Introduction: Geologic analyses in Tyrrhena Terra (13°-30°S, 265°-280°W) have revealed a complex history of impact cratering and fluvial activity [1-5]. MOC, THEMIS, and Viking Orbiter images and MOLA topographic data have been used to characterize and map fluvial systems. Fluvial features in this region include widespread, well-integrated valley networks, such as Vichada Valles (Figure 1), smaller networks and single channels, and gullies incised along the rims of impact craters [5,6]. ArcGIS has been used in conjunction with MOLA DEMs to model drainage basin divides, simulate valley networks, and derive basin and network morphometric parameters useful in characterizing basin "maturity" and processes of watershed development. Comparison of mapped and modeled watersheds allows both the evaluation of terrestrial techniques applied to Mars and provides a means to characterize the nature of Martian watersheds.

Geologic Setting: Tyrrhena Terra displays a shallow (0.23°) southward-trending slope toward Hellas basin. Geologic units consist of interlayered sedimentary, volcanic, and impact-related (e.g., ejecta, impact breccia) materials [1,2,5] that are believed to be laterally and vertically variable [7], both regionally and within individual drainage basins.

Tyrrhena Terra shows abundant evidence for erosion and deposition by fluvial processes, including valley networks that dissect an extensive Noachian-aged intercrater plains unit [5]. Vichada Valles, composed of at least eleven sub-basins, is the major watershed in this region [4,5,8-11]. Much of the erosion that formed valleys and eroded craters in this area is believed to have occurred in the Late Noachian Epoch and continued into the Early Hesperian Epoch [2,3,5,12]. Previous researchers [e.g., 13,14] have suggested some valleys in Tyrrhena Terra formed by combinations of runoff-induced mass wasting and sapping processes; however, questions regarding the ability of sapping to be sustained along crater rims are applicable here. Furthermore, the ability to sustain an interconnected aquifer system in Tyrrhena Terra is problematic where interlayered sequences of volcanic, sedimentary and impact materials [5] would likely restrict groundwater flow.

Methodology: Insight into the hydrologic history of Tyrrhena Terra is provided by detailed mapping of fluvial features combined with modeling of valley networks using Arc/Info and MOLA DEMs.

Hydrologic Mapping: Viking Orbiter (10-90 m/pixel), THEMIS day IR and VIS (~100 and 20 m/pixel, respectively), and MOC narrow-angle (1-8 m/pixel) images were used to identify valleys and produce a detailed hydrologic map of the Tyrrhena Terra study area. High-resolution data have allowed significantly more tributaries to be identified than in previous studies [e.g., 9] for which minimum widths and lengths were typically ~900 m and ~10 km, respectively. At the time of our mapping, THEMIS IR and VIS images provided the highest resolution coverage and most consistent lighting conditions for the study area, allowing identification of valleys to be made on a consistent basis.

Hydrologic modeling: Drainage divides and valley networks were modeled using standard techniques for terrestrial drainage networks [e.g., 15-20], including the Arc/Info GRID functions FILL and FLOWACCUMULATION, applied to MOLA DEMs (64 pixel/degree). The modeling approach involved running the model using different values for these two functions, specifically for sink-fill depths (SFDs - FILL) and flow accumulation values (FAVs - FLOWACCUMULATION), in order to find the "ideal" values that produced basins and networks that best approximated the mapped watersheds.

The FILL function removes local sinks, which here include artifacts from DEM generation and the deepest pixels found within impact craters or other enclosed depressions in the topographic data set. Removal of these pixels is a standard and required step in terrestrial surface water runoff modeling [e.g., 15,17,21-23]. Sinks are filled to the 'sink-fill depth' (SFD), which...
represents the specified maximum depth of a sink that will be filled. In general, filling sinks increases the ability of the DEM to be fully drainable. Part of the modeling technique has been to determine the appropriate SFD to model drainage basins at a scale adequate to approximate basins identified from mapped valley distributions. Identification of the ideal SFD involved running iterations of the model using several SFDs to determine if (1) the number of modeled drainage basins equal the number of mapped networks and (2) the modeled drainage divides enclose the mapped networks. The optimal SFD value is selected based on the match of predicted drainage divides to the topography of the region, taking into account the potential for impact generated topography following fluvial incision. For derivation of network morphometric parameters, the ideal SFD is later coupled with an ideal FAV that is selected based on the best match of model-predicted and mapped valleys.

The FLOWACCUMULATION function is used to calculate an accumulation grid, which is a grid of accumulated flow to each 'downstream' pixel [17,20,21]. Accumulated flow is based upon the number of upstream pixels that contribute to each subsequent downstream pixel. Arc/Info uses a flow accumulation threshold method to determine the locations of stream channels. Lowering the flow accumulation value (FAV) results in a corresponding increase in drainage density. The software accumulates the weight for all pixels in the grid that flow into each downslope cell; in general, pixels with zero flow are topographic highs and determined to be the drainage divides, and pixels with high accumulation are areas where water is concentrated and are used to determine the locations of stream channels. Several iterations of the model were run using FAVs ranging from 100 to 5583; the resulting networks were compared to the image-based mapped networks (Figure 2). Two criteria were used to determine which model iteration most closely approximated the mapped networks: 1) the locations of valley heads and along-stream portions of the modeled valleys and 2) the number of modeled valleys. Selection of the optimal FAV also takes into consideration competition between cratering and fluvial activity. However, unlike selection of a SFD, selection of an ideal FAV is a basin-dependent value due to the inconsistencies in topography between basins.

**Figure 2.** Comparison of mapped networks and closest-match modeled watersheds for basin #89 (SFD=575). The mapped watershed shows higher drainage densities on steep slopes (northwest) and lower densities on flat terrain (east and south). FAV=100 best approximates the dense networks and FAV=775 best approximates the networks on the flatter terrain.

**Results:** The following results are based on (a) valley networks mapped from image data sets and (b) basin divides and networks modeled using a SFD=575 m, FAV values ranging from 190 to 5583, and a 64 pixels/degree MOLA DEM.

**Valley Network Morphology:** Vichada Valles and several smaller networks, separated from Vichada Valles by impact craters or ejecta, dissect large portions of the highlands. These networks display dendritic to (sub)parallel patterns. Here, isolated networks have been treated as separate sub-basins, but many were likely connected to Vichada Valles at one time. MOC images show that valleys are highly degraded with rounded banks, layers or terraces along valley walls, and dune-forming sediments covering their floors [5]. MOLA profiles show that most trunk valleys have flat or gently sloping floors and many tributaries are V-shaped in cross-section; valley depths and widths range between ~70 to 200 m and ~0.9 to 10.5 km, respectively.

Some valleys, particularly those that have no tributaries or form dense (sub)parallel networks, are smaller and appear less incised than Vichada Valles and other large dendritic systems in the region. The tributaries of these smaller systems typically head at crater rim crests and are generally not more than a few kilometers long. Their occurrence on relatively steep slopes results in more closely spaced tributaries. None of these smaller networks are observed to intersect the trunk valley of Vichada Valles. The morphologic differences between these smaller networks and Vichada Valles could be due to differences in processes of formation (sapping versus surface runoff), age, lithology, and (or) slope.

**Delineation of Watersheds:** Modeling at SFD=575 m yielded 151 drainage basins and several networks with no associated divides that extend beyond the limits of the study area. Drainage divides consist of combinations of impact crater rims, ridges associated with upland terrains, and degraded, discontinuous craters. Of the 151 basins, 119 correspond to impact craters (79%), of which 111 are single craters (93%) and 8 are clusters of two or more craters (7%). Of the 119 crater basins, 58 of these (49%) correspond to impact craters (single and clusters) that postdate fluvial activity in Tyrhenna Terra, as determined from our geologic mapping. Many of these craters may have formed after the period of fluvial dissection.

**Comparison of mapped and modeled watersheds:** Our model uses the DEM to delineate valleys within a watershed based on topography; thus modeled networks and morphometric parameters calculated from modeled valley data can be considered to be ideal for these basins, reflecting mature systems in idealized watersheds.

Visual inspection of mapped and modeled watersheds for 11 selected basins shows an overall good match for the locations of valley networks, but an overall
poor match for the amount of dissection. Regional differences between mapped and modeled networks can be seen in Figure 3. Second and third order modeled valleys are good approximations of the equivalent mapped valleys in terms of both the numbers and locations of valleys, but the numbers and locations of modeled valleys are less accurately predicted for first order tributaries. The iterative process for selecting the FAV and the reasonable match for lower order mapped and modeled valleys suggests that either this approach needs additional constraints on the surface geology, that a modeled variable intra-basin FAV is needed, and (or) that there are differences in watershed formation between Earth and Mars resulting in less dissection of the Martian surface.

Impact crater-derived topographic effects on hydrology: In order to properly interpret network and basin morphometric parameters, temporal relationships between impact cratering and fluvial activity within 11 selected drainage basins were assessed. Each basin was categorized according to the relative numbers of pre- and post-fluvial craters (PrFCs and PoFCs, respectively). This categorization is used to evaluate the degree of topographic change within a basin relative to the fluvial activity. Impact craters identified within the 11 basins are grouped into D>3 and D>10 km bins, including only craters whose rims are contained entirely within the drainage divides and do not form any parts of the divides. Craters whose rims form part of the drainage divide were not selected because their topographic signatures have already been recognized by the model and will affect the locations of delineated valleys. In addition, the topographic effects of craters with D<3 km, are believed to be insignificant for the current study. These small-diameter craters would generally not hinder valley development, and valleys could easily adjust their pathways around them.

For craters with D>3 km, four basins contain more PrFCs than PoFCs, four basins show the opposite relationship, and three basins show equivalent numbers of PrFCs and PoFCs. For craters with D>10 km, five basins contain significantly more PrFCs than PoFCs, five basins contain no craters larger than 10 km in diameter. Six basins show equivalent or less modification by PoFCs. Finally, only three basins contain craters larger than 10 km in diameter, suggesting only these basins have topography that has been significantly modified by PoFCs, which would affect the results of the Arc/Info model.

For example, all of the mapped valleys in basin #89 clearly postdate the surface materials in which they occur (Figure 4), and all of the larger craters (D>10 km) found within basin #89 and those that form portions of the drainage divide clearly predate valley formation. Conversely, in basin #3, many of the modeled valleys do not reflect observed cross-cutting relationships with craters, but modeling predicts valleys where they are not observed in order to "avoid" topographic obstructions such as for the fourth order mapped trunk valley of Vichada Valles in basin #3 that is clearly truncated by a cluster of at least 16 large (D > 10 km) craters. For this and other parts of the study area, knowledge of temporal relationships between fluvial activity and cratering is critical, and the model alone cannot be accurately used to evaluate Martian valley network development.

Drainage Patterns: Drainage patterns are generally consistent between the modeled and mapped data. Mapped networks in Tyrrhena Terra show dendritic and (sub)parallel patterns, but the mapped networks within some basins appear less integrated than the corresponding modeled networks. Regional slopes in the study area are low, which is consistent with the large dendritic pattern of the Vichada Valles system. (Sub)parallel drainage patterns occur on steeper slopes, such as along the rims of impact craters. Variations in geology (lithology, structure, etc.) could have also influenced drainage patterns where spatial variations in layered sequences might influence infiltration and thus the amount of runoff produced [24].

Drainage Density: Drainage densities for the 11 basins range from 0.004 to 0.122 km\(^{-1}\) for mapped valleys (average=0.043 km\(^{-1}\)), and 0.015 to 0.123 km\(^{-1}\) for modeled valleys (average=0.046 km\(^{-1}\)). Previous studies (<1:2M scale) of highland terrains found that Martian drainage densities ranged from 0.001 to 0.34 km\(^{-1}\) [10,13,14,25-28] with extremes of 0.0032 km\(^{-1}\) for Noachian units, 0.00047 km\(^{-1}\) for Hesperian units, and 0.00007 km\(^{-1}\) for Amazonian units (1:2M scale) [9]. Recent studies calculating drainage densities from automatically extracted networks from MOLA topography were found to be 0.193 km\(^{-1}\) [29-32] and 0.06 to 0.22 km\(^{-1}\) [33-35], comparable to densities calculated in this and other studies of Martian drainage basins.

**Figure 3.** Comparison of (a) modeled (SFD=575 m; FAV=775) and (b) mapped watersheds for 11 drainage basins (labeled) that are believed to comprise the Vichada Valles system.
CONCLUSIONS: We have completed geologic and geomorphic mapping and hydrologic surface waterflow modeling in the highlands of Tyrrhena Terra, Mars. The presence of valley networks, the establishment of integrated dendritic and (sub) parallel drainage patterns, and the distribution of valleys and eroded impact craters throughout Tyrrhena Terra suggests that fluvial dissection of the highlands was widespread. Morphologic observations, crater-valley relationships, impact crater distributions, and the lack of evidence for significant reactivation of valleys by later pulses of fluvial activity suggest that most Tyrrhena Terra valleys are ancient, most likely Noachian in age.

Comparisons of mapped and modeled watersheds show that the Martian networks observed in images do not approach an idealized case of a precipitation-dominated system over large areas or of uniform, widespread dissection. As a first order attempt to identify watersheds on the present Martian surface, the hydrologic model used in this study appears to adequately delineate drainage divides and large-scale networks, at least down to second order valleys. Delineation of drainage divides and valleys are affected by the spatial (~64 pixels/degree) and vertical (~10 m) resolution of the MOLA DEM. As a result, the model most accurately predicted valleys greater than half a kilometer wide and 10 meters deep. The hydrologic model shows widespread development of valley networks, which is inconsistent with large areas of apparently undissected terrain observed in images. SFD and FAV selection are important factors in using the model to best predict the locations, numbers, and patterns of mapped valleys. Rigorous comparisons of the model results to image data have helped to produce accurate maps of Martian drainage basins and their associated valley networks. Understanding the timing and extent of fluvial and impact processes from geologic mapping provides key information for quantitative characterization of fluvial systems using hydrologic models.

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