed dams.

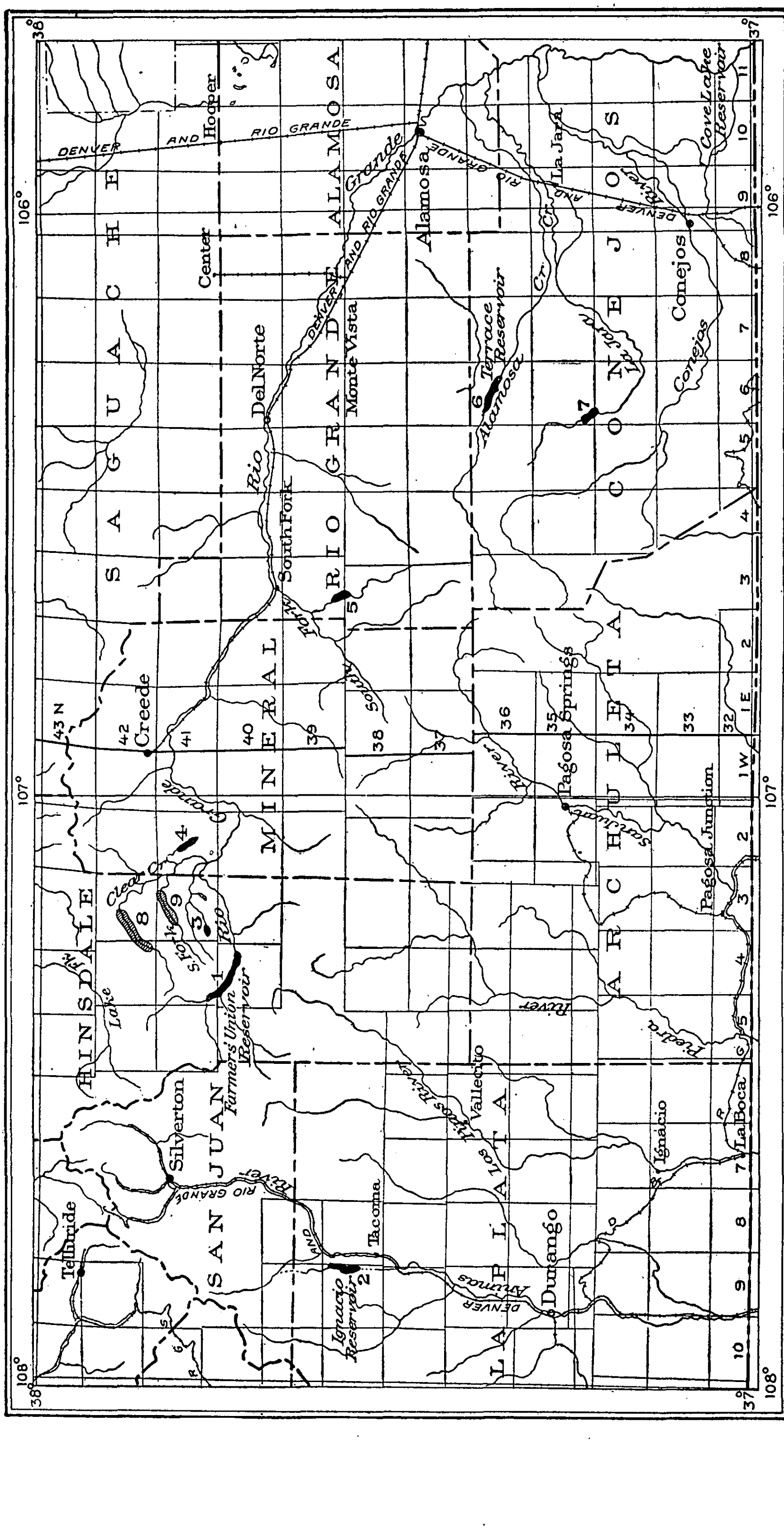


FIGURE 1.—Index map showing location and drainage features of reservoir projects in the San Juan Mountains. 1, Farmers' Union or Rio Grande reservoir; 2, Ignacio reservoir; 3, Road Canyon reservoir; 4, Santa Maria reservoir; 5, Mosca reservoir or Beaver Creek project; 6, Terrace reservoir; 7, La Jara reservoir; 8, proposed reservoir site on Clear Creek; 9, proposed reservoir site on South Fork of Clear Creek. Scale about 17½ miles to an inch.

Inasmuch as experience has shown that many landslide masses and certain of the glacial deposits are not able to withstand the pressure of a high head of water without serious leakage, it seems desirable to publish a description of the mountain canyons and the deposits commonly found in them and of the geologic conditions associated with the lakes in the mountains; so that, in the future, no expensive errors need be due to a failure to recognize the geologic formations bordering a proposed reservoir site.

LOCATION.

The San Juan Mountains are in the southwestern part of Colorado. (See fig. 1.) The loftier summits in the range rise to elevations of over 1,400 feet, and the highest peak, known as Uncompahgre, has an elevation of 14,306 feet. Much of the range is above 10,000 feet in elevation. To the west the bordering lower lands form the Colorado Plateau, whose elevation is between 7,000 and 8,000 feet above the sea. The Uncompahgre Plateau lies at the northwest and ranges in elevation from 9,000 feet near the mountains to 8,000 feet, and at a still greater distance from the mountains, to 7,000 feet above sea level. North of the range, in the vicinity of Montrose, in the great valley of the Uncompahgre River, there is an area at about 5,000 feet, but just east of this area is another plateau district connecting the San Juan Mountains with the West Elk Mountains, and into that plateau the Black Canyon of the Gunnison has been cut. To the east is the broad San Luis Valley, with a general elevation of about 7,500 feet, and on the south the plateau and mesa country of northern New Mexico.

PHYSICAL GEOGRAPHY.

PHYSIOGRAPHIC EVOLUTION OF THE REGION.

The San Juan district has passed through a remarkable geologic history. The earlier chapters of that history need not be reviewed here,[1] but the later chapters, which cover an interpretation of the present topography, should be outlined.

At the end of Cretaceous time the range appeared as a great mountain mass—a huge dome. (See fig. 2.) Rivers went to work upon that uplifted land and carved out the early Tertiary San Juan Mountains. Alpine glaciers were formed in the basins among those mountains and descended to the neighboring lowlands. In time, through the combined efforts of rivers, glaciers, winds, and all agents of weathering, the mountains were removed and the region was re-

[1] The early geologic history of the range is clearly stated in the Telluride, Silverton, Needle Mountains, and Ouray folios of the Geologic Atlas, published by the United States Geological Survey.

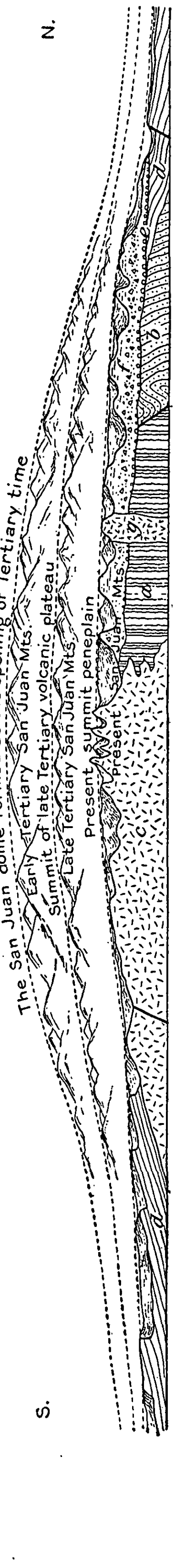


FIGURE 2.—Diagrammatic cross section showing the physiographic evolution of the San Juan region since the beginning of Tertiary time. *a*, Pre-Cambrian schist and gneiss; *b*, Algonkian quartzites; *c*, pre-Cambrian granitic intrusive; *d*, Paleozoic and Mesozoic rocks; *e*, Ridgway till and Telluride conglomerate; *f*, middle and late Tertiary volcanic rocks; *g* Tertiary intrusive rocks.

duced to one of low relief, not far above sea level. Before this work was completed volcanoes had broken out in the range, and by the end of the Oligocene epoch vast amounts of sand and gravel were spread out over the western part of the area.

Next came a second series of violent and extensive volcanic outbursts. From numerous vents fragmental materials were thrown into the air, and lavas were poured out over the surface. Little by little these formations, coming from many centers, built up an extensive volcanic plateau, which, if restored, would rise at least a few thousand feet above the highest summits of the present range. By this time the Pliocene or late Tertiary epoch had been reached.

After the development of the great volcanic plateau the streams again undertook their work of dissection. Another range of mountains was carved out, and once more, after the rivers had worked for a long time, the region was reduced to a lowland not much above sea level. The old surface produced at that time is represented by many of the broad summits and intercanyon ridges of the present range.

Still later the San Juan area was again uplifted. This time the erosion surface that had just been produced was domed. The streams were invigorated by the greater elevation of the mountains and began at once to lower their courses. A long period of stream erosion followed, and associated with it were at least three stages of glaciation, during each of which the mountain canyons were occupied by ice. Through the combined efforts of ice and water the major features of the present topography were developed.

Since the melting away of the last glaciers there has been a renewed and vigorous attack on the mountains by streams and by all those agents which assist in the weathering or disintegration of rocks. Vast quantities of loose material have been taken down the canyon walls. The mountain slopes left too steep to stand when the last ice melted have loosened, and great areas of landslides have been formed. The morainic deposits left by the glaciers contain lake basins, and at many places such deposits have partly filled the valleys and even ponded the streams. In the higher mountains there are places where the ice actually gouged basins out of the solid rock, and in such basins waters have accumulated. Mud flows and torrential fans have also ponded certain of the streams and caused lakes to come into existence. Some lakes have been filled and others have been drained. Broad flood plains have been developed, and by the intrenchment of stream courses below former flood plains many terraces have been left. The range is to-day being actively eroded, and great masses are slipping or sliding from the oversteepened mountain slopes. There are reasons for believing that the range is also being slowly uplifted.

GREAT CANYONS.

The great canyons of the San Juan region head in the central part of the mountain area and lead radially to the bordering plateaus. At their heads and at the heads of the several tributaries to these major canyons there are broad, open semicircular areas where the snows collected during the several glacial stages and formed the alpine glaciers. The vigor of ice action, even at the very beginning of movement, is recorded in these ancient catchment basins or cirques by deep gouging into the solid rock and by grooved, polished, and striated surfaces. The bordering wall of a cirque is usually very steep, in places precipitous, for the work underneath the glacier led to a continual enlargement of the catchment area, so that the intercanyon or intercirque ridges became narrower and narrower, locally even coming to have sharp, jagged, sawtooth forms. During the period of maximum formation of ice the sharp peaks were all that rose above the glaciers and the associated snow fields. The catchment areas as examined to-day range in area from a fraction of a square mile to as much as 15 square miles.

Downstream from the cirques the canyons usually retain an open or U-shaped form, being in sharp contrast to unglaciated canyons, such as the Black Canyon of the Gunnison, at the north margin of the range, and the Toltec gorge, at the southeast, for such stream-eroded canyons are V-shaped. The walls of the great canyons in the range are in places smooth and even polished from ice action. The bold or fantastic rock features which certainly must have existed there before the ice passed through the canyons have been removed, and there is a general simplicity to the canyon walls. On the floors of the canyons it is evident, at many places, that there has been vigorous ice action. Grooved, polished, and striated surfaces are still preserved, and vast deposits of glacial débris are lodged in the lower portions of the valleys.

Many of the tributary canyons terminate several hundred feet above the bottom of the main canyon, so that their waters now tumble or fall into the main gorge. Such hanging valleys were usually occupied by ice, but the deepening work of the tributary glaciers fell far short of that accomplished by the glaciers in the main canyons.

The floors of the glaciated canyons are very irregular and do not have the normal gradients of stream courses, for the work of glacier ice is not controlled by the same laws that control the work of running water. In some places the ice has gouged out holes much below the general gradient; in others rock hills or knobs have been left on the floors of the valleys. The débris left by the ice during its advance and upon its final melting has added numerous details in the topography of the canyon floors and the lower slopes, so that many of the postglacial streams in such canyons flow here on gentle gradients through meadow lands, there over rocky places where cataracts and rapids exist, or through some narrow notch cut in a rock ledge or morainic ridge. Some of the lakes in the canyons are due to these irregularities in the stream bed, either in the solid rock or in the glacial débris. At many places vast quantities of material have slumped into the canyon from one side or the other, or from both sides, so as to block the course of the stream. At a few places muds have formed and come down the canyon slopes, and opposite the mouth of each small tributary stream there is usually a torrential fan. The recognition of these looser deposits is of special significance in the selection of reservoir sites, and each class is described in detail below.

GLACIAL DEPOSITS IN THE CANYONS.

TERMINAL MORAINES.

While a glacier occupies a mountain canyon there is constant movement of the ice down that canyon. The walls and floor of the canyon are scraped bare of loose material. At the margin of the ice in the position of maximum advance excessive melting is taking place and heavy deposits of glacial drift accumulate. Upon the final melting away of the ice this débris is uncovered. Such a deposit, which should normally cross the valley as a curved or crescentic belt or ridge, is known as a terminal moraine. As the ice carries different kinds and amounts of débris in its different portions, the deposit will not be of uniform composition or uniform thickness. As the ice during seasonal variations moves forward or retreats irregularly at its margin, such a deposit will have a very irregular or hummocky surface form. The terminal moraine in many valleys in the San Juan Mountains is a belt that crosses the valley and ranges from a few rods to a mile in width. At either side of the canyon this moraine may blend or connect with a lateral moraine deposited at the side of the valley or on the lower slopes, as the ice melted away.

The recognition of the terminal moraine rests upon (1) its topography, which is rough or hummocky, with knobs and kettles; (2) its composition, for it is a mass of stones and boulders of various dimensions, as much as 10 or 15 feet in diameter, intermingled with gravels, sands, and clays; (3) its structure, for in most cross sections it is apparent that much of the material was not carried and deposited by running water, or deposited in standing water, the greater part of the material being unstratified, though within many such deposits there are pockets of stratified sands and gravels; (4) the subangular shapes of the stones; and (5) the scratches or striae found on many of the stones.

When such a terminal moraine is approached from the downstream side it may appear as a rough or hilly belt, usually well wooded, extending across the valley. The stream may have cut but a narrow notch through the moraine, and rapids or cataracts occur at such places. As seen from the upstream side the terminal moraine is not commonly so conspicuous, for on that side the morainic deposits usually become gradually less and less.

RECESSIONAL MORAINES.

When the ice front remains stationary for a considerable time during the general melting and recession of the glacier morainic deposits accumulate at such marginal positions. Those deposits resemble the terminal moraines very closely in topography, material, and topographic relations, and in being frontal, but they are unlike the terminal moraines in that they do not represent the position of the ice front at its maximum advance. Several such recessional moraines may be lodged in a single valley, and at each moraine the stream course may be somewhat constricted. Upstream from such moraines, as from the terminal moraine, the valley floor may be less heavily mantled with glacial drift and so appear broader or more open. Many recessional moraines serve as natural dams, blocking the drainage and causing lakes. In certain of the valleys among the San Juan Mountains there are chains of lakes caused in this way and connected by small streams. The lowering of outlets has drained many lakes that existed for a time after the melting of the ice, and those lake basins now appear as meadows or swampy lands in the course of the stream. Thus the mountain stream may flow for some distance through a meadow where it has a low gradient and meander there much as rivers of extreme old age wind about in their flood plains. Where such a stream leaves the old lake bottom and crosses the moraine it may have to flow through a narrow gorge, and with falls and rapids in its course it may literally tumble down to the level of the next meadow, again to meander through an old lake bottom and tumble to a still lower level, and so on, until the glaciated portion of the canyon is passed. The constricted courses of the streams just below such lake-bottom meadows have often been selected as dam sites, and the former lake basins as the sites for reservoirs.

LATERAL MORAINES.

When a valley glacier is in place vast quantities of material loosened by weathering, rain work, or streams are carried down the mountain slope and deposited as ridges on the ice but near its margins. Such ridges of débris are lateral moraines, and on the final melting of the ice they come to rest at the sides of the valley. They commonly connect at the downstream end with the terminal moraine or with one of the recessional moraines. Upstream they become less and less prominent and die out before the catchment basin is reached.

The lateral moraine commonly resembles a ridge. Its upper surface may have so low a gradient as to suggest an old railroad grade on the canyon wall. There may be a depression between the lateral moraine and the mountain slope, and locally small lakes are held in such depressions. Where a lateral moraine crosses the mouth of a tributary stream ponding may follow and a small lake thus come into existence. Such lakes have commonly overflowed, their outlets have been lowered, and to-day the formerly ponded tributary streams flow through meadows occupying the sites of the former lakes, then cross the lateral moraines, and come into the main valleys.

The position of the lateral moraine on the valley wall represents the minimum elevation of the ice that occupied the main canyon. The ice was certainly somewhat greater in thickness than the elevation of the lateral moraine above the stream channel, for the material of such a moraine is let down perhaps 100 or 200 feet during the melting of the ice before it becomes lodged on the slope.

At some places in these mountain canyons the walls are too steep to permit the lodgment of such lateral deposits, and the material that would otherwise have formed a lateral moraine comes to rest on the floor of the valley. There it does not have a distinct ridgelike form but is mingled with the general mantle of ground moraine left on the final melting of the ice.

In composition and structure the lateral moraines resemble the terminal and recessional moraines, but they do not contain pockets of stratified materials such as are common in the frontal moraines. The stones in the lateral moraines are more commonly angular than those that were carried near the base of the glacier.

MEDIAL MORAINES.

When a tributary glacier unites with ice in the main canyon the lateral moraine on the upstream side of the tributary glacier joins the lateral moraine of the main glacier and forms a medial moraine. Material so accumulated rests upon the surface of the glacier, but on the final melting of the ice it is deposited on the floor of the canyon. Here and there a distinct medial-moraine ridge now exists on the floor of a glaciated valley. It would seem that as the material of the medial moraine was gradually let down during the melting of the ice, it became distributed or dispersed, and so became a part of a general mantle of drift on the floor of the valley. Short medial-moraine ridges may be present at the junction of a tributary with the main valley.

OUTWASH DEPOSITS.

Downstream from the terminal and recessional moraines vast quantities of sand and gravel are carried out by the waters that come from the melting ice. These sands and gravels load the streams to their utmost capacity and thus commonly lead to the aggradation or building up of the floors of the valleys beyond the position of the ice front. Such outwash deposits are called valley trains. They extend from a few miles to as much as 20 or 30 miles below the terminal moraine. When the glaciers finally melted away and the streams became clearer, having less débris to carry, their velocities were increased and they were able to lower their courses through these loose deposits of sand and gravel. Possibly an uplift of the range helped to quicken their velocities. Thus the stream channels are to-day intrenched below the old flood-plain levels of glacial time, and the remnants of the old flood-plains appear as terraces or benches as much as 100 feet above the present streams. At each stage of the retreat of the ice vast quantities of silts were washed out beyond the ice front, so that bodies of stratified sand and gravel may be found at several localities in the valley, but usually they lie just below the frontal moraines.

DEPOSITS OF DISTINCT GLACIAL EPOCHS.

In the San Juan region proof has been obtained of at least three distinct glacial stages during the last long period of erosion.[1] In the earliest of these, which is called the Cerro stage,[2] the glaciation was the most extensive, and the moraines of this stage have been largely removed. A few scattered remnants, all of which are above or outside of the modern canyons, have been found at several places about the margin of the range.

The glaciers of the intermediate stage, known as the Durango, were intermediate in extent, but they occupied the modern canyons, and their moraines are farther down those canyons and higher on the slopes than those of the last stage. The Durango glaciers were as a rule from 2 to 5 miles longer than the glaciers of the last or Wisconsin stage. Most of the terminal moraines of the Durango glaciers have been removed by subsequent erosion. The lateral moraines remain, and at many places the outwash deposits of that stage may be identified.

The glacial deposits which are of immediate significance in the present discussion are those of the last or Wisconsin glacial stage, which have been described above in detail.

LANDSLIDE DEPOSITS.

When the last glaciers disappeared from the San Juan Mountains the canyon walls were at many places so steep that as weathering and disintegration of the rocks progressed vast quantities of the material slumped off and slid to the bases of the cliffs. The geologic conditions at many places are especially favorable for the development of landslides. Loose or soft formations underlie heavy flows of lava, and as the less resistant formations are weathered out, the heavy load above is undermined, breaks off, and pushes a great mass of the fine material with it down the slope. Again the volcanic rocks become very thoroughly weathered or disintegrated, and such a mass when saturated from heavy rains or from the melting of snow may move or slide down the mountain. Where there is a somewhat impervious layer overlain by loose materials the ground waters collect just above the impervious layer. Such waters may issue as springs at the base of the loose material, but they also serve as a lubricant and hasten the movement of great masses of the overlying rock down the hill. Thus the cliff is forced back and may retreat for

[1] Atwood, W. W., and Mather, K. F., The evidence of three distinct glacial epochs in the Pleistocene history of the San Juan Mountains, Colo.: Jour. Geology, vol. 20, pp. 385–409, 1912.

[2] Atwood, W. W., Eocene glacial deposits of southwestern Colorado: U. S. Geol. Survey Prof. Paper 95, pp. 14–15, 1915.

many hundreds of feet. At some localities this process has continued until the cliff is a large fraction of a mile back of its former position.

The landslide masses as they accumulate have an exceedingly rough topography. This topography may resemble somewhat that of a glacial moraine, but in contrast to the moraine the individual landslide mass commonly has one longer axis, which makes it ridgelike, and the longer axis or crest of the ridge will be approximately parallel to the cliff from which the mass slid. The landslide materials differ from the glacial deposits in that they are angular, and the individual stones do not have polished and striated surfaces such as are present on the stones of the glacial drift. The landslide masses do not contain so large a variety of stones as the glacial deposits, for their materials must come from the few formations represented in the cliffs above them. The landslide masses are also of smaller extent than the glacial deposits, and the cliffs from which they have come are usually to be seen. There is no assortment of the material in the landslide masses, and in that respect they resemble the deposits left by the melting ice.

Among the landslide masses there are small undrained depressions, and in such depressions lakes may form. Thus the presence of lakes or ponds in the loose deposits of the mountains is not a proof of glacial origin for those deposits. At some places landslide masses check drainage lines and pond the streams, so that lakes have come into existence. Landslides may come from the opposite sides of a mountain canyon and meet on the floor, or they may come with so great velocity from one wall of a canyon that they cross the stream course and ride several hundred feet up the farther slope.

The accumulation of loose angular material at the base of a cliff in the upper portions of a canyon, especially in the great catchment areas, is spoken of as talus. The individual blocks have fallen a few at a time. Locally in these basins, and in a few places farther down the canyons, huge masses of talus material have ridden out or flowed out from the cliffs, and as this process is continued, one mass after another following the same track down the mountain slope, land forms are produced that resemble great mud flows, but they are composed of angular talus blocks. Such deposits have been described as rock streams[1] and are sometimes called rock glaciers, the term implying that the mass was frozen and moved as a glacier, although it was heavily loaded with the angular fragments of rock waste. The significance of the landslide and talus accumulations is referred to in the descriptions of special reservoir sites.

[1] Howe, Ernest, Landslides in the San Juan Mountains, Colo.: U. S. Geol. Survey Prof. Paper 67, 1909.

LAKES AMONG THE MOUNTAINS.

By far the greater number of the lakes in the San Juan Mountains are due in one way or another to glaciation. High among the mountains, where ice erosion was intense, small basins were gouged out of the solid rock, and in those basins waters have accumulated. In the valleys below the basins, where deposition predominated over glacial erosion, the deposits of drift have been so irregularly lodged on the floors of the canyons that many undrained areas were left, and in those undrained areas waters from subsequent rainfall have formed small lakes or ponds. In the terminal and recessional moraines the depressions are relatively small, being sometimes appropriately described as "kettle holes," and many of them contain water. Upstream from the great recessional moraines the waters are sometimes held on the floor of the valley awaiting overflow and discharge. In the tributary valleys there are examples of lakes held in by the lateral moraine of the main canyon glacier. Such a lake may in time rise until it overflows, and in cutting its outlet through the lateral-moraine dam it may soon lower its water even to the point of extinction. In a few places lateral moraines retain waters against the mountain slopes, and occasionally a lake may come into existence where two lateral moraines from adjoining canyons meet to form a medial moraine in a small triangular space just above the junction of the lateral moraines. The blocking of drainage by landslides, as has been suggested above, accounts for some of the lakes in the range, such as Emerald Lake, in the valley of Pine Creek, and Lake Santa Maria. Mud flows may be of such dimensions as to block drainage. One of the most remarkable lakes in the range is caused by a mud flow coming across the canyon of the Lake Fork of the Gunnison about 4 miles above Lake City. The ponding of the waters by this mud flow explains the presence of Lake San Cristobal. Glacial deposits and landslides, or other combinations of the loose deposits so commonly found in the mountain canyons, may form undrained depressions. Many of the lakes among the mountains invite investigation by those looking for reservoirs. The outlets may be narrow V-shaped canyons, and the retaining walls may appear high enough so that, if the outlet is blocked, a large supply of water may be readily stored, but the geologic conditions of the areas bordering the present lakes, and especially above their present high-water mark, are of great significance in the selection of reservoir sites.

TORRENTIAL DEPOSITS IN THE LARGE CANYONS.

In addition to the glacial, landslide, and mud-flow deposits in the canyons there are great fanlike accumulations opposite the mouths of tributary streams. The side stream usually comes over a very steep gradient and brings large quantities of fragmental material or stones, which have been somewhat rounded, and when the gradient is decreased as the tributary reaches the main valley it must deposit its load. The heavier material is dropped first, the stream separates into several distributaries, and more and more of the load is dropped, until in the small streams that result from the continual division of the waters the fine sands and silts are laid down. Such an accumulation has its apex at the mouth of the tributary gorge and slopes radially for nearly 180° from that point toward the bottom of the valley, so that it comes to have a fanlike form. Deposits of this kind from the two sides of the canyon may meet, or a single fan may advance to the farther wall of the canyon, and thus the stream course will be blocked and a lake will come into existence.

STREAM COURSES IN THE LARGER VALLEYS.

The actual channel which the stream follows through a canyon that has been glaciated and affected by landslides, mud flows, and torrential deposits is extremely varied. In places, more commonly in the upper portion of the course, the channel lies on bedrock. Falls and rapids occur where the ice has left a cliff or a very steep slope on the floor of the canyon. Again the stream is diverted to one side or the other because of some huge mass of loose material. The stream course may pass through an old lake bottom or wind in and out among the heavy deposits of a recessional or terminal moraine. Here and there the stream has a meandering course above torrential deposits, or perhaps it has been forced to cut into solid rock far to one side of the canyon by the alluvial fan deposit of a tributary stream. Throughout its course it is usually vigorous. Certain streams have rock walls on one side and at first glance may appear to be cutting into solid rock, but the opposite wall consists of loose material of glacial or landslide origin, and after waters are ponded by a dam at such a location the ponded waters may find easy passage through the loose materials. What appears to be a firm rock gorge has in fact but one wall of firm rock. Or a stream may be in a rock gorge far to one side of a valley, and the preglacial channel may be much lower and in the middle of the valley but filled with débris. The conditions are so variable and the number of possible combinations of the factors that have influenced the location of the stream is so great that the selection of a site for the dam for a reservoir requires a careful examination of the canyon for some distance up and down stream from the proposed site, and a full appreciation of the geologic conditions across the entire width of the canyon just below the reservoir.

The streams of the San Juan Mountains are all youthful. Even after the great deepening accomplished during the three stages of Pleistocene glaciation the streams are lowering their courses. It appears that the mountains are still growing, and the base-level to which the streams are deepening their courses is being lowered in the great mountain mass.

RESERVOIRS.

FARMERS' UNION OR RIO GRANDE RESERVOIR.

The headwaters of the Rio Grande are in the central portion of the range, where the relief is very great and the combined rainfall

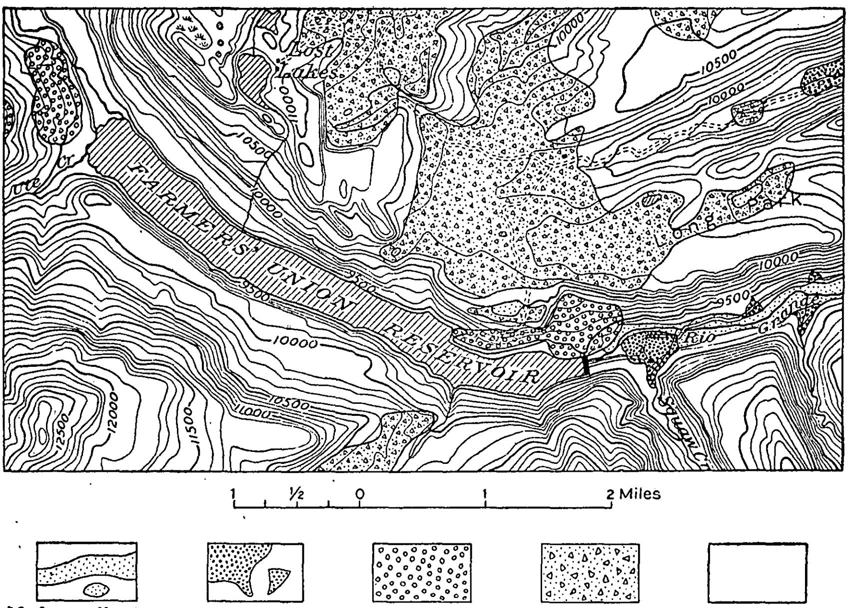
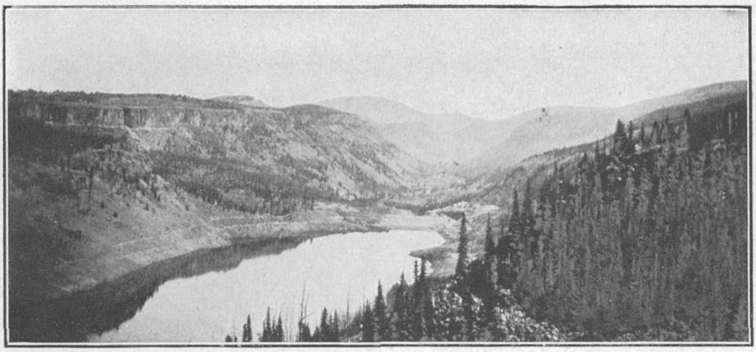


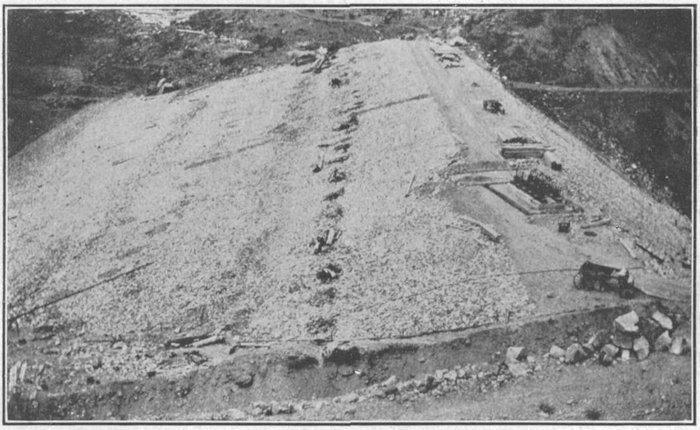
FIGURE 3.—Map of a part of the San Cristobal quadrangle, showing the location and topographic relations of the Farmers' Union or Rio Grande reservoir and the distribution of the loose or unconsolidated formations within the area shown.

and snowfall are so large that each of the streams contributing to this large trunk channel is a vigorous mountain torrent. The portion of the valley that was selected as a reservoir site (Pl. I, *A*) is in the central part of the San Cristobal quadrangle and extends from the mouth of Ute Creek 7 miles downstream to a point near the mouth of Big Squaw Creek (fig. 3). This portion of the valley of the Rio Grande is south of Lost Lakes and Long Park. The reservoir site may be reached by road most readily from Creede, about 33 miles away.



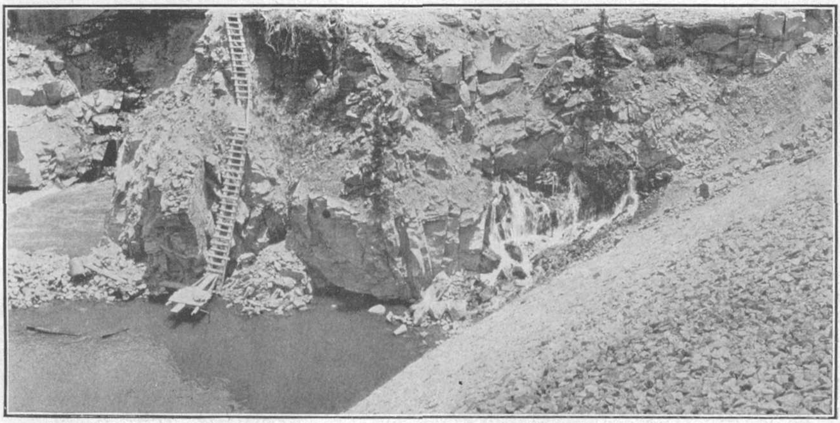
A. FARMERS' UNION RESERVOIR, LOOKING DOWN THE VALLEY OF THE RIO GRANDE FROM A POINT ON THE WEMINUCHE TRAIL.

View showing the location of the dam and the great landslide area to the north.



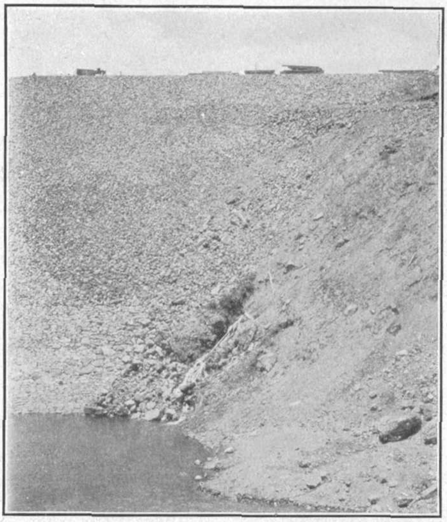
B. DAM OF THE FARMERS' UNION RESERVOIR FROM THE SOUTH.

The spillway appears in the foreground, and the reservoir is to the left. Control gates are near the roadway on the crest of the dam.



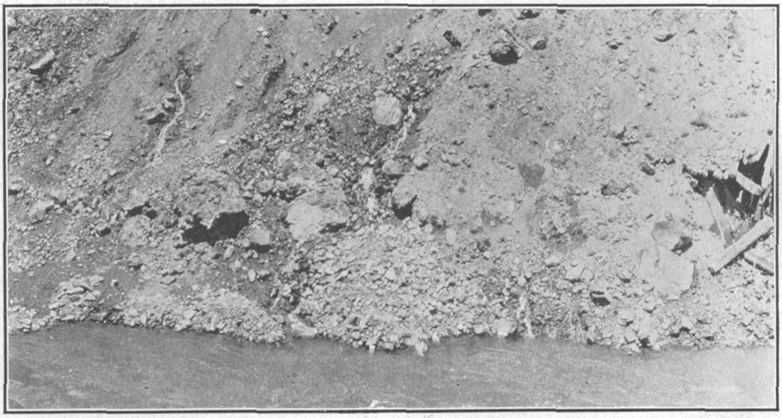
C. SOUTH MARGIN OF THE DAM ON THE DOWNSTREAM SIDE, SHOWING LEAKAGE AROUND THE SOUTH END OF THE DAM.

This leakage is through fractured rock. The tunnel opening is near the left margin of the view.



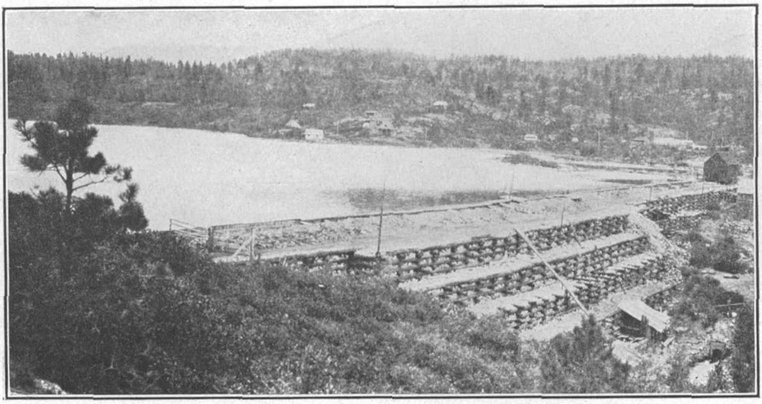
A. NORTH MARGIN OF THE FARMERS' UNION DAM FROM DOWNSTREAM SIDE.

The landslide mass appears at the right, and near the edge of the dam seepage is shown.



B. SEEPAGE THROUGH THE LANDSLIDE MASS JUST BELOW THE FARMERS' UNION DAM.

At the right is the opening of a prospect tunnel.



C. IGNACIO RESERVOIR AND DAM.

The floor of the valley where the waters have been stored was formerly a broad stretch of meadowland. Much of that land had been taken up by ranchmen, who had established their homes. The site of the dam was a narrow place in the stream course just below the broad flat-bottomed portion of the valley. The constriction where the dam has been placed is due to a large landslide area associated with the neighboring cliff at the north. (See fig. 4.) In this cliff there is a thick, heavy flow of lava over a volcanic tuff or breccia. Such conditions are very favorable for landslides and have caused similar accumulations at many places in the range.

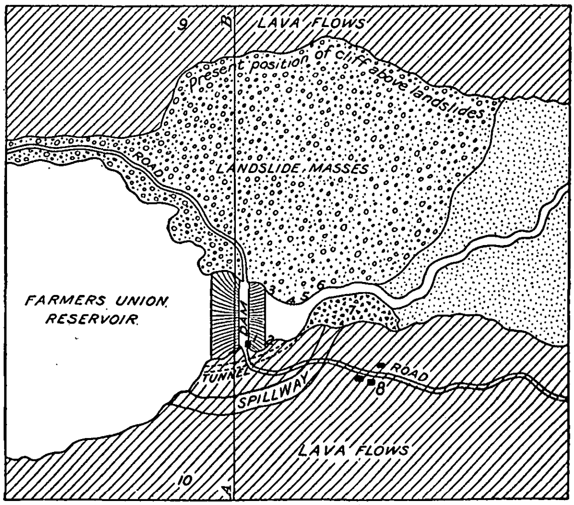


FIGURE 4.—Sketch map showing the geologic conditions immediately adjoining the dam of the Farmers' Union reservoir. 1, Control gates; 2, lower opening of tunnel; 3, 4, 5, 6, places where seepage flows have been noted; 7, angular débris opposite lower end of spillway; 8, construction camp; 9, 10, canyon walls; *A–B*, position of cross section shown in figure 5.

The dam is built of earth and rock and contains a concrete core wall. (See Pl. I, *B*.) It is about 100 feet high and 400 feet wide and appears to be watertight. The tunnel and spillway (fig. 5) are near the south side of the valley and are cut through rock, which is in place, though somewhat fractured. The level of the spillway permits waters to accumulate in the reservoir to a height of 85 feet just above the dam, and with that height of water there would be a reservoir 7 miles in length and from a quarter to half a mile in width. The capacity of the reservoir has been estimated at 4,500 acre-feet.

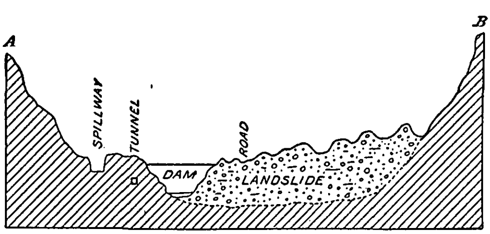


FIGURE 5.—Cross section along the line *A–B* on figure 4. The diagonal lining simply indicates the extent of the consolidated rock formations, which lie nearly horizontal.

Before constructing the dam some prospecting was done by tunneling into the great landslide mass at the north side of the stream course. Bedrock was not found, and it could not have been expected unless the tunneling had gone perhaps a quarter of a mile, so as to reach the north wall of the canyon. (See fig. 5.)

This reservoir has proved to be very serviceable, and the waters are furnished to ranchmen and farmers in the San Luis Valley. Some difficulty has been encountered, however, for the waters have seeped through the landslide mass around the north end of the dam, and have come out into the stream a short distance below the dam. (See fig. 4.) There is one locality where seepage is noticeable from the dampness of the ground, and one other very near the dam (3, fig. 4) where, during September, 1915, there was some water flowing. These indications of seepage were present at a time when the water in the reservoir was very low. In June, 1916, when the waters stood much higher in the reservoir than during the preceding fall and yet far below the maximum possible height, the seepage at both the north and south ends of the dam was notably free. At the south the waters came through the much fractured rock near the lower tunnel opening and issued as a cascade 6 to 8 feet wide. (See 2, fig. 4, and Pl. I, *C*.) More of the fractured rock should have been removed before the dam was constructed. At the north side of the dam small streams were issuing at points marked 3, 4, 5, and 6 in figure 4, through the landslide material. (See Pl. II, *A* and *B*.) Between points 4 and 5 the entire bank was saturated, and waters were flowing freely into the stream. At point 5 an old testing tunnel had become the channel of an underground stream which issued here.

The possibility of checking this seepage by cribbing is under consideration, and every effort will be made by those in charge of the project to prevent this leakage from becoming serious or endangering the success of the project. The landslide mass through which the waters seep appears to consist of very coarse material mixed indiscriminately with finer detritus. If a body of landslide material contains sufficient clay to block up the interstitial spaces and thus form an impervious mass, it may be safely used to retain water. Here the waters have evidently passed through an eighth to a quarter of a mile of this material. It is conceivable that as the waters pass through they may carry and deposit clays in just such places as to block up the subterranean routes, but on the other hand there is evidently the danger of waters going through in such volume and with such velocity that the finer materials in the landslide mass may be washed out and the underground routes become larger and larger.

IGNACIO RESERVOIR.[1]

On a high bench west of the canyon of Animas River in the Engineer Mountain quadrangle a large supply of water is held in what

[1] The report on this reservoir is based largely on field work done by Kirtley F. Mather.

is called the Ignacio reservoir (fig. 6). The nearest railroad station is Tacoma, but the reservoir may be easily reached from Durango by road, a distance of about 22 miles. The waters are turned through a great flume into a lesser reservoir near the brink of the canyon wall, and then through a smaller flume down the canyon wall and through a power plant.

The reservoir site is in a country of slight relief and rolling topography, where glacial ice has rubbed off the hilltops and removed

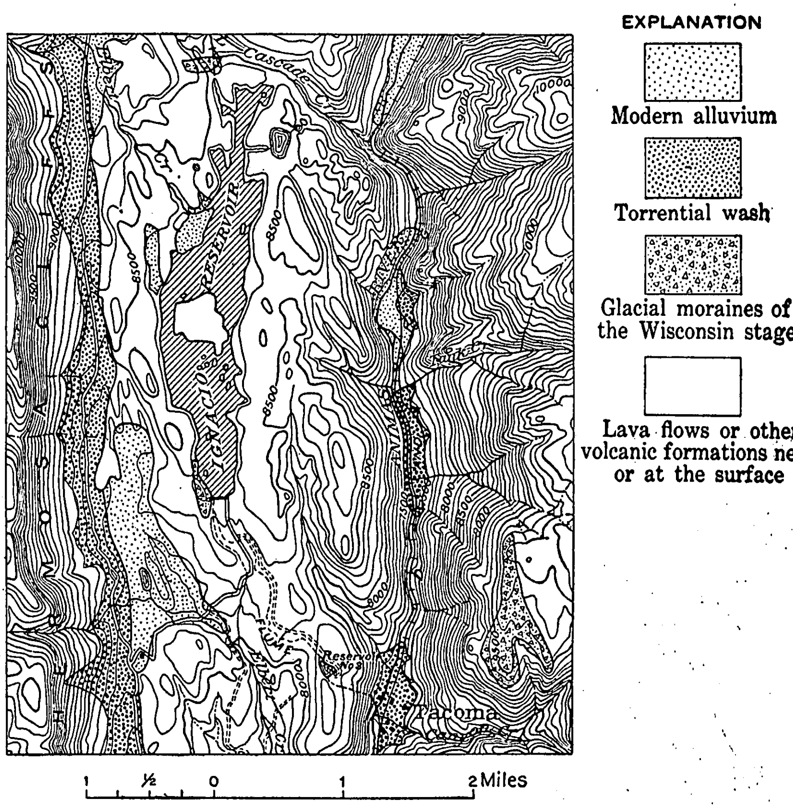


FIGURE 6.—Map of a part of the Engineer Mountain quadrangle, showing the location and topographic relations of the Ignacio reservoir and the distribution of the loose or unconsolidated formations within the area shown. The bench on which the reservoir lies has been severely glaciated, and there is a scattering of glacial drift over most of its surface.

most of the loose material. There is a thin scattering of glacial drift on the bench in the vicinity of the reservoir, and a small area of ground moraine at the west side near the lower end. The area now covered by the waters of the reservoir may have held several small glacial lakes, similar to the ponds and marches on the same bench north and south of the reservoir site.

A dam with a vertical face of about 52 feet in the center was constructed, and several small streams were turned into the basin. The dam is built of log cribbing with rock fill. (See Pl. II, *C*.) It is faced with three thicknesses of planking with tar paper between. Ordinarily this dam will hold from 48 to 50 feet of water. No overflow is allowed, for the waters come into the reservoir through flumes and, when necessary, may easily be diverted. The outlet from the reservoir is through a large pipe in the dam, and thence into a 6-foot concrete tunnel through a morainic hill. The intention may have been to rest this dam upon bedrock throughout its length, but as several serious leakages have occurred beneath the dam it appears that the base of the dam was not at all places below the glacial débris.

The dam was not constructed at so great expense or with so much care as many of the more modern structures, and there is always some leakage. It has been reported that twice in the history of the reservoir large leaks have developed. The timbers are now very badly rotted, and the remaining life of the dam would appear to be relatively short.

ROAD CANYON RESERVOIR.

A short distance above the junction of Road Canyon with the canyon of Crooked Creek, in the central part of the San Cristobal quadrangle, there is a small reservoir (fig. 7). The valley has a broad, open, flat-bottomed area immediately upstream from a few morainic hills, and it was conceived by persons who wished an extra supply of water that a small dam thrown across the valley at these morainic hills would make it possible to store water. The dam is a mere embankment of earth and stone, of very simple construction, and though it is leaking badly not very much has been invested in it nor very much expected from it. The reservoir is now used as a fish pond. It illustrates the use of a recessional moraine and the meadowland, probably a former lake basin, just upstream from the moraine.

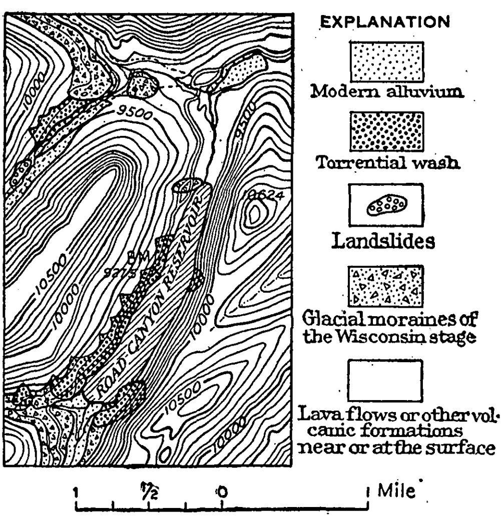


FIGURE 7.—Map of a part of the San Cristobal quadrangle, showing the location and topographic relations of the Road Canyon reservoir and the distribution of the loose or unconsolidated sediments within the area shown.

SANTA MARIA RESERVOIR.

Santa Maria Lake is a beautiful body of water resting in a long, narrow trough just west of Bristol Head, 4 miles northwest of Antelope Springs, near the eastern margin of the San Cristobal quadrangle. (See fig. 8 and Pl. III, *A*.) This reservoir may be reached from Creede by road, a distance of approximately 19 miles.

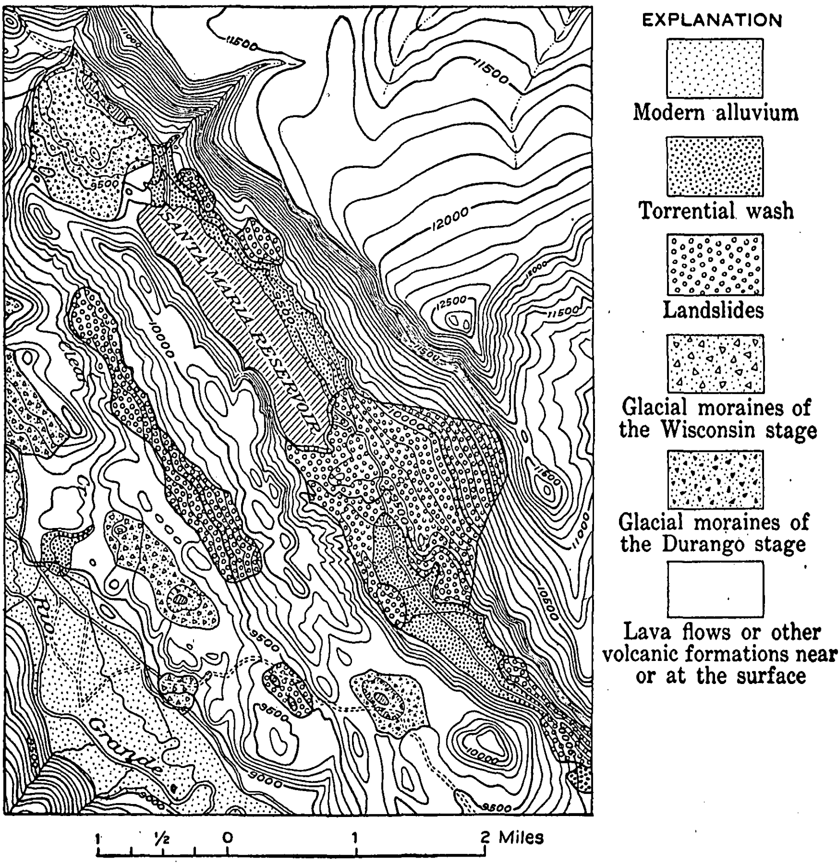


FIGURE 8.—Map of a part of the San Cristobal quadrangle, showing the location and topographic relations of Santa Maria reservoir and the distribution of the loose or unconsolidated formations within the area shown.

The nearly vertical wall of Bristol Head, to the east of the lake, rises over 3,000 feet above the lake level. To the west there is also a steep wall, but this one rises only 800 feet above the average level of the lake. Vast quantities of débris have fallen from the cliff immediately below Bristol Head and partly filled the depression just west of the mountain and south of the lake. (See fig. 8.) There is now a landslide mass at this locality fully 1 mile wide and 500 feet thick, extending for a distance of nearly 2 miles along the axis of the trough. At the north end of the lake basin there are deposits of glacial drift resting upon bedrock.

To provide for the storage of flood waters in this lake basin an earth dam with a concrete-core wall was constructed at the north end, a tunnel was driven at the northwest corner near the dam, a spillway was built near the dam, and an aqueduct was constructed so that the surplus waters of Clear Creek could be conducted to this basin. (See Pl. III.) The waters of several small streams from the east were also led into the lake basin. The tunnel driven through bedrock near the northwest corner is the outlet of the reservoir, and the waters as they issue from the tunnel follow an open ditch and soon enter Clear Creek, thence flowing into the Rio Grande. These waters are furnished to the ranchmen and farmers of the San Luis Valley. The engineering work and the mechanical construction appear to have been excellent. There is no leaking through or about the dam, and a very considerable head of water has been successfully held. At the south end, where the recent landslide masses form the

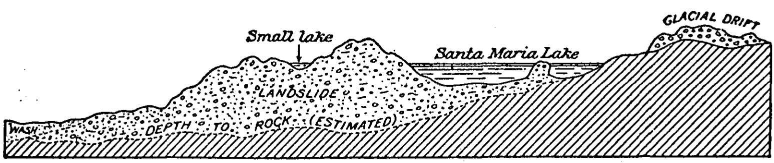
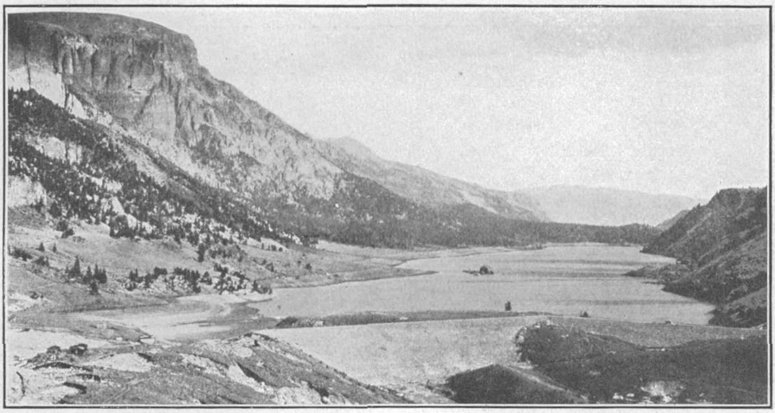


FIGURE 9.—Diagrammatic north-south section through the Santa Maria trough. The actual position of the bedrock surface beneath the lake and beneath the landslide mass south of the lake can not be given accurately.

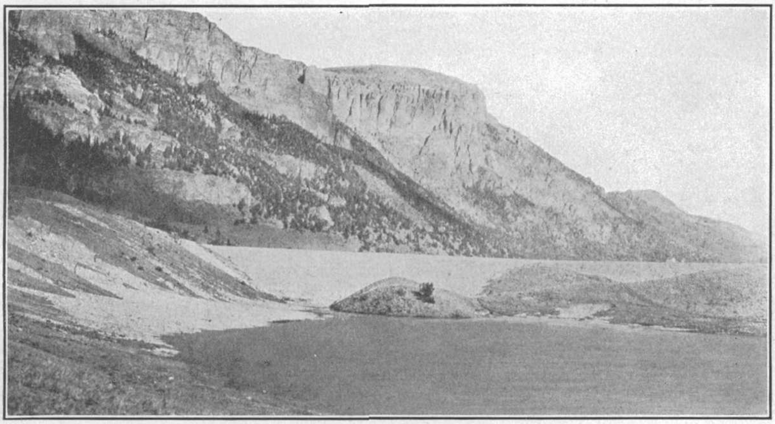
rim of the lake basin (fig. 9), large quantities of water have seeped through and issued fully a mile and a half to the south, forming a small pond from which, at times, a rushing torrent flows by Antelope Springs and into the Rio Grande. About the south end of the reservoir, however, no signs of leakage appear in the great landslide mass; the surface is apparently entirely unmodified. The water appears at the south margin of this landslide mass not from a single exit, like an underground stream, but probably from general seepage through this huge mass of material. About half a mile below the reservoir there is a small lake or pond in the midst of the landslide masses (fig. 9), and the waters in this small lake have risen and fallen with the waters in the reservoir. It is clear, therefore, that the seepage is quite free as far south as this lake, and the stream already referred to makes it also very apparent that the seepage is free still farther south and, indeed, throughout the mass.

During September, 1915, the waters were being withdrawn from this reservoir. Exploratory work was being carried on at the south margin to determine the nature of the material where the leakage was taking place. This work did not seem to yield significant results,



A. SANTA MARIA RESERVOIR FROM THE NORTH.

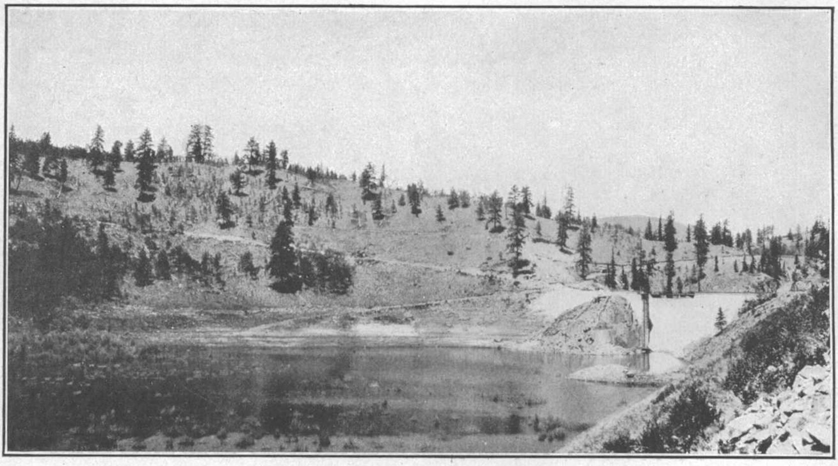
Bristol Head is at the left. The landslide mass blocking the reservoir at the south appears just beyond the water. The dam appears in the foreground. At the left in the foreground glacial drift is exposed.



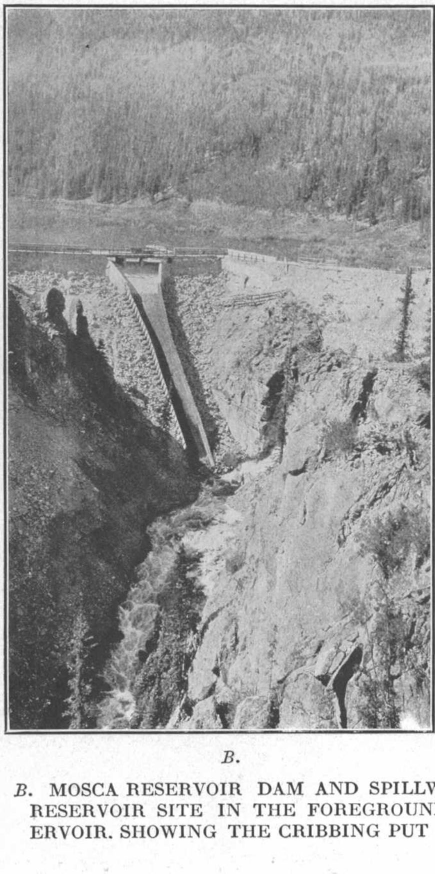
B. SANTA MARIA RESERVOIR DAM FROM THE NORTH.

A spillway appears near the left end of the dam. The control gate is regulated from the little house on the dam.

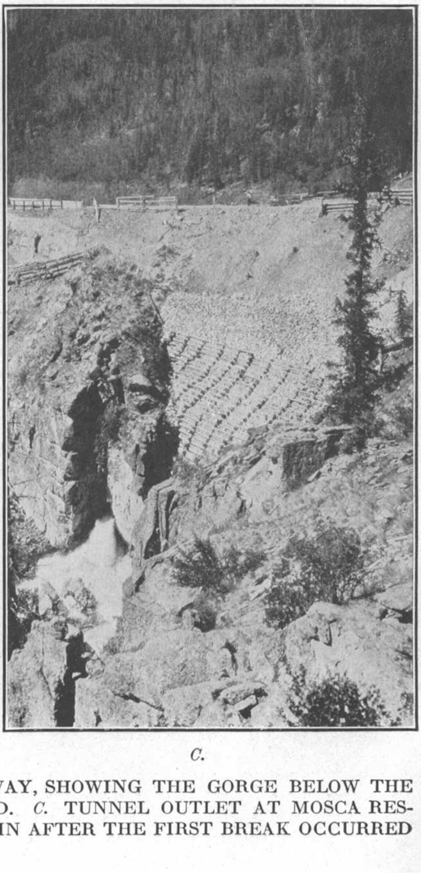
C. OUTLET OF THE SANTA MARIA RESERVOIR.



A. LOWER END OF MOSCA RESERVOIR, SHOWING DAM AND, AT THE LEFT ABOVE THE RESERVOIR, THE FRONTAL MORAINE.



B.



C.

B. MOSCA RESERVOIR DAM AND SPILLWAY, SHOWING THE GORGE BELOW THE RESERVOIR SITE IN THE FOREGROUND. *C.* TUNNEL OUTLET AT MOSCA RESERVOIR, SHOWING THE CRIBBING PUT IN AFTER THE FIRST BREAK OCCURRED and could not be expected to, for the nature and composition of a landslide mass can not be judged as well from a few small openings as from the surface. Tunnels and pits might be driven at a hundred places, and the only result could be to ascertain that the mass is heterogeneous detrital material that has fallen from the cliff at the east. It is composed of large and small angular blocks, rocks crushed in the falling and intermingled with some silts and sands. It may even have within it vast quantities of forest growth, which were enveloped in the sliding of the rocks from the mountain, and it may vary in composition greatly within short distances. It is safe to estimate its thickness at 500 feet, and its areal extent is shown in figure 8. Much of the torrential wash just south of this landslide area is interpreted as a mantle over other landslide material.

A serious problem confronts the engineer here, for the south end of the reservoir, where seepage is so generally taking place, has a very irregular outline. The covering of this slope with clay has been considered. One difficulty appears at once in the lack of an abundant supply of clay near at hand, and if this were done it would be very expensive. This reservoir presents a very interesting question. If the waters will not stand at the height desired, why is it that the lake waters have been held at all? It seems possible that the lower portion of the landslide mass may be more dense; perhaps the greater pressure has filled in more of the spaces. Possibly after the waters began to accumulate in this depression behind the landslide mass they leaked freely through to the south for many years. This leakage or seepage, however, passing through 2 miles of material, may have finally, with the help of rainfall and the waters seeping through the ground from above, sealed up with fine materials the passageways that had been used—effecting a sort of automatic puddling. Through this natural process the lower portion of the landslide mass may have become almost if not quite impervious. It is true that before the reservoir project was undertaken there was some water flowing southward toward Antelope Springs. Those interested in the reservoir are justified in hoping that as the waters continue to seep through they may again seal up the underground routes and thus make the landslide mass at the south end a satisfactory barrier. It was believed by those in charge of the reservoir that the leakage during 1916 was less than during the preceding years. If the leakage continues for a term of years without ever causing a real break through to the south it seems that the same processes that made possible the lake may make possible the larger reservoir.

In June, 1916, when this site was revisited, the water was much higher in the reservoir than during the preceding September, and yet the outflow to the south was much less, and the water in the small lake in the landslide mass just south of the reservoir had not risen with the rise of the water in the larger basin. Perhaps the ground was still frozen beneath the surface at that time early in the season, but if not, the reduction in the amount of seepage would seem to have removed all fear of serious trouble from that source. There are no other serious difficulties associated with this project.

MOSCA RESERVOIR.

By J. Fred. Hunter.

The dam of the Mosca reservoir project was built in 1913–14 to impound and store the flood waters of the Beaver Creek basin for

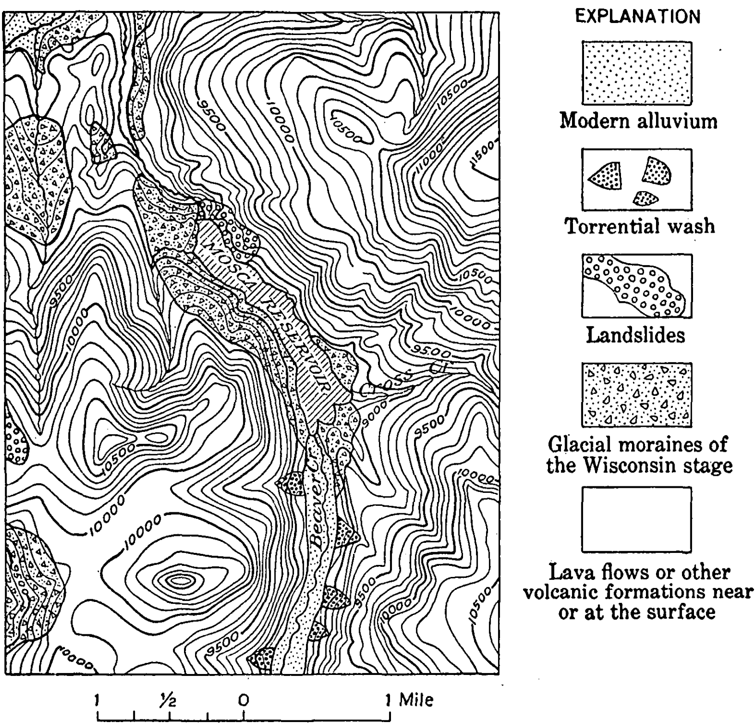


Figure 10.—Map of a part of the Creede quadrangle, showing the location and topographic relations of the Mosca reservoir and the distribution of the loose or unconsolidated formations within the area shown.

the irrigation of lands in San Luis Valley. It is 2 miles from the junction of Beaver Creek with the South Fork of the Rio Grande and 5.6 miles in an air line west of south (about 7 miles by road) from the town of South Fork, on the Creede branch of the Denver & Rio Grande Railroad. (See fig. 10.) The dam is built across a narrow gorge at the lower end of a long stretch of meadow land known as Beaver Creek Park and is of sufficient height to back water for approximately 1½ miles. The valley for this distance has a flat alluvial floor several hundred feet in width, from which the slopes rise rather abruptly on either side from 8,800 feet above sea level to more than 10,500 feet.

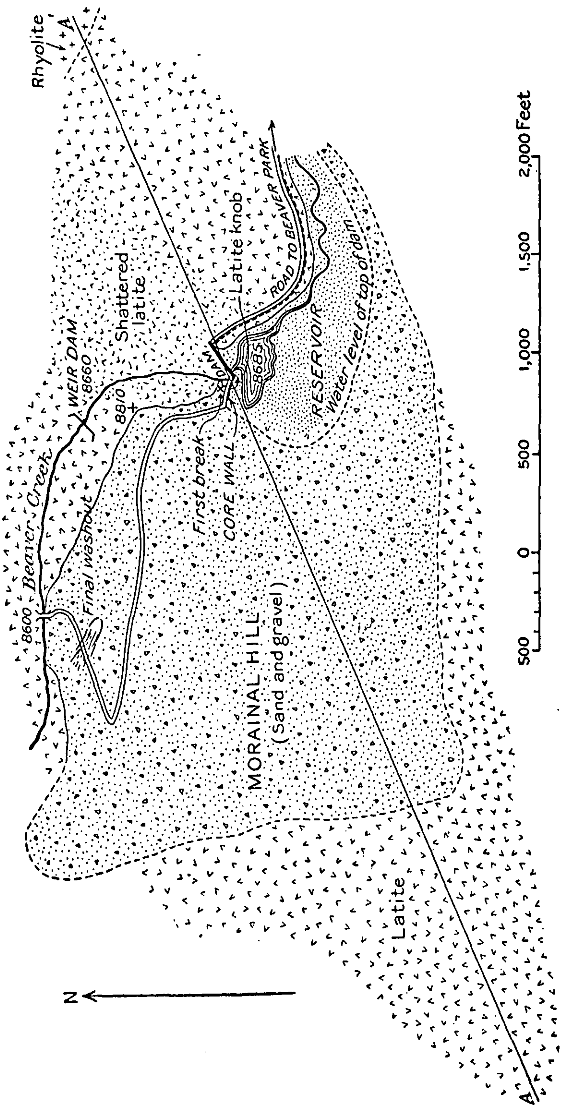


FIGURE 11.—Sketch map of Mosca reservoir project and environs, showing approximate boundaries of geologic formations. (The exact location of the core wall is not known.)

The distinctive feature of the site, which has attracted the engineer, is the abrupt closing in of the broader valley. A low, sparsely timbered morainal hill with gentle slopes and flat or rolling profile, rising 200 feet or more above the meadow, affords a natural barrier to the valley, crowding Beaver Creek against the foot of the steep north slope, where it is restricted to a narrow, V-shaped canyon.

At the entrance of this canyon is the dam, which is of concrete, reinforced by batter masonry on the downstream side, and is 85 feet high at its breast and 210 feet long at the top. It is built between walls of considerably shattered volcanic rock of the variety known as quartz latite. However, west of the dam this rock continues for only a short distance, giving way to unconsolidated glacial débris as indicated in the profile section of figure 12. (See also Pl. IV.) This volcanic rock forms a knob between the canyon and and the extensive deposit of sand and gravel which rests against and on it, filling a former channel in the harder rock to an unknown depth. The outlet of the reservoir is by a channel driven through this knob of latite in a northwesterly direction for approximately 40 feet.

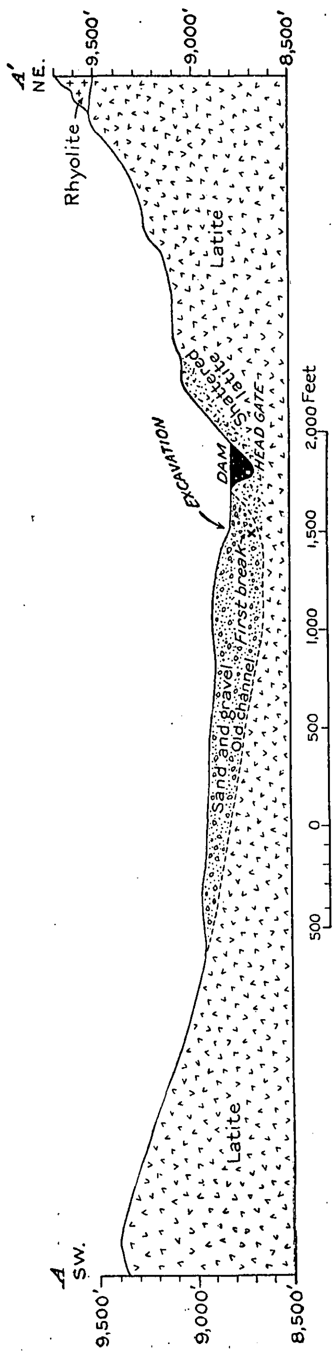


FIGURE 12.—Pofile section across Beaver Creek at Mosca dam, along line A–A' of figure 11.

The conditions can be best understood from the sketch of the dam and its environs (fig. 11) and the profile section across Beaver Creek just below the reservoir (fig. 12). These drawings are intended to present the relations graphically rather than to afford accurate maps of the locality. It should be understood that the contact between the volcanic rock and the gravels in the profile of figure 12 is hypothetical except for the points where it meets the surface.

The Mosca dam project is of especial interest as a demonstration of the inefficiency of a barrier of a certain geologic type to retain water. Several attempts have been made to fill the reservoir, but in each attempt the porosity of the barrier hill has led to leaks and to serious washouts. The first of these developed around the southwest end of the dam (see Pl. IV, *C*), and later ones resulted in a large washout along the road 1,500 feet to the northwest. (See fig. 11.)

Although the physiographic features that led to the selection of the dam site are rather obvious, the peculiar geologic conditions that make it undesirable and have resulted in its failure to retain water are apparent only after more detailed study. It is the purpose of this section to describe briefly the character of the formations and their structural relations; also to discuss the causes of failure and certain suggested remedies.

The bedrock in the vicinity of the Mosca dam is entirely of one kind, which may be best classified as a quartz latite.. This is the prevalent type of rock in the region and has an extensive distribution along the lower slopes of Beaver Creek and throughout the length of the South Fork of the Rio Grande. It is white or pinkish gray, is of easy fracture, and consists of scattered crystals of feldspar, biotite, augite, and orthoclase, less than 2 millimeters in diameter, set in a rather dense and obscure groundmass composed chiefly of an indistinctly polarizing aggregate, feldspar microlites, tridymite, and ferritic material. The lava has picked up a few angular fragments of andesites and other rocks in the process of its eruption, and where weathering has taken place small quantities of calcite, chlorite, and limonitic minerals have been developed. This latite has been poured out as molten lava, cooled, buried by younger flows, and later exposed by stream erosion.

The rock knob at the southwest end of the dam and the immediate rock mass at the other end of the dam have been interpreted as of landslide origin. This would account for the hillside topography shown in Plate V, *B*, and for the shattered condition of the dock at both ends of the dam. A serious leakage has occurred around the northeast end of the dam.

A close examination of the nature of the morainal deposits west and north of the bedrock knob shows that the faith which has manifestly been reposed in them is hardly warranted. A small cut west of the dam and above the road reveals its porous, unconsolidated character and shows that it consists of irregular stratified sand and fine gravel.

A better exposure has resulted from the washouts along the road some 1,500 feet to the northwest. Here nearly 50 feet of section shows alluvial layers of irregular, cross-bedded coarse and fine sands, grits, gravels, and conglomerates.

Partial section of material exposed in the largest washout from Mosca reservoir.

	Feet.
1. Coarse conglomerate	10
2. Rather fine, homogeneous, unconsolidated sand of dark-brown color, saturated with water	10
3. Black sandy member with thin layers of volcanic pebbles, largely black glass, becoming coarser at base	15±
4. Sandy member, similar to No. 2, with thin lenses of grit and fine gravel	10

The pebbles of the conglomerate are all of volcanic origin, such as might be derived from the Beaver Creek basin, are well rounded, and range in size from fine grit to boulders 10 inches in diameter. The coarser boulder beds show more irregular bedding and were doubtless deposited by torrential stream wash, whereas the sandy members are even bedded and suggest delta or pond deposits. No striations could be discovered on the boulders.

An examination of the hill above the dam reveals at once its morainal origin, for the country west of the dam for a distance of half a mile, included within the 8,900-foot contour as shown on the Creede topographic map, is of abnormal configuration, is poorly drained, and is covered with a thick mantle of boulders and wash.

Save for a small V-shaped area of till on the west wall immediately north of the latite knob, the waters of Beaver Creek now travel through a canyon of latite as far as the road bridge at the 8,600-foot contour crossing. At that place the morainal débris comes down to the creek and for 120 to 150 yards makes the south side of the stream channel. Below this a wall of latite rises gradually downstream. From the west end of the reservoir to this point, just below the bridge, an earlier, premorainal stream probably flowed through a fairly straight channel, now filled with glacial material. It was by way of this same route that the underground seepage waters from the reservoir found their escape. Below this point the earlier Beaver Creek channel coincides with that of the present stream.

The unconsolidated deposits here mentioned are believed to represent the accumulations of débris gathered by great glaciers descending from points high in the adjacent mountains of the Beaver Creek basin. After the retreat of the glaciers and after the South Fork had established itself in a deepened channel, Beaver Creek commenced the task of cutting another channel, releasing its impounded waters, and cleaning its valley of the vast accumulations of débris. In this process it seems to have found its easiest path to be coincident with its earlier channel except in a stretch below the Mosca dam as far as the road bridge. Here, by reason of the immense accumulations, it was forced to cut an entirely new course through the detrital material and into the harder volcanic rocks, forming the present gorge. This work was the more easily done by reason of the immense amount of unconsolidated gravel and boulders available in the upper course of the basin, which increased the abrasive power of the stream.

Many of the principal facts relating to the Mosca reservoir were established on the ground; other details have been acquired from fragmentary reports of persons who have knowledge of the project. With all the data so far available it is possible to construct an incomplete history of the project.

On the completion of the dam, in the summer of 1914, the head gate was closed and the filling of the reservoir commenced. The rising water brought an increasing pressure against the very porous gravel barrier which is really the major feature in the damming of the valley. Immediately the water began to seep around the latite knob at the southwest end of the dam, as indicated in figure 2—the knob which projects for about 90 feet above the valley floor through the accumulations of sand and gravel.

Before the reservoir was two-thirds full the fine till began to give way and to wash out so that it became necessary to construct cribbing filled with broken rock along the upstream limb of the V-shaped contact of the latite and gravel. (See Pl. IV, *C*.) A core wall about 120 feet in length has been built in a westerly direction from bedrock at the contact of the moraine with the latite. This contact is said to dip 45° along the line of the wall.

When the water was allowed to rise in the reservoir a second time a much larger leak developed at a point some 1,500 feet from the reservoir, on the slope 100 yards south of the road bridge. This leak proved to be even more serious than the first and quickly developed into a disastrous washout. The water escaped so rapidly and abundantly that the soft, unconsolidated sands and gravels are described as having been catapulted out of the hill, leaving a ravine as much as 20 feet deep and being washed down the slope to the valley bottom to form a large torrential fan. Although the beds at once became saturated and seepages appeared over nearly the entire slope, the bulk of the water is reported to have come out at about 20 feet below the bottom of the reservoir. This leakage proved so great and serious that it was necessary to reopen the head gate at once and relieve the pressure from the head of water in the reservoir. For several months during the winter of 1914–15 no effort was made to use the dam. In the spring of 1915 an attempt was made to puddle the reservoir west of the dam but without success.

The essential causes of the failure of the Mosca reservoir to retain water are clearly the presence of the buried channel and the unusually high porosity of the sands and gravels that fill it. This porosity is shown by the fact that at the time of the examination the exposures in the vicinity of the larger washout were saturated to a high degree and the sands and gravels were still in the process of draining, although the water was out of the reservoir save for the normal flow of Beaver Creek through it. Furthermore, the surface waters have no doubt taken advantage of the porosity and looseness of the material and have established more or less definite subterranean channels, as is indicated by the number of permanent and periodic springs scattered here and there over the area. The intakes of the subterranean channels are represented by smaller, partly choked openings near the base of the gravel embankment of the reservoir a short distance west of the latite knob. Flow lines of sand and débris into these holes indicate the passage of water out of the reservoir. In view of these conditions it is not surprising that when the water rose in the reservoir, exerting an unusual pressure against the morainal barrier, the gravels at once became saturated, subterranean channels were established, and the breaks resulted. It seems clear that the morainal deposits, in this locality at least, are not competent to retain a large head of water.

In view of the large sum of money already expended the further utilization of the project became a very serious question with the promoters, stockholders, and engineers. It is not within the province of this report to offer an opinion as to the feasibility of diminishing the leakage to such an extent that the reservoir could be used. However, it is very evident that to attempt to hold water in the reservoir without reinforcing the morainal end of the dam would be simply to invite disaster. Indeed, from past experience it is not improbable that the entire hill between the reservoir and the washout would be tunneled by the rush of water, and possibly the buried channel would be exhumed. Puddling of reservoir levees and embankments has been found practicable in many places but is only questionably applicable to this reservoir because of the absence in the vicinity of silt, clay, or fine shaly material with which to line the embankment. Revetments of masonry, concrete, macadam, asphalt, or logs have been suggested but should be adopted only after careful estimates by the engineers as to their cost and practicability. It would be highly advisable as a preliminary step to make a careful survey in an effort to ascertain the lowest point in the reservoir at which leakage begins. From the meager geologic examination so far made it seems probable that the leaks may have originated in the floor of the reservoir itself. If this is found to be the case, a revetment of the embankment alone would not be sufficient, but it would have to extend for greater or less distances out upon the floor of the reservoir, amounting to many hundreds of square yards.

SUPPLEMENTARY NOTE BY W. W. ATWOOD.

When the writer visited the Mosca reservoir in June, 1916, a group of engineers were at work trying to prevent the leakage. On the east side of the dam, where the leakage had been very great, they were drilling holes at intervals of 10 feet and to the depth of 90 feet. Farther south the interval between the holes was to be 20 feet. Into these holes they were forcing cement under a pressure of 40 pounds, in the hope that the cement, spreading through the fractured rock, would seal up all openings. The holes were drilled from the roadway, and 90 feet took them nearly to the bottom of the reservoir.

Another project was also under way. A tunnel had been driven into the moraine a little to the north of west from the cribbing near the west end of the dam. This tunnel had been driven 180 feet, and it was proposed to take it 135 feet farther. The base of the tunnel is 13 feet below the reservoir gate and about 7 feet above the base of the reservoir. At intervals of 6 feet perforated iron pipes were driven from the roof of the tunnel upward through the sands and gravels, in the hope that the waters seeping into the moraine would enter the small holes in the pipes and be led off by the tunnel into the stream below the dam, thus preventing the seepage from passing through the moraine and washing it away.

Early in the season, before this work had been completed, the gate was closed and the water was allowed to rise in the reservoir. Before it reached the desired height a serious leak occurred near the east end of this tunnel. It appeared that not all the escaping water was accommodated by the pipes then in place, and that some ran directly into the tunnel. This water washed with it sands and gravels, and a large mass fell and broke down that end of the tunnel. The engineers concluded that the timbering must be made exceedingly strong and that the work must be carried much farther into the hill before the water was again allowed to rise. It was their intention to complete the work thus outlined and in the spring of 1917 to make another trial. The device put into the moraine was called a "drip curtain."

TERRACE RESERVOIR.

The Terrace reservoir lies in the valley of Alamosa Creek, in the foohill belt of the San Juan Mountains in Conejos County, and may be easily reached by road from Monte Vista or Alamosa. (See Pl. V, *A*.) The "terrace," or broad alluvial land that receives the water from this reservoir, is a torrential fan spread out in the San Luis Valley beyond the base of the mountains. From the apex this fan slopes radially to the northeast, east, and southeast. Near the apex the slope is 75 feet to the mile. Farther east, lower on the fan, the slope is 10 feet to the mile. This fan form is admirably adapted to irrigation, as the main supply canal may be brought to the apex of the fan and lateral canals constructed to the right and left so as to supply waters over the entire area of the deposit. Near the apex the alluvial material is coarse and in places bouldery, but farther from the mountains it is finer and very suitable for agriculture. Thousands and thousands of sheep that spend their summers high on the mountains are brought to these lowland fields for the winter and fattened. Thousands of hogs are here fattened for market. During the winter horses and cattle that have been on the open range during the summer are brought into the irrigated fields and fed.

The dam is 5 miles above the mouth of the canyon. It is an immense earth dam, reported to be the largest in the United States. It

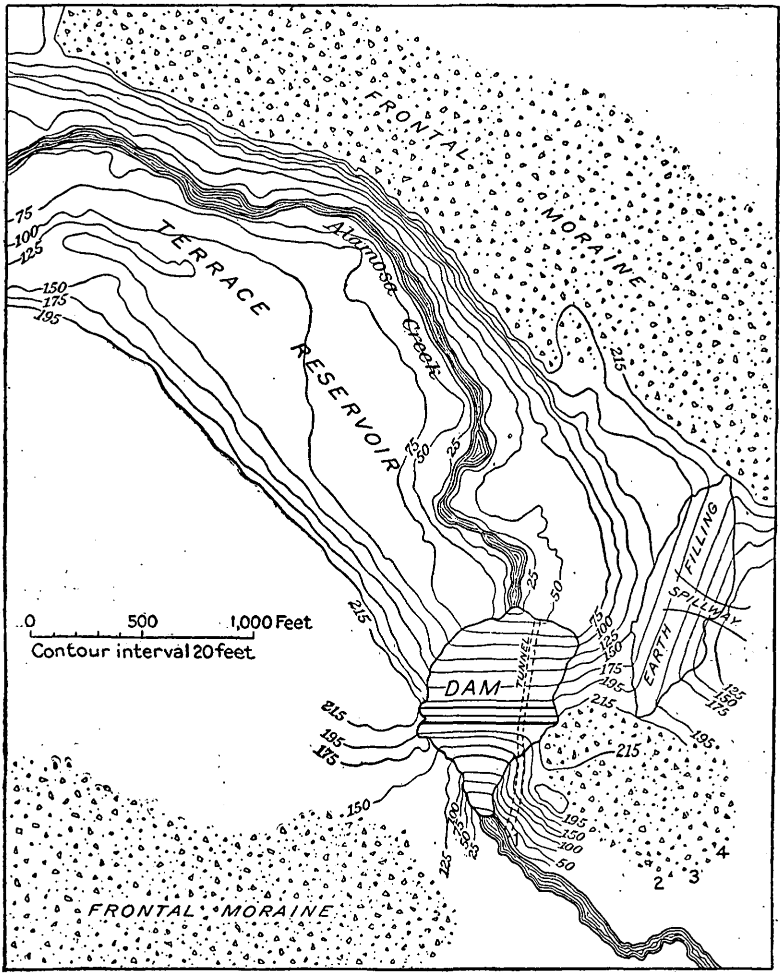
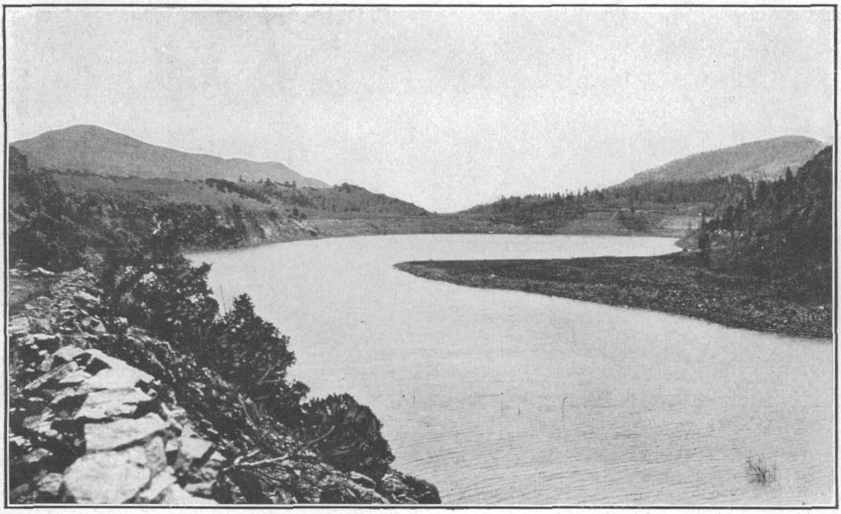


FIGURE 13.—Sketch map of the lower end of the Terrace reservoir, showing the general distribution of the frontal moraine that determined the location of the dam and reservoir site. 1, Lower opening of tunnel; 2, 3, 4, seepage vents. Contours have been taken from a map in the office of the State engineer of Colorado.

is 165 feet high, and its length at the base along the course of the stream bed is 1,075 feet. A tunnel driven through hard rock (see fig. 13) is 1,000 feet long, 7 feet high, and, on the average, 12 feet wide. The discharge, under a 70-foot head, is estimated at 1,300 cubic feet per second.

The dam is constructed in a narrow rock gorge just downstream from a broad, open portion of the valley. (See Pls. VI and VII.)

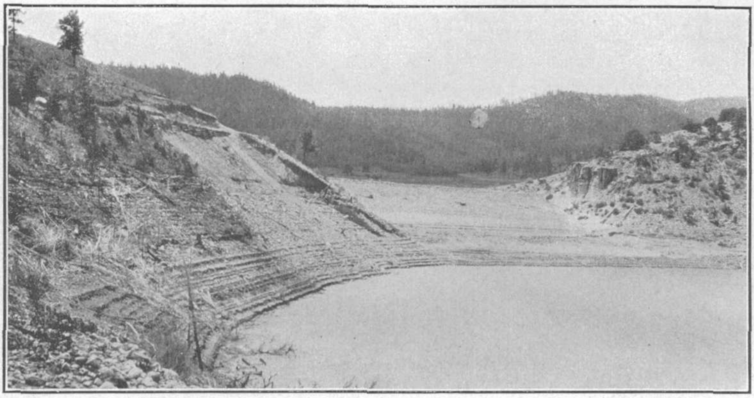


A. TERRACE RESERVOIR.

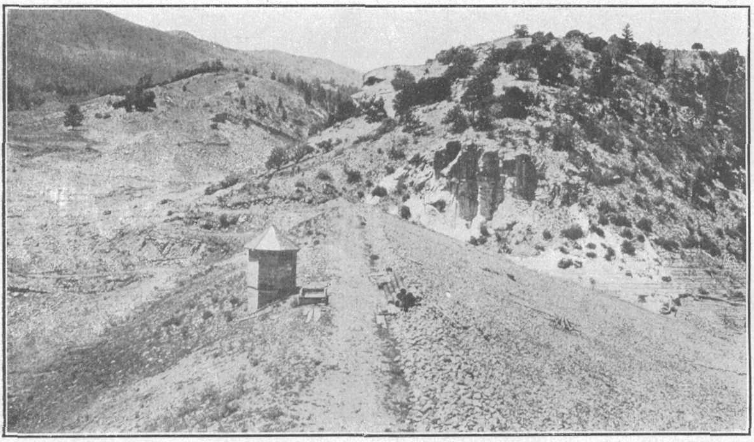
The dam is at the right, and the earth filling and spillway are in the middle ground beyond the water. The low hills at the left form a part of the moraine and rest upon a lava flow.

B. MOSCA RESERVOIR SITE.

This view shows the location of the dam, the cribbing where the first break occurred, the landslide mass at the left end of the dam, the great moraine at the right end of the dam, and the narrow gorge below the reservoir site.

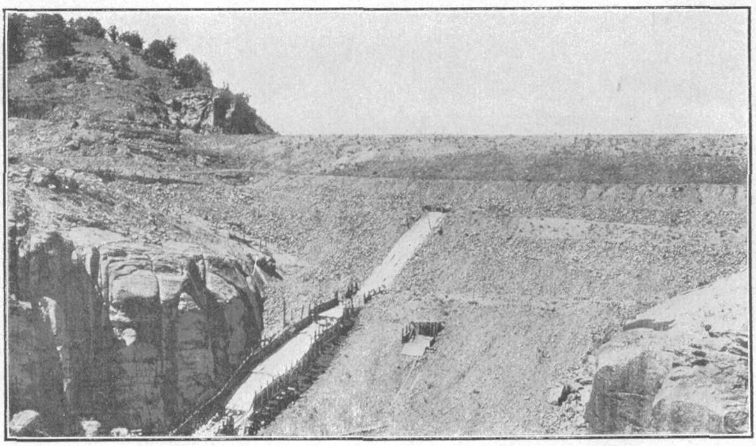


A. TERRACE RESERVOIR DAM FROM THE NORTH.



B. CREST OF TERRACE RESERVOIR DAM.

The gate in the tunnel is controlled from the house on the dam.



C. TERRACE RESERVOIR DAM FROM BELOW.

The spillway here shown was used during the construction of the dam.

In figure 13 the general topography and geologic conditions of the area surrounding the site of the dam are given. The glacial moraine at the north, east, and south indicates that for some time the front of a great alpine glacier rested at just this place in the valley of Alamosa Creek. While the ice was present the drainage must have found an outlet in part from beneath and in part from the surface of

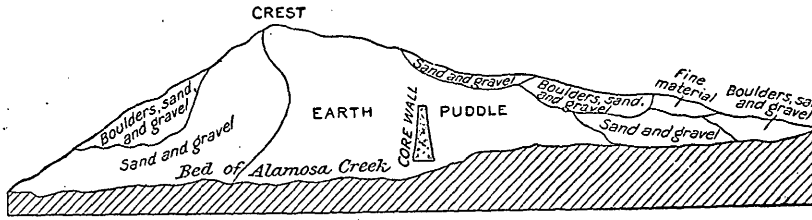


FIGURE 14.—Cross section of the earth dam of the Terrace reservoir, based on data furnished by R. I. Meeker, engineer in charge, 1916.

the glacier. The heavy morainic deposit completely filled the preglacial route of the stream, and as the ice retreated the water issuing from the melting glacier found a route at the south margin of the valley and there cut a narrow gorge in rock (Pl. VII, *C*). This gorge, due to a disarrangement of drainage caused by the glacier and the moraine it left, was chosen for the site of the dam because of the firm rock walls on either side. In constructing the dam a concrete baffling wall was firmly cemented to the sides of the gorge, and a concrete core wall 70 feet high was also constructed. (See figs. 14 and 15.) The earth material used was chiefly of glacial origin, and a gigantic puddle was formed in the central portion of the gorge about the core wall, so that an abundance of fine material might settle in that portion of the proposed dam.

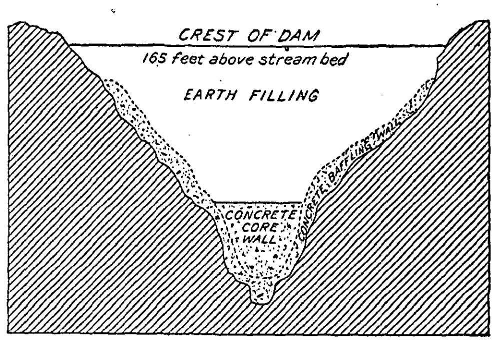


FIGURE 15.—Cross section of the gorge in which the earth dam of the Terrace reservoir has been placed, based on data furnished by R. I. Meeker, engineer in charge, 1916.

A lower earth dam or filling was constructed a little to the northeast and above the former channel of the stream. Through this filling a spillway has been provided.

This reservoir draws upon a large drainage area. Alamosa Creek and its tributaries head far back in the high mountain area to the west, and there is usually an abundance of water available. At points 2, 3, and 4 on figure 13 large leakages, which appear as springs on the loose glacial débris, but when seen in the summer of 1916 the water was issuing in a remarkably clear condition. Those in charge of this reservoir report that the seepages began soon after the water was first allowed to rise and have occurred during each succeeding season. The leaks suggest the danger of large subterranean routes through the glacial material, perhaps at the base of the drift and on the rock surface, but as they have continued for several years without producing any serious damage there seems to be no immediate reason for fear.

LA JARA RESERVOIR.

The La Jara reservoir is on La Jara Creek, in Conejos County, and may be reached most easily from Monte Vista. It was constructed in 1909. The geologic conditions of the area surrounding the lower end, where a dam has been placed, are shown in figure 16. At the north there are dense lava flows forming the gentle slopes of this foothill region, but at the south there is a heavy frontal moraine of an ancient glacier. The ice appears to have advanced from the high mountain region a little to the south of west and, on reaching this lowland country, deployed northward so that La Jara Creek was forced to flow between the margin of the ice and the lava hills. On the retreat of the ice the stream cut a narrow gorge in the margin of the moraine, where the present outlet of the reservoir is placed.

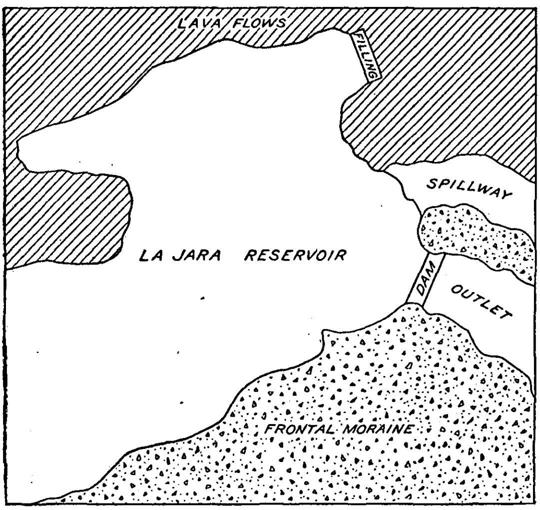
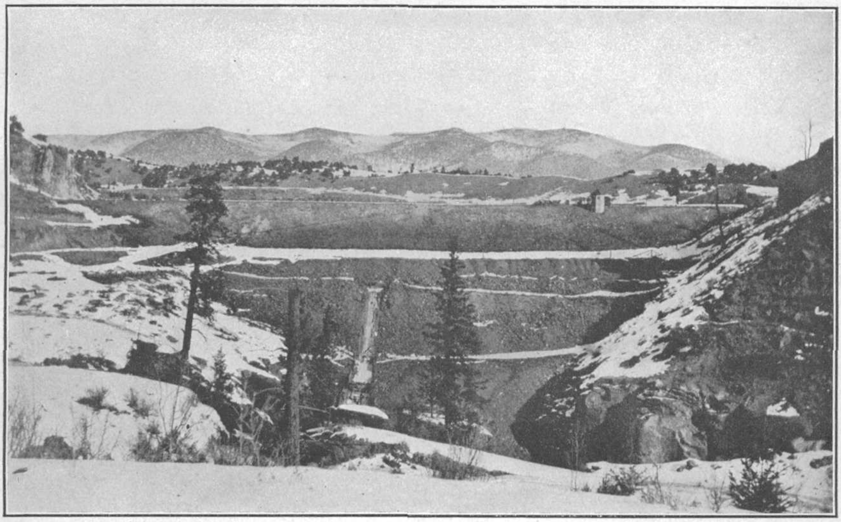


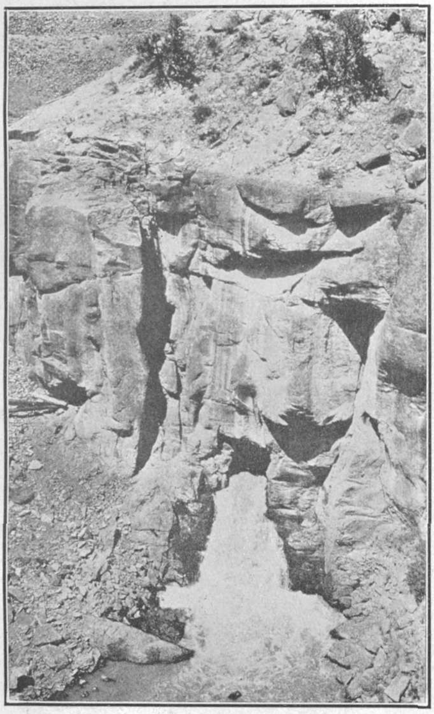
FIGURE 16.—Sketch map showing geologic conditions of the area immediately surrounding the lower end of the La Jara reservoir, based in part on a map in the office of the State engineer of Colorado.

Two dams were constructed of the surface débris of glacial origin and the weathered volcanic rocks. One is 759 feet long and 51½ feet high. The other and more northern one is 23½ feet high and 495 feet long. The slope of these earth dams is 3 to 1 on the upper side, facing the reservoir, and 2 to 1 on the lower side. Their crests are about 15 feet above high water and 12 feet wide. A spillway has been provided through a low trough just north of the glacial moraine, by a route that was probably used by the stream when the ice was present. The estimated area tributary to this reservoir is

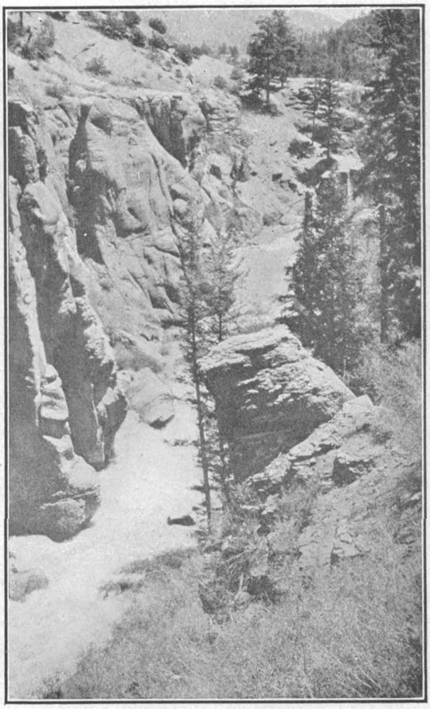


A. GENERAL VIEW OF TERRACE RESERVOIR DAM FROM THE SOUTH.

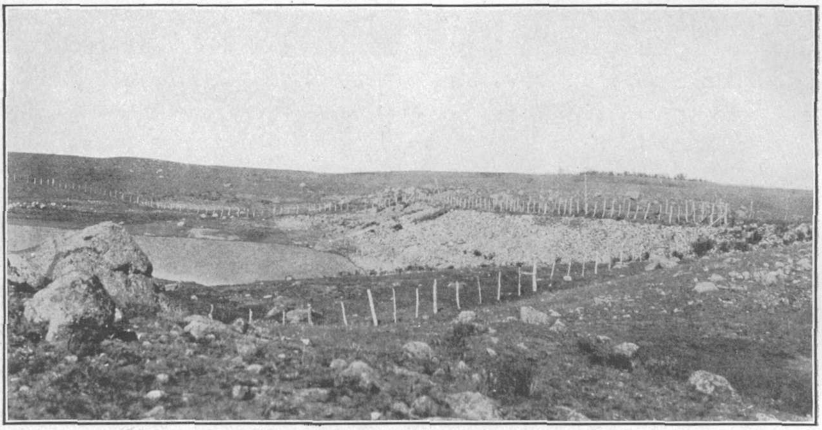
The rock walls of the canyon appear, in the midde ground is the spillway used during the construction, the house from which the gates are controlled appears on the dam, and the line of hills in the distance next below the sky line is a portion of the great frontal moraine.



B. OUTLET OF TERRACE RESERVOIR TUNNEL.

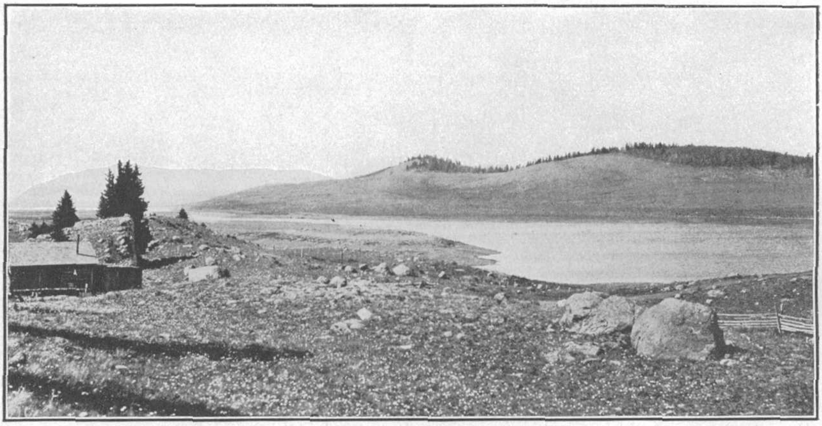


C. POSTGLACIAL GORGE BELOW TERRACE RESERVOIR.



A. LA JARA RESERVOIR DAM.

Morainic material appears in the foreground.



B. LA JARA RESERVOIR.

The moraine shows in the foreground. The distant hills are composed of lava flows.

C. TUNNEL OPENING IN THE LA JARA DAM.

50 square miles, and the claim is made for the full capacity of the reservoir, estimated at 20,000 acre-feet. The water is taken from La Jara Creek and all its tributaries, including Lost Creek, and may be used for domestic purposes, irrigation, power, or any other beneficial purposes.

This reservoir has become the property of the Terrace Reservoir Co. and is used as an "exchange reservoir." Water is taken from Alamosa Creek, and in return the La Jara water is carried into that creek a little farther downstream to satisfy old priorities. This exchange is permitted by a State statute.

There is some seepage through the dam, but it has never become dangerous. The reservoir as constructed will hold much more water than is available. To the south of the great frontal moraine, and from a quarter to half a mile south of the reservoir, a number of large springs have developed, and those who are familiar with the history of this project report that these springs have appeared since the damming of La Jara Creek, and that they are affected by the height of the water in the reservoir. This would indicate that the great morainic mass is not sufficiently compact to hold all the water collected in the reservoir to the north of it. The water presumably sinks through to the base of the glacial débris and follows the rock surface beneath.

Plate VIII gives good general views of the reservoir, of the larger dam where the outlet is located, and of the massive moraine south of the reservoir.

PROPOSED RESERVOIR IN CLEAR CREEK.

The upper portion of Clear Creek is in the north-central part of the San Cristobal quadrangle. A short distance above the point where the stream turns toward the southeast to flow to the Rio Grande the valley is constricted, as shown in figure 17.

The constriction is due in part to rock, but the rock is overlain by glacial débris. Upstream the valley is broad, open meadowland. Before construction work is begun a detailed study of the geology at and near the dam site should be made. The clearing away of the glacial débris and all loose rock and the construction of the spillway in solid rock should make this project safe so far as leakage is concerned. The drainage area that furnishes water to this creek, however, is relatively small.

PROPOSED RESERVOIR ON SOUTH FORK OF CLEAR CREEK.

The South Fork of Clear Creek is nearly due west of Santa Maria Lake, in the central part of the San Cristobal quadrangle (fig. 17). The upper part of the valley is broad and open, and its floor is an extensive meadowland. Near the point where the stream turns southeastward the valley is rather narrow, and the narrow portion has been thought of as a possible site for a dam, above which the waters would collect on the present meadows. This is a very unfortunate selection for a reservoir site, as the deposits at the proposed site are of glacial and landslide origin. It is extremely doubtful whether that material would hold in more than a low head of water. The fate of the Mosca reservoir, in the Creede quadrangle, should be a

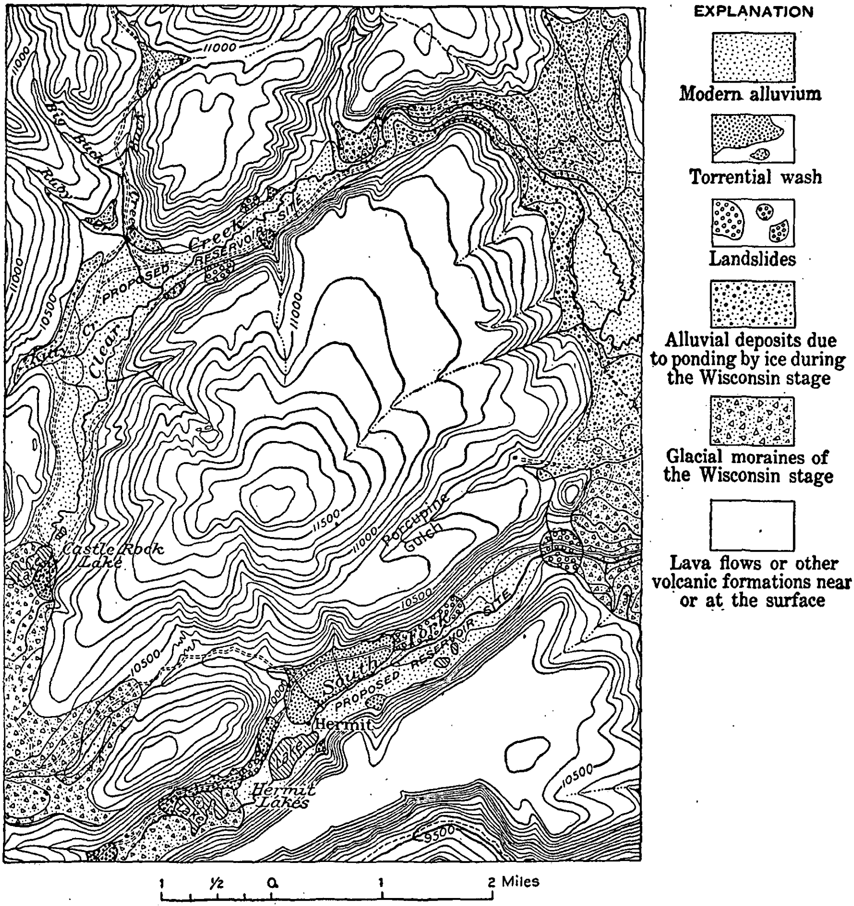


FIGURE 17.—Map of a part of the San Cristobal quadrangle, showing the location and topographic relations of the proposed reservoir sites in Clear Creek and South Fork of Clear Creek and the distribution of the loose or unconsolidated formations within the area shown.

sufficient warning against undertaking a project under geologic conditions such as exist near the mouth of the South Fork of Clear Creek. Furthermore, the surplus waters of that fork are exceedingly small, and the project would certainly not justify large investments. Before construction work is begun a detailed geologic study should be made of the land immediately adjoining the proposed site for the dam.